European
Commission

Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage under FWC ENER/C3/2015-619-Lot 1

TASK 1 Report

Scope (Definitions, Standards and Legislation)
For Ecodesign and Energy Labelling

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Version 2:

- is a review based on the input from the stakeholder comments which resulted mainly in a reviewed and updated scope proposal
- includes several updates on the text and system definitions
- refers to the newly elaborated annex on standards complementary to task 1

Version 2b (final version):

- text correction on the interpretation on p. 42 related to the Battery Directive (2006/66/EC)
- changed scope from '.. with lithium chemistries..' to '..with solid lithium cathode chemistries..
- added in section 1.8 on scope a footnote 'Batteries with liquid electrodes like ceramic batteries are excluded from the scope because they are not used in electric vehicles and their Ecodesign and recycling is much less challenging due to the used materials'

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ABBREVIATIONS

Abbreviations	Descriptions
AC	Alternating current
AD	Acidification
ADR	European Agreement Concerning the International Carriage of Dangerous Goods by Road
Ah	Ampere-hour
Al	Aluminum
ADN	European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways
AS	Application service energy
BAT	Best Available Technologies
BAU	Business As Usual
BC	Base case
BEV	Battery Electric Vehicle
BJB	Battery junction box
BMS	Battery Management System
BNAT	Best Not-yet Available Technologies
BOM	Bill-of-Materials
C	Capacity
CAPEX	Capital Expenditure
Cd	Cadmium
CE	European Conformity
CED	Cumulative energy demand
CF	Characterisation Factor
CIT	International Rail Transport Committee
CMC	Carbon methyl cellulose
C_n	Rated capacity
CNT	Carbon nanotube
Co	Cobalt
CPA	Statistical Classification of Products by Activity
CPE	Composite polymer electrolytes
CPT	Cordless Power Tools
CRM	Critical Raw Materials
DC	Direct Current
DEC	Diethyl carbonate
DG	Directorate General
DMC	Dimethyl carbonate
DoC	Declaration of Conformity
DOD	Depth of Discharge
E	Energy
EC	European Commission
EC	Ethylene carbonate
ECHA	European Chemicals Agency
ED	Ecodesign Directive
EDLC	Electrical Double-Layer Capacitor
EEI	Energy efficiency index

Abbreviations	Descriptions
EGDME	1, 2-dimethoxyethane or ethylene glycol dimethyl ether
ELR	Energy Labelling Regulation
ELV	End of Life of Vehicles
EMC	Ethyl Methyl Carbonate
EOL	End-of-Life
EPA	Environmental Protection Agency
EPD	Environmental Product Declaration
EPTA	European Power Tool Association
eq.	equivalent
E_{Rated}	Rated energy
ESS	Electrical Energy Storage Systems
EU	European Union
EU-28	28 Member States of the European Union
EUP	Eutrophication
EV	Electric vehicle
FC	Full cycle
Fe	Iron
FESS	Flywheel energy storage systems
FTP	Federal Test Procedure
FU	Functional Unit
GER	Gross Energy Requirements
GHG	Greenhous Gases
GVW	Gross vehicle weight
GWP	Global warming potential
HDT	Heavy-duty truck
HDTU	Heavy-duty tractor unit
HE	High-energy
HEV	Hybrid Electric Vehicle
Hg	Mercury
HMa	Heavy metals to air
HMw	Heavy metals to water
HREEs	Heavy rate earth elements
HV	High-voltage
I	Current
IATA	International Air Transport Association
ICEV	Internal combustion engine vehicles
ICT	Information and Communications Technology
IEC	International Electrotechnical Commission
IM	Implementing Measure
IMDG	International Maritime Dangerous Goods Code
IMO	International Maritime Organization
ISO	International Organization for Standardization
I_t	Reference test current
JRC	Joint Research Centre
kWh	Kilowatt hour
LCA	Life Cycle Assessment

Abbreviations	Descriptions
L_{Cal}	Calendar life
LCC	Life Cycle Costs
LCI	Life Cycle Inventory
LCO	Lithium-ion Cobalt Oxide
LCOE	Levelized Cost Of Energy
LCV	Light commercial vehicles
L_{Cyc}	Cycle life
LFP	Lithium-Ion Phosphate
Li	Lithium
LIB	Lithium ion battery
Li-Cap	Lithium-ion Capacitor
LiFSI	Lithium bis(fluorosulfonyl) imide
LiPF6	Lithium Hexaflurophosphate
LLCC	Least Life Cycle Costs
LMNO	Lithium-Ion Manganese Nickel Oxide
LMO	Lithium Manganese Oxide
LMP	Lithium-Metal-Polymer
LREEs	Light rare earth elements
LTO	Lithium-Ion Titanate Oxide
LVD	Low Voltage equipment
MEErP	Methodology for Ecodesign of Energy related Products
MEEuP	Methodology for Ecodesign of Energy-using Products
Mn	Manganese
NACE	Statistical Classification of Economic Activity
$NaNiCl_2$	Sodium nickel chloride
NaS	Sodium-sulphur
nC	C-rate
NCA	Lithium Nickel Cobalt Aluminium
NCM	Lithium Nickel Manganese Cobalt Oxide
NEDC	New European Driving Cycle
Ni	Nickel
NiCd	Nickel-Cadmium
NiMH	Nickel-metal hydride
NMC	Lithium-ion Nickel Manganese Cobalt Oxide
NPV	Net Present Value
OCV	Open Circuit Voltage
OPEX	Operational expenditure
P	Phosphor
PAH	Polycyclic Aromatic Hydrocarbons
Pb	Lead
Pb	Lead-acid
PBB	Polybrominated biphenyls
PBDE	Polybrominated diphenyl ethers
PC	Passenger car
PC	Propylene Carbonate
PCM	Protection Circuit Module

Abbreviations	Descriptions
PCR	Product Category Rules
PE	Polyethylene
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
PEm	Primary energy for manufacturing
PEM-FC	Proton exchange membrane fuel cell
PEr	Primary energy for recycling
PGMs	Platinum Group metals
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matter
POP	Persistent Organic Pollutants
PP	Polypropylene
PRODCOM	Production Communautaire
PTC	Positive Thermal Coefficient
PV	Photovoltaic
PVD	Physical vapour deposition
PVDF	Polyvinylidene fluoride
PWF	Present Worth Factor
Q_{FU}	Quantity of functional units
R	Internal resistance
R&D	Research and Development
RE	Round-trip efficiency
REACH	Regulation on the registration, evaluation, authorisation and rustication of chemicals
RFB	Redox-flow battery
RID	International Carriage of Dangerous Goods by Rail
RoHS	Restriction of hazardous substances
RRR	Recyclability, Recoverability, Reusability
RT	Room temperature
SASLAB	Sustainability Assessment of Second Life Application of Automotive Batteries
Sb	Antimony
SBR	Styrene-Butadiene Rubber
SD	Self-discharge
SEI	Solid-electrolyte interphase
Si	Silicon
SOC	State of Charge
SOH	State of Health
SOH_{cap}	Capacity degradation
SPE	Solid polymer electrolyte
SVHC	Substances of Very High Concern
T	Time
TIM	Thermal interfacial material
TMS	Thermal Management System
TOC	Total Cost of Ownership
TRL	Technology Readiness Level
UN	United Nations

Abbreviations	Descriptions
UNECE	United Nations Economic Commission for Europe
UPS	Uninterruptible Power Supply
V	Voltage
VAT	Value Added Tax
VKT	Vehicle kilometres travelled
V_L	Voltage limits
V_{OC}	Open circuit voltage
VOC	Volatile Organic Compounds
vPvB	Very persistent and very bio accumulative
V_R	Rated voltage
WEEE	Waste electrical and electronic equipment
WLTP	Worldwide Harmonized Light Vehicle Test Procedure
WVTA	Whole Vehicle Type-Approval System
ZrO_2	Zirconium Oxide
ZVEI	Zentralverband Elektrotechnik- und Elektronikindustrie e. V.
η_E	Energy efficiency
η_V	Voltaic efficiency

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1. Task 1: Scope, standardisation and legislation

AIM OF TASK 1

The aim of this Task 1 was to analyse the scope, definitions, standards and assessment methods as well as other legislation of relevance to the product group and to assess their suitability for classifying and defining products for the purposes of analysing Ecodesign and Energy Label requirements.

SUMMARY OF TASK 1

The proposed scope for this study and subsequent tasks 3 to 6 is 'high energy rechargeable batteries of high specific energy with solid lithium cathode chemistries for e-mobility and stationary energy storage (if any)'. Herein batteries are either a pack or a system as defined within this study and in line with the international standards. This does not include power electronics neither heat or cool supply systems for thermal management which can be part of what the study defined as a battery application system. The rationale for this scope definition is included in this task report and it took also into account the Task 2 market data. Herein a high volume in total mass of e-mobility lithium batteries are expected to enter the market and therefore also a significant impact could be expected from Ecodesign policy measures, which will be discussed in Task 7. Similar batteries for grid energy storage will also be looked at, especially from the point of view of second life applications. Independent from the proposed scope this Task 1 report introduces the broader range of batteries and their applications on the market.

More details, product categories, applicable regulation, standards and definitions are given in this task report and its annex on standards.

The current version is a reviewed and updated task report based on the first stakeholder meeting held on 20 December 2018 and the comments received on the draft report, amongst others the proposed scope was updated taking into account the various comments received.

Be aware that in parallel to this study the EC hosts a website that provides the latest information for the related regulation making process and that information included in this report can be outdated, therefore please consult also:

https://ec.europa.eu/info/law/better-regulation/initiatives/ares-2018-5951053_en

1.1 General Introduction to the study

The general aim of this study is to support developing of a new Ecodesign Regulation for batteries[1] [1], [2], which means; to set the performance and sustainability criteria that batteries will have to comply to be placed on the EU market. This may eventually be a different regulation using the analyses performed during the complete study.

This study follows the Methodology for Ecodesign of Energy-related products (MEErP)[2], as established in 2011. It was developed to allow evaluating whether and to which extent various energy-related products fulfil certain criteria according to Article 15 and Annex I and/or II of

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[1] http://europa.eu/rapid/press-release_IP-18-6114_en.htm

[2] http://ec.europa.eu/growth/industry/sustainability/ecodesign_nl

the Ecodesign Directive that make them eligible for implementing measures. This methodology requires to carry out 7 tasks, ranging from product definition to policy scenario analysis; they are:

The tasks in the MEErP entail:

- Task 1 – Scope (definitions, standards and legislation);
- Task 2 – Markets (volumes and prices);
- Task 3 – Users (product demand side);
- Task 4 – Technologies (product supply side, includes both BAT and BNAT);
- Task 5 – Environment & Economics (Base case LCA & LCC);
- Task 6 – Design options;
- Task 7 – Scenarios (Policy, scenario, impact and sensitivity analysis).

This means that specific issues on market, use, technologies, etc. will be discussed in more detail in later tasks and not in Task 1 neither its introduction.

1.2 Preliminary definitions for Task 1

In the following list a set of preliminary definitions and terminology related to batteries is presented. It is useful for the reading of subsequent introductory section on batteries and therefore has been provided preceding this. This is not an exhaustive list but contains basic concepts that are needed in order to understand how a battery can be included in an electric application. The definitions are based on different international standards and regulations like from ISO, IEC, UN. The definitions are written as they have been defined in the standards indicating for each the standard from where they have been taken from. When they are not found in existing standards, the study team will provide its own draft definition. Furthermore, these concepts are implemented in the creation of a functional product and unit defining the boundaries of the system that will be considered in this study. In Figure 1 a schematic representation of the battery pack and system can be observed.

1.2.1 Storage

Electrochemical cell: Electrochemical system capable of storing in chemical form the electric energy received and which can give it back by reconversion, i.e. a secondary cell (IEC 60896-21) [3].

Secondary rechargeable cell: Basic manufactured unit providing a source of electrical energy by direct conversion of chemical energy, that consists of electrodes, separators, electrolyte, container and terminals, and that is (IEC 62133) [4], [5]. Cell or battery which is designed to be electrically recharged (IEC 62281) [6]

Primary cell: Any kind of electrochemical cell in which the electrochemical reaction of interest is not reversible (IEC 60730-1) [7]

Flow cell: Secondary cell characterized by the spatial separation of the electrode from the fluid volumes which contain active materials (IEC 61427-2) [8].

Battery: Two or more cells fitted with devices necessary for use, for example case, terminals, marking and protective devices (IEC 61427-2) [8].

Electrochemical battery: An electrochemical system capable of storing in chemical form the electric energy received and which can give it back by conversion (IEC 60050) [9]

Battery with internal storage: Electrochemical batteries that have the active materials in the cells to store the energy; they are in the agreed scope of this study. (Definition from the study)

Flow battery or battery with external storage: Two or more flow cells electrically connected in series and including all components for their use as an electrochemical energy storage system (IEC 61427-2) [10]

Battery lithium cell (secondary): Secondary cell where electrical energy is derived from the insertion/extraction reactions of lithium ions between the negative electrode and positive electrode. The lithium ion cell has an electrolyte that typically consists of a lithium salt and organic solvent compound in liquid, gel or solid form and has a metal or a laminated casing. It is not ready for use in an application because it is not yet fitted with its final housing, terminal arrangement and electronic control device. (IEC 62620) [11]

Ceramic battery: Battery with internal storage characterised by liquid electrodes separated by a solid ceramic electrolyte. They are typically operated around 300°C with sodium-ion passing through a beta-alumina ceramic (definition from the study)

Solid State battery: Battery that is incorporated with solid electrodes and solid electrolytes (definition from the study)

Accumulator: A device that receive, store and releases energy. This energy can be thermal, mechanical or electrical. It is very common to define an accumulator as a battery. The main difference is that an accumulator is always rechargeable while a battery can be also non-rechargeable (definition from the study)

Note: an overview of more battery technologies is included in a later section.

1.2.2 Battery hierarchy

Cell block: Group of cells connected together in parallel configuration with or without protective devices (e.g. fusesthermal sensors) and monitoring circuitry. It is not ready for use in an application because it is not yet fitted with its final housing, terminal arrangement and electronic control device. (IEC 62620) [11]

Battery Module: Group of cells connected together either in a series and/or parallel configuration with or without protective devices (e.g. fuse or PTC) and monitoring circuitry. (IEC 62620) [11].

Battery Pack: Energy storage device, which is comprised of one or more cells or modules electrically connected. It may incorporate a protective housing and be provided with terminals or another interconnection arrangement. It may include protective devices and control and monitoring, which provides information (e.g. cell voltage) to a battery system. (IEC 62620) [11].

Battery System: System which incorporates one or more cells, modules, or battery packs. It has a battery management unit to cut off in case of overcharging, over current, and overheating. It may have cooling or heating units. (IEC 62620) [11]. Completely functional energy storage system consisting of the pack(s) and necessary ancillary subsystems for physical support, thermal management and electronic control with the thermal management system and protective circuit module respectively [12].

Note: additional definitions about the battery hierarchy is provided in section 1.5

1.2.3 Additional battery components

Battery Management System: Electronic system associated with a battery, which monitors and/or manages its state, calculated secondary data, reports that data and/or controls its environment to influence the battery's safety, performance and/or lifetime. The function of the BMS can be assigned to the battery pack or to equipment that uses the battery. (IEC 62620) [11].

Cell electronics: Electronic device that collects and possibly monitors thermal and electric data of cells or cell assemblies and contains electronics for cell balancing. (ISO 8713) [13]

Protective devices: Devices such as fuses, diodes or other electric or electronic current limiters designed to interrupt the current flow, block the current flow in one direction or limit the current flow in an electrical circuit. (IEC 62281) [6].

Power electronics: The field of electronics which deals with the conversion or switching of electric power with or without control of that power (IEC 60050) [9].

1.2.4 Battery metrology

Gravimetric energy density: Amount of stored energy related to the battery cell, module, pack or system weight expressed in Wh/kg. (ISO 12405) [14]–[16].

Volumetric energy density: Amount of stored energy related to the battery cell, module, pack or system volume expressed in Wh/l. (ISO 12405) [14]–[16].

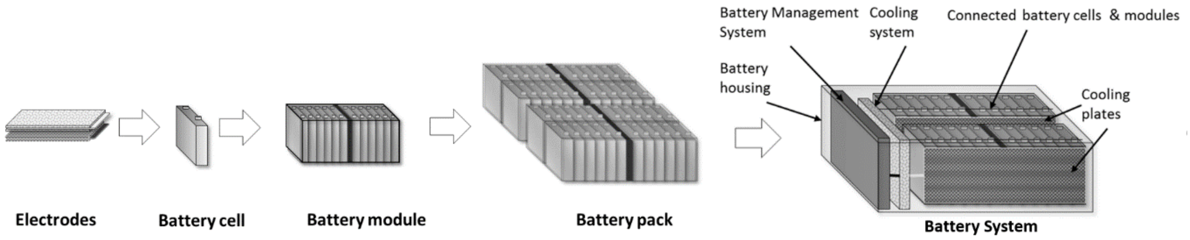

Figure 1: Schematic summary of the key components of a battery pack after [17].

1.2.5 Sustainable, resource-efficient production and consumption

It is needed to establish appropriate definitions and metrics for sustainable and resource efficient production.

The MEErP methodology[3] already defined some parameters that will be further explained in subsequent Tasks 3-5. They include amongst other definitions on lifetime, warranty, recoverability of material/product, recyclability of material/product, Recyclability Recoverability

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[3] https://publications.europa.eu/en/publication-detail/-/publication/7c3d958d-42cc-4af7-985c-2a3347b66fa8

and Reusability (RRR) rates (ISO 22628, IEC 62635), reparability of component/product and reusability of component/product.

Apart from the existing MEErP methodology (2013), new definitions on circular economy aspects are also work in progress within a new CEN standardization committee (CEN CLC JTC 10). This means that new terminology and definitions can be expected in future. It is a reply to the EU standardization mandate/543 on Ecodesign requirements on material efficiency aspects for energy-related products. Herein in particular the proposed standard prEN 45555 aims to define general methods for assessing the recyclability and recoverability of energy related products, it is not available (see Annex on Standards).

1.3 Introduction to rechargeable electrochemical battery technologies

The following sections provide a brief introduction to rechargeable electrochemical batteries with internal storage. A comparison of the most common battery technologies found in the market is included, comparing their operational characteristics to each other and the type of electrical application wherein they are commonly incorporated. This is followed by a list of existing definitions of the different components of a battery and their surrounding systems are established. This provides the basis in defining the boundaries, functional unit and parameters of a battery system that is commonly found in electric applications. Finally, the scope of the study is based on the analyses performed for the development of an Ecodesign and Energy label strategy for rechargeable electrochemical batteries with internal storage.

1.3.1 Introduction to electrochemical batteries

A battery is an electrochemical system that can convert chemical energy into electrical energy to power and/or conserve energy for different electrical applications [14], [18]–[22]. This can be single battery cells attached directly to an application or battery cells that are included in modules and packs which are connected to different external power electronics depending on the application. The exact definition of the system will be given in section 1.8 These applications can range from electrical devices as electric watches to portable computers (i.e. laptop), vehicles (i.e. e-bikes, electrical vehicles, buses) to stationary applications such as uninterruptible power supply (UPS), grid support and to store PV energy for self-consumption optimisation.

The first electrochemical battery was developed by Italian physicist Alessandro Volta in 1800 and was made of a stack of copper and zinc plates separated by brine-soaked paper disks. In 1836 a British chemist created the first battery that could power up electrical telegraph networks consisting of a copper pot filled with copper sulphate solution [1], [23]. Rechargeable Nickel-Cadmium batteries were invented in 1899 by Swedish scientist Waldemar Jungner combining nickel and cadmium electrodes under a solution of potassium hydroxide. Following multiple developments in battery technology during the 1970s M. Stanley Whittingham proposed the first lithium battery (main type of battery for electrical and electronic devices) composed of titanium sulphide and lithium metal as electrodes [2]. While in 1989 the first Nickel-Metal hydride batteries and became commercially available.

A main distinction for batteries is made by primary and secondary batteries. A primary battery cannot be recharged and the chemical energy that was initially stored can be turned into electrical power only once. On the contrary a secondary battery can be recharged for multiple uses providing electrical energy over a longer lifetime compared to a primary battery.

A battery cell is composed of two electrodes and its current collector called the anode (negative) and cathode (positive), a separator separating the electrodes and the electrolyte allowing the ions to move [17]. In Figure 2 an example of a structure of a battery cell can be observed.

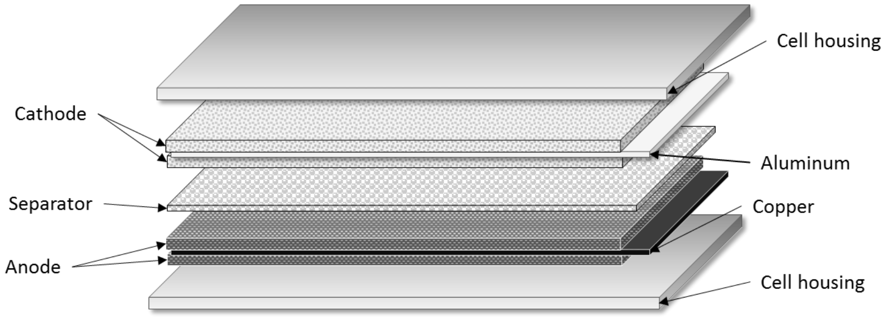

Figure 2: Exemplary structure of a battery cell [17]

The current collectors connect the electrodes to the battery poles. When a battery cell is being discharged electrical energy is provided from the battery to the application attached. Electrons are moving from the anode through the external electrical circuit of the application towards the cathode due to the difference in potential between both electrodes. Inside the battery, through the separator, the current flows as ions. The electrons and ions are combined by electrochemical reactions. The opposite flow of electrons is occurring when a battery is being charged. A higher voltage than the cell possesses under rest is applied, forcing the reverse electrochemical reaction and restoring the energy that is available in the battery cell.

When a battery is fully charged it is denoted as 100% State of Charge (SOC). On the contrary when a battery is fully discharged this is denoted as 0% SOC. This occurs when for a certain current the minimum allowed voltage is attained. The exact definition when a cell is fully charged depends on the cell chemistry. For Li-ion, a cell is fully charged when the current falls below a certain threshold while the potential is maintained at maximum allowed voltage. For lead acid batteries, often a series of charge currents is applied coupled to a duration after being fully charged, maintaining the voltage of the battery stable to account for the full capacity and compensating for self-discharge. For Nickel–metal hydride (NiMH), a cell is fully charged when the cell voltage starts to decrease. A complete discharge and charge procedure defines one operational cycle of the battery system. This should be theoretically from 100% to 0% but in many electrical applications a complete operational cycle is usually performed between an optimized SOC smaller range (e.g. Li-ion battery in electric vehicle) to degrade the battery at a slower rate.

Due to the energetic electric losses during charging, discharging and storage and since the discharge voltage is lower than the charge voltage, the battery cell efficiency is not 100%. It is also possible that more current is needed to charge a cell than can be discharged. This further lowers the efficiency. Furthermore, it should be understood that as the battery is a chemical system, different degradation mechanisms may take place during use and storage. These are affecting the capacity and internal resistance, degrading the energy and power output of the system [24]–[27]. The coulombic efficiency which is the electric efficiency of the battery for a specified charge/discharge procedure will be above 99+% for most its lifetime for Li-ion batteries. This will be further be investigated in Task 3 and 4 of this study.

A typical lithium-ion battery has the three basic functional components like discussed previously for a general cell. These are namely the anode, cathode and electrolyte (Figure 3). There is a thin separator between the electrodes usually made of a micro perforated plastic foil that allows Li-ions to pass through. Anodes are typically made of graphite pasted on a current collector from copper. The cathode active material is either a layered oxide or a phosphate of spinel type. The different chemistries of the cathode are indicated in Figure 4. The electrolyte is a mixture of organic carbonates containing complexes of lithium ions.

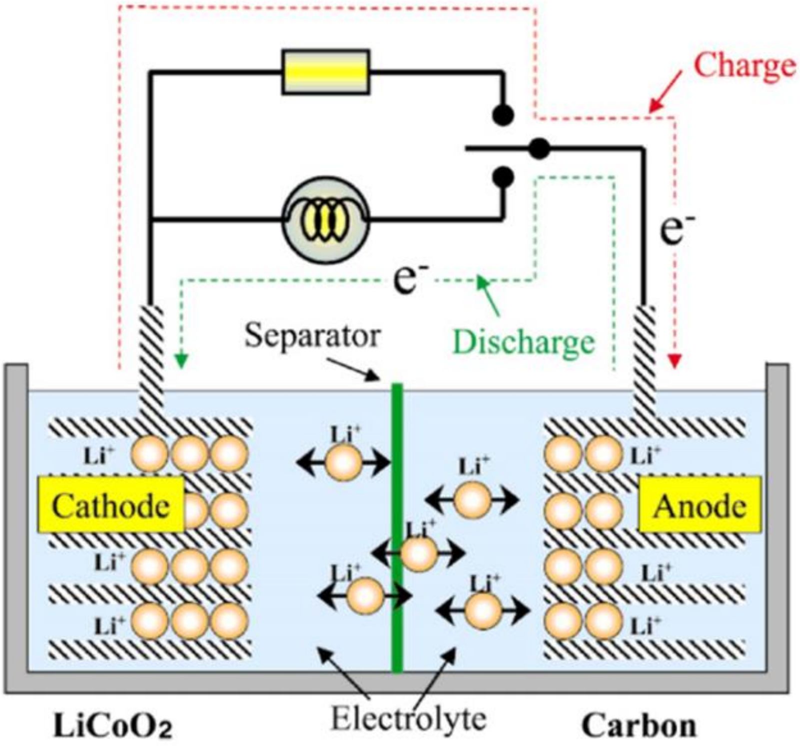

Figure 3: Typical working schematic of Lithium batteries [28]

During the charging process, lithium ions intercalate from the cathode to anode. Intercalation means that the Li-ions are adsorbed in the host material without significantly changing the structure. During the charging process Li-ions and electrons settle themselves between the the graphite layers. During discharge, the process is reversed where the lithium ions go from the anode to cathode and the electron flow direction is also reversed. This is also an intercalation process: the Li-ions settle themselves within the cathodic material, without forming a chemical reaction or an alloying, what would have essentially changed the structure.

1.4 Main product categories of batteries

1.4.1 Rechargeable electrochemical batteries classified according to their chemistry

In Table 1 the most common battery chemistries existing in today's market are compared detailing the advantage that each technology has over the others [29]. Inspecting the different battery technologies, it is observed that each has specific advantages. The lead-acid battery, although it represents one of the lowest in terms of specific power and energy density, has the advantage that its price remains lower with respect to the other technologies for the same energy content. Furthermore, Europe is strong in the manufacturing of lead-acid batteries. Lead-acid batteries are easily recyclable. The lead components of the battery are smelted and refined to be used to make new batteries, in a closed-loop system. Another important advantage of lead-acid battery is their cold cranking ability at temperatures as low as -30°C. This is one of the areas where until recently Li-Ion batteries had not yet reached parity and one of the reasons why they are still not widely considered for automotive battery applications (i.e. SLI batteries). The presence of cadmium (Cd) in portable batteries is banned through the Batteries Directive (2006/66/EC) due to toxic properties, i.e. nickel cadmium portable batteries are banned for most applications. Although the Batteries Directive provides a few exemptions: portable Ni-Cd batteries are granted for example for emergency batteries. The advantage of the ickel-cadmium technology is that it can be operated in a wide range of temperatures without losing substantially its energy and power characteristics. Due to these intrinsic characteristics, the Ni-Cd technology is the preferred solution for very demanding industrial power back-up solutions. Industrial Ni-Cd batteries have also high recycling efficiency. The nickel-metal hydride on the contrary shows a greater specific energy and power to respect to the lead-acid or nickel-cadmium but still cannot reach the levels of a lithium-ion battery. The main advantage of this technology is its volumetric energy density and a long lifetime if used in a restrained SOC window, i.e. not fully depleting nor fully charging the battery but staying within e.g. 10%-90% SOC. Finally, the lithium-ion battery technology provides the higher energy and power densities in terms of weight and volume. They have a higher cell voltage and a lower self-discharge rate making them a perfect match for e-mobility (high power, high energy), ICT (high volumetric energy density) and stationary (long lifetime and low self-discharge) applications.

Table 1: Comparison of battery technologies advantages to respect to each other after [29]

Advantage of… …..On		Lead acid	Nickel cadmium	Nickel metal hydride	Lithium-ion	
					Cylindrical - prismatic	Pouch
Lead acid			● Energy density ● Operating temperature ● Self discharge rate ● Reliability	● Gravimetric energy density ● Volumetric energy density ● Self discharge rate	● Gravimetric energy density ● Volumetric energy density ● Voltage output ● Self discharge rate	● Gravimetric energy density ● Volumetric energy density ● Voltage output ● Design characteristics
Nickel cadmium		● Higher cyclability ● Voltage output ● Price		● Gravimetric energy density ● Volumetric energy density	● Gravimetric energy density ● Volumetric energy density ● Voltage output ● Self discharge rate	● Gravimetric energy density ● Volumetric energy density ● Voltage output ● Design characteristics
Nickel metal hydride		● Higher cyclability ● Voltage output ● Price	● Operating temperature ● Higher cyclability ● Self discharge rate ● Price		● Energy density ● Operating temperature ● Higher cyclability ● Voltage output ● Self discharge rate	● Gravimetric energy density ● Volumetric energy density ● Operating temperature ● Design characteristics ● Self discharge rate
Lithium-ion	Cylindrical - prismatic	● Price ● Safety ● Recyclability	● Operating temperature ● Higher cyclability ● Price ● Safety	● Price ● Safety ● Discharge rate ● Recyclability		● Gravimetric energy density ● Volumetric energy density ● Safety ● Design characteristics
	Pouch	● Price ● Safety ● Recyclability	● Recyclability ● Operating temperature ● Higher cyclability ●Price	● Volumetric energy density ● Higher cyclability ● Price	● Operating temperature ● Higher cyclability ● Price	
Absolute advantages		● Higher Cyclability ● Price	● Operating temperature ● Price	● Volumetric energy density	● Gravimetric energy density ● Volumetric energy density ● Voltage output ● Self discharge rate	● Energy density ● Design characteristics ● Voltage output ● Self discharge rate

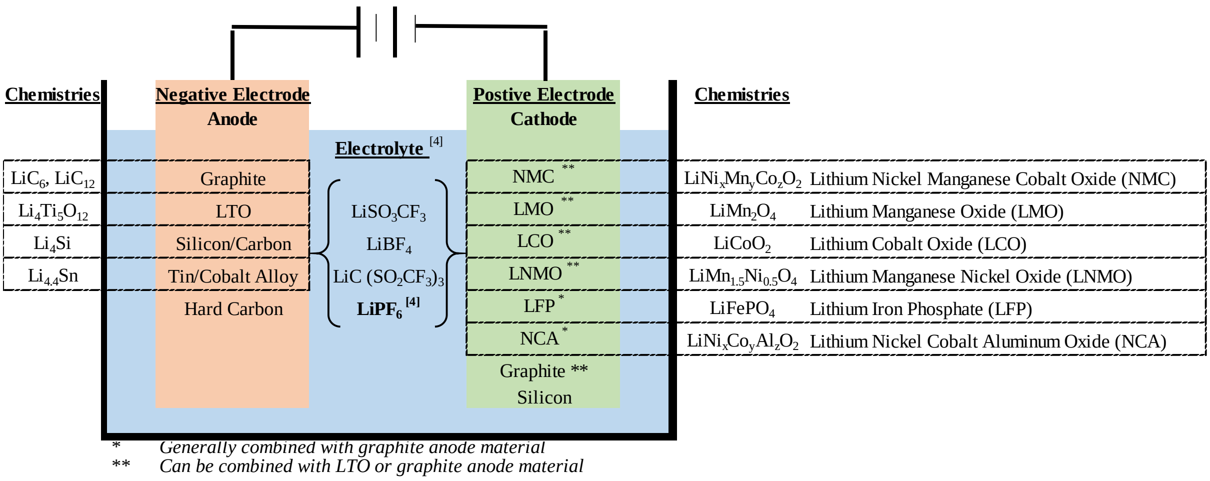

Figure 4: Different types of lithium-ion chemistries [30]–[32]

As illustrated in Figure 4, different types of lithium-ion batteries exist. The materials used in battery cells play a substantial role in the characteristics and performance. In the following list the most common types of lithium-ion cells are denoted. They are mostly designated by the cathode material or anode material (for LTO chemistry), being:

- Lithium-ion Cobalt Oxide (LCO)
- Lithium-ion Nickel Manganese Cobalt Oxide (NMC)
- Lithium-Ion Phosphate (LFP)
- Lithium-Ion Titanite Oxide (LTO)
- Lithium-Ion Manganese Oxide (LMO)
- Lithium-Ion Manganese Nickel Oxide (LMNO)
- Lithium Nickel Cobalt Aluminium (NCA)
- Lithium Metal Polymer (LMP)

In Figure 5 the composition of commonly found materials of a lithium battery system in a mobile application can be also observed [33].

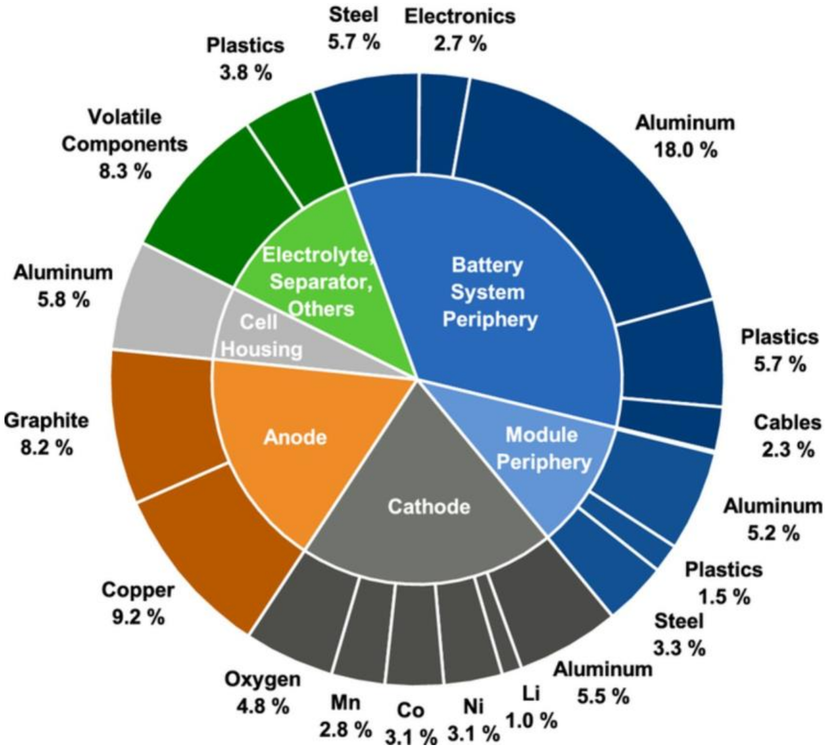

Figure 5: Composition of different materials of a lithium battery system in an mobile application [33]

Li-ion cells are constructed in different forms (Figure 6). Cylindrical cells, being the most widely used formats, are made by winding long strips of electrode into a “jelly roll” configuration. This is encapsulated in a can commonly made of aluminium. In a typical prismatic cell, the cell is created by stacking in a layered approach or winding the electrodes into flat wraps. The casing is a hard structure out of metal or thick plastic. Pouch cells as the name goes, are stacked electrodes typically enclosed in a foil. This is a comparatively weaker structure.

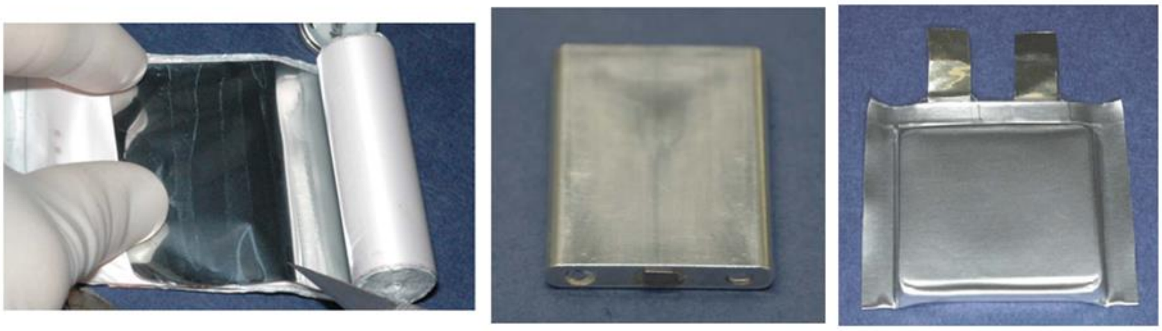

Figure 6: Types of lithium-ion cells : Cylindrical (left), Prismatic hard (centre) and Pouch type (right) [34]

In Table 2 a list of different energy storage systems characteristics including electrochemical batteries is presented. Flow batteries store energy outside the battery. Rechargeability is provided by two chemical components dissolved in liquids that can be stored in two separate storage vessels apart from the battery anode and cathode. They are referred hereafter as batteries with external storage and they are not in the scope of this study. Batteries with internal storage have solid active materials as electrodes that stores the energy. They are in the proposed scope of this study.

The energy output that a battery can deliver, depends on multiple internal and external factors. The useable capacity of a battery strongly depends on the load profile of the application. When a high current is drawn from the battery a lower amount of energy can be extracted from it in comparison to a low current rate. There are two reasons. The voltage drop created by the current increases with the current. Since the energy is a multiplication of voltage, current and discharge time, this leads automatically to a lower energy output. Moreover, the lowest allowed voltage is quicker attained, reducing the discharge time more than linearly. Secondly, the energy output of the battery is directly affected by the ambient temperature at which the battery is operated [35]. At high temperatures the chemical molecules (e.g. ions) in the battery have a greater kinetic energy leading to a lower voltage drop. While this provides a higher energy output of the system, it increases the degradation mechanisms of the battery, reducing the lifetime that it can be operated efficiently and safely. At low temperatures the kinetic energy of chemical molecules is restricted thus raising the voltage drop. As a consequence, the energy output of the system is negatively affected. Therefore, it is important to operate batteries at temperatures that are adequate to efficiently provide the energy required but also restrict the degradation mechanisms. In applications such as destined for e-mobility, grid support or grid and home storage, the temperature of the batteries is directly monitored and managed for optimum performance.

A more detailed technical analysis will be included in Task 4.

Table 2: Energy storage systems main characteristics (own expert assumptions)

Energy Storage Technology	Electro-chemical	Primary - Secondary	Internal - External Storage	[Wh/kg] (range) @ cell level
High-energy LIB (NCA/Graphite, NMC/Graphite)	NCA/Graphite or NMC/Graphite	sec	int	200-300
Mid-energy LIB (LFP, LMO/Graphite)	LFP, LMO/Graphite	sec	int	140-200
High power LIB (LFP, NCA or NMC/Graphite, thin electrode)	LFP, NCA or NMC/Graphite	sec	int	140-200
Heavy duty LIB, high power (NMC, NCA, LFP / LTO)	NMC, NCA, LFP / LTO	sec	int	80-120
Long-life / cycle life LIB (e.g. NMC/LTO)	NMC/LTO	sec	int	80-120
Ultra-high cycle life LIB (e.g. LFP/LTO)	LFP/LTO	sec	int	70-100
Lithium metal polymer	LMP/Carbon	sec	int	100-265
Lead-acid	PbO2 / Pb	sec	int	30-45
Lead-acid sealed	PbO2 / Pb	sec	int	30-45
NiCd	Cd / NiO2H	sec	int	40-60
NiMH	M / $Ni(OH)_2$	sec	int	60-120
Li-primary	numerous / Li-metal	pri	int	250-700
Zn-primary	Zn / C, air	pri	int	100-450
Flywheel storage system	N/A	sec	ext	100 - 130
Compressed air storage	N/A	sec	ext	20 - 83
Pumped hydro storage	N/A	sec	ext	Unknown
Redox flow	numerous	sec	ext	25 - 50
Molten salt batteries	Na-S or Na-NiCl2	sec	int	130-230

1.4.2 Categories and definitions found in Eurostat PRODCOM codes

The EU's industrial production statistics are compiled in the Prodcom (PRODuction COMmunautaire) survey and also in the Europroms database, which includes external trade statistics. The economic activities surveyed by Prodcom are classified according to the Statistical Classification of Economic Activity (NACE). The statistics for production under each economic activity are in turn reported by each member state according to Statistical Classification of Products by Activity (CPA) codes. The link between the NACE and CPA codes is illustrated in Figure 7.

The main indicators of the production sold during the calendar year are collected and published both in monetary units (EUR) and physical units of production (kg, m^2, number of items, etc.). Data is provided, where available at member state level, for:

- the physical volume of production sold during the survey period,
- the value of production sold during the survey period,
- the physical volume of actual production during the survey period, including any production which is incorporated into the manufacture of other products from the same undertaking.

These statistics provide an outlook on the volume of imports, as well as enabling the actual and apparent production to be estimated based on the balance of EU sales and trade.

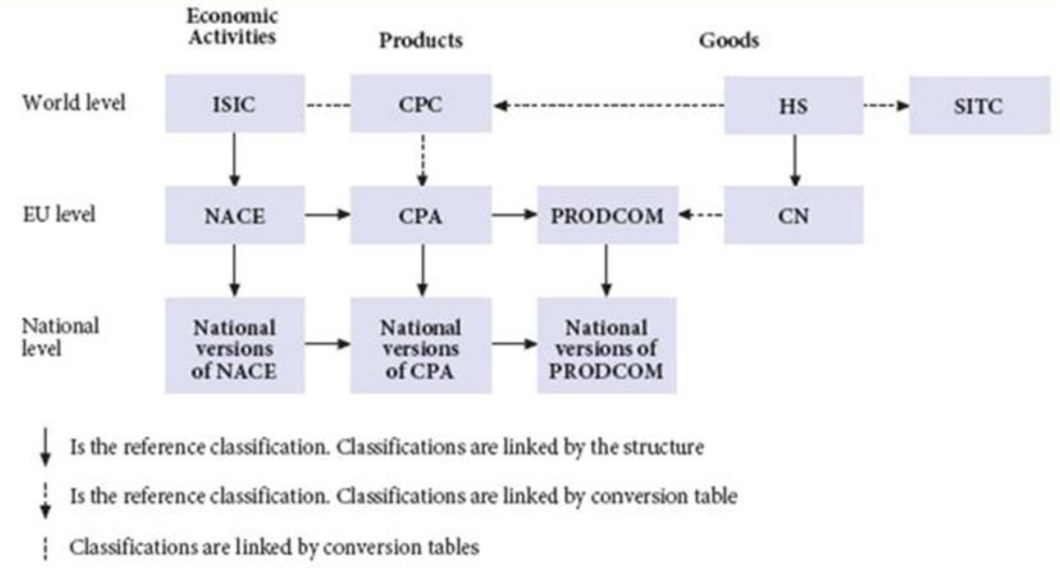

Figure 7: Overview of the revised EU system of integrated statistical classifications. Source: Eurostat (2017)

In Table 3 the Prodcom codes related with battery technologies are listed. In this study the technologies that would be considered are under the 27.20.23 code “Nickel-cadmium, nickel-metal hydride, lithium-ion, lithium polymer, nickel-iron and other electric accumulators”.

Table 3: Prodcom categories and codes

Code	**Prodcom categories**
27.20	Manufacture of batteries and accumulators
27.20.11	Primary cells and primary batteries
27.20.12	Parts of primary cells and primary batteries
27.20.21	Lead-acid accumulators for starting piston engines
27.20.22	Lead-acid accumulators, excluding for starting piston engines
27.20.23	**Nickel-cadmium, nickel metal hydride, lithium-ion, lithium polymer, nickel-iron and other electric accumulators**
27.20.24	Parts of electric accumulators including separators

The conclusion is that the official Prodcom codes provide little disaggregation of battery products and therefore they cannot be further used in this study for defining the scope in Task 1 neither to source market data in Task 2.

1.4.3 Categories and definitions of battery categories according to the Battery Directive

The Batteries Directive (2006/66/EC) discriminates three battery types according to its application. These are separated in industrial, automotive and portable applications, defined as:

- ‘automotive battery or accumulator’ means any battery or accumulator used for automotive starter, lighting or ignition power;
- ‘industrial battery or accumulator’ means any battery or accumulator designed for exclusively industrial or professional uses or used in any type of electric vehicle;
- ‘portable battery or accumulator’ means any battery, button cell, battery pack or accumulator that (a) is sealed; and (b) can be hand-carried; and (c) is neither an industrial battery or accumulator nor an automotive battery or accumulator;

In the context of this study accumulators are not of interest but have been included in the definitions through the Battery Directive. Thus, accumulators have been incorporated in the battery definition. Furthermore, the Batteries Directive details what kind of batteries can be considered industrial or portable batteries stating that:

1) Examples of industrial batteries and accumulators include batteries and accumulators used for emergency or back-up power supply in hospitals, airports or offices, batteries and accumulators used in trains or aircraft and batteries and accumulators used on offshore oil rigs or in lighthouses. Examples also include batteries and accumulators designed exclusively for hand-held payment terminals in shops and restaurants, bar code readers in shops, professional video equipment for TV channels and professional

studios, miners' lamps and diving lamps attached to mining and diving helmets for professionals, back up batteries and accumulators for electric doors to prevent them from blocking or crushing people, batteries and accumulators used for instrumentation or in various types of measurement and instrumentation equipment **and batteries and accumulators used in connection with solar panel, photo-voltaic**, and other renewable energy applications. Industrial batteries and accumulators also include batteries and accumulators used in electrical vehicles, such as electric cars, wheelchairs, bicycles, airport vehicles and automatic transport vehicles. In addition to this non-exhaustive list of examples, any battery or accumulator that is not sealed and not automotive should be considered industrial.

2) Examples of portable batteries and accumulators, which are all-sealed batteries and accumulators that an average person could carry by hand without difficulty and that are neither automotive batteries or accumulators nor industrial batteries or accumulators, include single cell batteries (such as AA and AAA batteries) and batteries and accumulators used by consumers or professionals in mobile telephones, portable computers, cordless power tools, toys and household appliances such as electric toothbrushes, razors and hand-held vacuum cleaners (including similar equipment used in schools, shops, restaurants, airports, offices or hospitals) and any battery or accumulator that consumers may use for normal household applications.

Taking into consideration these definitions and examples the batteries that are considered in this study are ‘industrial batteries’ including energy storage systems for stationary application and batteries for mobile applications according to the current Directive (2006/66/EC).

For more details see section 1.10.4.

1.4.4 Application categories of batteries and relation to battery chemistries

Batteries are used in a multitude of applications such as e-mobility, ICT, computer applications, various consumer electronics, Cordless Power Tools (CPT), Uninterruptable Power Supplies (UPS) and various electrical Energy Storage Systems (ESS), see Table 4. Such applications can have different criteria or priorities related to capacity, specific weight, efficiency, self-discharge, cycle life, etc. As indicated in Table 4 the potential applications and their typical user requirements will be further investigated in later Tasks 3 and 4. Based on our own investigations on battery properties for different technologies they can be linked as suitable candidate to different applications. In Table 4 a list of electrical applications is given. For each application different characteristics based on the importance of low specific weight, efficiency, self-discharge and cycle is provided. It is mainly observed that the energy storage that can be implemented in most of the electric applications is based on lithium-ion technologies. Road-based electric vehicles such as electric buses can have a maximum of 550 kWh under current applications. While electric vehicles can have a minimum of 5 kWh to 20 kWh for plug-in hybrid electric vehicles, 0.9 kWh to 2 kWh for hybrid electric vehicles and 20 kWh to 100 kWh for battery electric vehicles. This could change in the future as newer applications based on advance technologies come into the market. Other applications such as drones and airplanes can reach a battery system capacity of 900 kWh and a minimum of $1*10^{-5}$ kWh for electronics and electronic consumer applications.

A more detailed analysis of user requirements and their typical parameters will be in Task 3.

Table 4: Typical electric applications characteristics and the type of battery technologies that can be integrated.

	Most **typical applications** (see **Task 2 on market**)															
	E-mobility applications									other				Energy Storage Systems		
Typical application parameters (See **Task 3 on use**)	Vehicle (BEV)	Vehicle (PHEV)	Vehicle (HEV)	Buses (BEV)	Trucks (BEV)	Rail (BNAT)	Drones / Airplanes (BNAT)	Scooter / E-bikes	Forklift / industrial	ICT	Consumer electronics	CPT	UPS (server, lift, ..)	Residential Energy Storage	Grid support	Grid Energy storage
importance of low specific weight	high	high	high	high	high	medium	high	high	low	medium	medium	high	low	low	low	low
Importance of efficiency	high	high	high	high	high	high	high	high	high	medium	medium	medium	low	high	high	high
importance of self-discharge	medium	medium	medium	low	low	low	low	medium	low	high	high	high	high	medium	low	medium
importance of long cycle life	high	high	high	very high	high	high	high	high	high	medium	medium	medium	low	high	very high	high
Typical electrochemical battery technologies (See **Task 4 on Technologies**)																
High-energy LIB (NCA/Graphite or NMC/Graphite)	x			x	x	x	x	x	x	x	x	x	x	x	x	x
Mid-energy LIB (LFP, LMO/Graphite)	x			x	x	x		x	x	x	x	x	x	x	x	x
High power LIB (LFP, NCA or NMC/Graphite, thin electrode)		x		x	x	x										
Heavy duty LIB, high power (NMC, NCA, LFP / LTO)		x		x	x	x			x						x	
Long-life / cycle life LIB (e.g. NMC/LTO)															x	
Ultra-high cycle life LIB (e.g. LFP/LTO)															x	
Lithium Metal Polymer	x			x	x										x	x

	Most **typical applications** (see **Task 2 on market**)															
	E-mobility applications									other				Energy Storage Systems		
Typical application parameters (See **Task 3 on use**)	Vehicle (BEV)	Vehicle (PHEV)	Vehicle (HEV)	Buses (BEV)	Trucks (BEV)	Rail (BNAT)	Drones / Airplanes (BNAT)	Scooter / E-bikes	Forklift / industrial	ICT	Consumer electronics	CPT	UPS (server, lift, ..)	Residential Energy Storage	Grid support	Grid Energy storage
Lead-acid									x				x	x	x	x
Lead-acid sealed									x				x	x	x	x
NiCd													x			
NiMH		x	x								x	x				
Li-primary										x	x					
Zn-primary										x	x					

acronyms for electric vehicles (EV):	BEV = Battery Electric Vehicle, PHEV = Plug-in Electrical Vehicle, HEV = Hybrid Electric Vehicle

1.5 Definition of a battery system and a battery application system for use in this study

In this section the system boundary of a battery system found in different electrical applications is defined. These definitions are important for defining the scope in this Task 1 or market data in Task 2 or the use phase in later Task 3. In the proposed definitions hereafter, we follow the terminology of the IEC standards, see 1.2. Note that in Task 3 however new ‘MEErP system scope boundaries’ might be defined for further analysis in Tasks 5 to 7 according to the MEErP Methodology, see 15.

A graphical representation of the battery system and overarching battery *application* system definition proposed for use in this study is included in Figure 8. According to this representation, the main components of the battery system can be separated into the following items:

- Battery cell
- Battery module
- Battery pack
- Battery Management System (BMS)
- Cooling/Heating
- Battery system
- Battery application system

Connecting two or more battery cells through their terminals in a parallel and/or series configuration constitutes a battery module. By placing battery cells in series, the total voltage output is the sum of the cell voltage of the cells connected in series while the current passing through each is the same for all battery cells. By connecting battery cells in parallel the voltage level remains the same and the current passing through is the sum of the current output of each cell. Through these configurations additional control over the voltage, current and available capacity of each battery module can be achieved. Each battery module is normally fitted with measurement sensors such as one or more temperature sensors and a control unit wire communicating with the Battery Management System (especially necessary in case of Li-ion chemistry). Through these the BMS can monitor the temperature and electrical behaviour of each battery module and cell.

A battery pack is then formed by connecting the battery modules in series and/or parallel configurations. A battery pack can be incorporated in a protective housing and can be fitted with the terminals connecting the pack to the application if no other voltage or power regulation is needed. The electrical and thermal sensors included inside the battery pack through the battery modules can communicate with the BMS to control the electrical and thermal performance of each battery pack. The electrical supervision of the battery pack is performed through the Protection Circuit Module (PCM) and the thermal control is performed through the Thermal Management System (TMS).

The battery pack is then placed inside a battery system. A battery system can be incorporated with multiple battery packs if necessary, which are supervised by the BMS. The battery system can be also integrated with a temperature control system (cooling/heating) that can be used to adjust the temperature of the battery packs. Depending on the type of application (e.g. e-mobility or stationary application) the battery system is connected to different current or voltage control systems called power electronics. For example, in electric vehicle applications it is possible to find systems such as DC/DC converters and DC links. These systems are not directly included in the boundaries of the investigated system that will be used in this study. However, the boundaries and focus of the system can be extended depending on the type of application attached to the battery system. These can be introduced between the application and the battery system. By incorporating the power electronics, it is possible to take into consideration the indirect energy losses due to their energy efficiency characteristics. The indirect energy losses can be taken into account during Task 3, where the use phase of the battery system will be modelled.

Furthermore, depending on the application multiple battery systems composed on one or more battery packs can be combined and attached to it to form a battery application system. This is the case mainly with stationary applications where a high capacity and energy is required for grid energy storage.

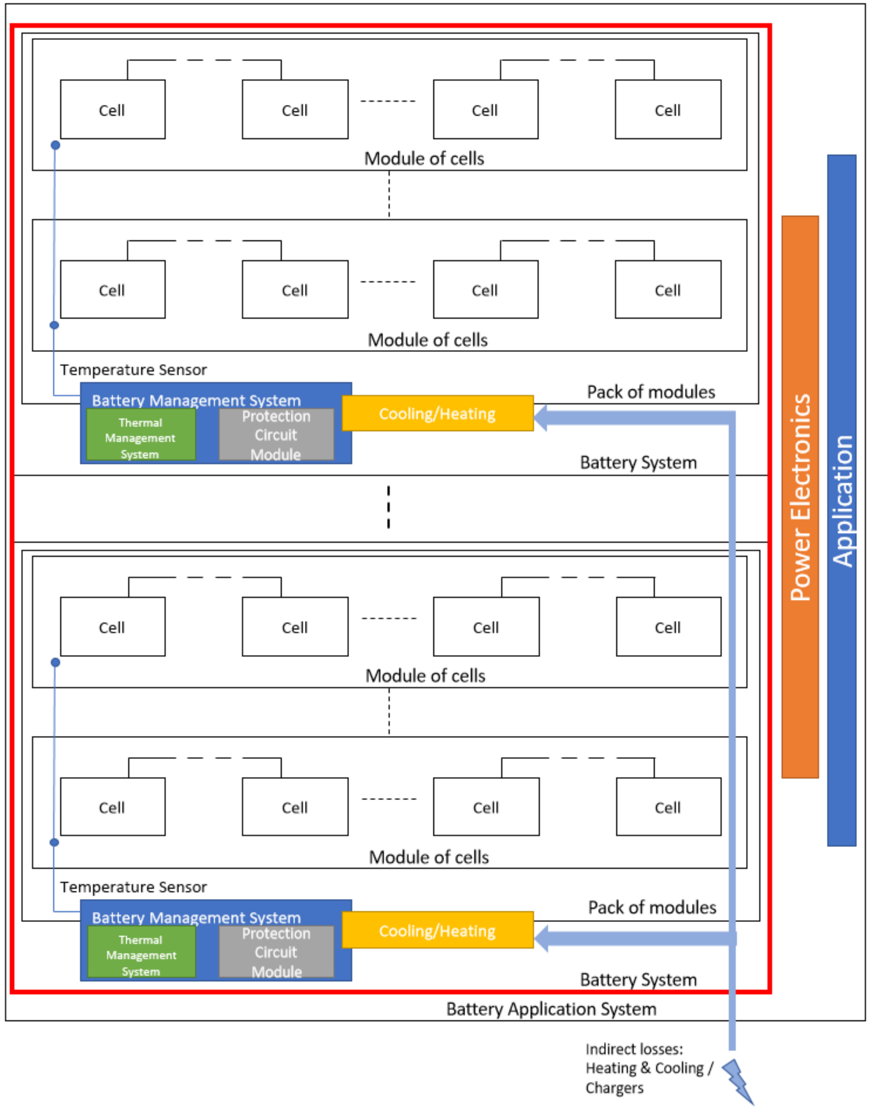

Figure 8: Representation of the battery system components and their system boundaries, forming finally the battery application system.

1.6 Definition of the primary functional parameter and unit

Hereafter is explained what is called the "functional unit" for batteries in the scope of this study.

In standard ISO 14040 on life cycle assessment (LCA) the functional unit is defined as "the quantified performance of a product system for use as a reference unit in life cycle assessment study". According to the MEErP, the primary purpose of the functional unit is to provide a calculation reference to which environmental impacts (such as energy use), costs, etc. can be related and to allow for comparison between functionally equal battery systems. This is especially important in later Task 6 to consider improvement options. Further product segmentations will be introduced in this study to allow appropriate equal comparison and therefore secondary functional parameters can be added. Note that an Ecodesign preparatory study is always built on a single functional unit and a corresponding product group to allow a consistent analysis according the MEErP in Tasks 3 to 6. As a consequence, considering different applications with different requirements and functional unit is not an option, it would require different studies. This issue has already been addressed within the work done to elaborate a harmonized Product Environmental Footprint (PEF) in Europe[4]. In the pilot phase (2012-2016) batteries have been analysed for both 'High Specific Energy Rechargeable Batteries for Mobile Applications' and 'Uninterruptible Power Supply (UPS)'. This study contract asked for building on the PEF study and to consider e-mobility and therefore it is obvious to build on what the PEF for mobile applications defined as functional unit.

The PEF for 'High Specific Energy Rechargeable Batteries for Mobile Applications' is proposed as '**functional unit (FU)**' of '**1 kWh (kilowatt-hour) of the total output energy delivered over the service life by the battery system (measured in kWh)'**.

Herein the energy consumption during the use phase of the battery takes into account losses linked to the battery but also the power electronics during charge, discharge and storage. Therefore, the PEF used the delta approach[5] or main-function approach to take the power electronics losses into account. The delta approach intends to model energy use impact of one product, in this case the battery, with taking into account the indirect losses of another product, in this case the charger. This means that the excess consumption of the charger shall be allocated to the product responsible for the additional consumption which is the battery.

This PEF pilot study for batteries for mobile applications used '1 kWh' instead of 'total kWh of a battery system' in the definition of the functional unit for Life Cycle Analysis (LCA). The rationale for this is easy to understand. The consequence is that a real battery system, which can deliver several kWh storage over its lifetime will have to be downscaled to a virtual 1 kWh battery system. For example, a battery storage system providing 2000 kWh of output energy over its service life will be downscaled to 0.05 % (1 kWh/2000 kWh).This might sound complex but the benefit of this rescaling is that life cycle cost (LCC) becomes equivalent to Levelized Cost of Electricity storage (LCOE) (€/kWh) and the calculated impact is per kWh (e.g. CO_2-eq/kWh), which are common metrics to compare energy production and storage solutions. This will become clear in Task 5 and 6 on LCC and LCA.

The PEF study also documented for the proper understanding of their impact modelling some key aspects of their functional unit, see Table 5. This study also defined the reference flow being the amount of product needed to fulfil the defined function and shall be measured in kg

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[4] http://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm

[5] http://ec.europa.eu/environment/eussd/smgp/pdf/OEFSR_guidance_v6.3.pdf

of battery per kWh of the total energy required by the application over its service life. Which is an important parameter to quantify the environmental impact from batteries.

For the sake of compatibility and harmonization of data **this study proposes to use the same functional unit as the PEF for high specific energy rechargeable batteries for mobile applications**.

Table 5: Key aspects of the functional unit for batteries (source: PEF pilot phase[4])

What?	Electrical energy, measured in Wh or kWh (current and voltage during a unit of time).
How much?	1 kWh of the total energy delivered over service life (quantity of Wh, obtained from the number of cycles multiplied by the amount of delivered energy over each cycle).
How well?	Maximum specific energy (measured in Wh/kg). Specific product standards and technical properties of the high specific energy rechargeable batteries PEF shall be declared in the PED documentation.
How long?	The amount of cumulative energy delivered over service life of the high specific energy rechargeable batteries (quantity of Wh, obtained from the number of cycles multiplied by the amount of delivered energy over each cycle). The time required to deliver this total energy is not a significant parameter of the service.

Note that the PEF study for UPS[6] has defined a different functional unit: 'To ensure the supply of power without interruption to equipment with load of 100 watts for a period of 1 year, including a backup time of 5 minutes during a power shortage'. This can be explained because for UPS other battery selection criteria matter, see Table 4 and Table 6. Moreover, these products have already been studied in a previous Ecodesign study 'Lot 27 UPS'. Hence, because UPS batteries have already been studied and have another functional unit it is recommended to exclude them from the scope of this study, see also 39. Also, electrical grid Energy Storage Systems (ESS) can sometimes have the same functional unit as previously defined, however the name ESS is sometimes also used to refer to grid ancillary, which has a different functional unit, e.g. maintain the grid power balancing.

Table 6: Comparing application criteria between BEV and UPS applications

Typical application parameters (See Task 3 on use)	Passenger car (BEV)	UPS (server, lift, light, etc)
Importance of low specific weight	high	low
Importance of efficiency	high	low
Importance of self-discharge	medium	high
Importance of long cycle life	high	low

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[6] http://ec.europa.eu/environment/eussd/smgp/ef_pilots.htm

1.7 The basic secondary product performance parameters

This section lists some of the basic secondary parameters that are required to describe and characterize the identified product on a functional level. These are important parameters that are mainly provided and defined based on European and International standards and UN manuals. There are some definitions that have been included and are required by the PEF but have not been found to be defined in any standard or regulation. When they are not found on existing standards the study team will provide its own draft definition. Note however that when deemed necessary additional parameters will added in subsequent tasks.

Capacity: Total number of ampere-hours that can be withdrawn from a fully charged battery under specified conditions. (ISO 12405) [14]–[16]. Strictly the ampere-hours is used in the standards, but this parameter can b also be expressed in ampere-hour or kilowatt-hour (Ah or KWh).

Rated capacity: Capacity value of a cell, module, pack or system determined under specified conditions and declared by the manufacturer. (IEC 61960) [36]. This parameter is expressed in ampere-hour (Ah).

Current rate or C-rate: the current that corresponds to the declared capacity by the manufacturer [37]. This parameter is expressed in amperes. For portable and industrial applications this has been defined to be at C/5 [11], [36], for BEV it is defined at C/3 [16], [21] and C/1 for HEV applications [16], [21].

State of Charge (SOC): Available capacity in a cell, module, pack or system expressed as a percentage of rated capacity. (IEC 62660) [19], [20], [38], [39]. This parameter is expressed in percentage (%)

Depth of Discharge (DOD): Percentage of rated capacity discharged from a cell, module, pack or system battery. (IEC 62281) [6] This parameter is expressed in percentage (%).

End of Life (EoL): Condition that determines the moment a battery cell, module or pack does not anymore reach a specified performance in its first designated application based on the degradation of its capacity or internal resistance increase. This condition has been set to 80% for electric vehicle application and 60% for portable applications of the initial capacity. (Study team's own definition, not found in any standards so far) [36], [38]. for electric vehicle application (condition B in the cycle life tests in IEC-62660-1) and 60% for portable applications of the rated capacity (in table 5 of IEC 61960, using the accelerated method). (IEC 61960, IEC 62660) [36], [38].

Full cycle: Means one sequence of fully charging and fully discharging a rechargeable cell, module or pack. (UN Manual of Tests and Criteria) [40]. This parameter is expressed as an absolute value (-).

Specified duty cycle: One or multiply sequences of charging or discharging a battery to a specified state of charge and discharging to a specified depth of discharge under a specified load. The charge and discharge may follow a dynamic profile. This cycle can either be defined by the cell manufacturer or the battery system manufacturer and is typically related to conditions the battery would normally be operated in (study team's own definition, not found in any standards so far). This parameter is expressed as an absolute value (%).

Cycle life: The total amount of specified duty cycles a battery cell, module or pack can perform until it reaches its End of Life condition related to its capacity degradation or power loss (study team's own definition, not found in any standards so far). This parameter is expressed as an absolute value (%).

Calendar-life or shelf-life: The time a battery cell, module or pack can be stored under specified conditions (temperature) until it reaches its end of life condition (study team's own definition, not found in any standards so far). This parameter is expressed in days (-).

Nominal voltage: Suitable approximate value (mean value between 0% and 100% DOD) of the voltage during discharge at a specified current density used to designate or identify the voltage of a cell or a battery. (IEC 62620) [11]. This parameter is expressed in Volts (V).

Voltage limits: Maximum and minimum cut-off voltage limits for safe operation of a battery cell. These limits are also implemented to achieve a complete charge and discharge that leads to the rated capacity under a specified current rate. This parameter is expressed in Volts (V).

Internal resistance: The resistance within the battery, generally different for charging and discharging, also dependent of the battery state of charge and state of health. As internal resistance increases, the battery efficiency decreases, and thermal stability is reduced as more of the charging/discharging energy is converted into heat. [41]. This parameter is expressed in Ohms (Ω).

Open circuit voltage (OCV): Means the voltage across the terminals of a cell or battery when no external current is flowing. (UN Manual of Tests and Criteria) [40]. The OCV depends on the state of charge current rate and state of health of a battery. This parameter is expressed in Volts (V).

Specific energy / Gravimetric energy density: Amount of stored energy related to the battery cell, module, pack or system weight expressed in Wh/kg. (ISO 12405) [14]–[16].

Specific power / Gravimetric power density: Amount of retrievable constant power over a specified time relative to the battery cell, module, pack or system weight expressed in W/kg (study team's own definition, not found in any standards so far).

Volumetric Energy density: Amount of stored energy related to the battery cell, module, pack or system volume expressed in Wh/l. (ISO 12405) [14]–[16].

Volumetric Power density: Amount of retrievable constant power over a specified time relative to the battery cell, module, pack or system volume expressed in W/l. (Study team's own definition, not found in any standards so far)

Coulombic efficiency: Efficiency of the battery, based on electricity (in coulomb) for a specified charge/discharge procedure, expressed by output electricity divided by input electricity. (ISO 11955) [42]. This parameter is expressed in percentage (%).

Energy efficiency: Ratio of the amount of energy provided by a battery during discharge and the amount of energy needed to re-charge the battery to its initial state of charge. This may cover a sequence of charge and discharge rates with a net discharge or charge effect. The storage efficiency on cell level is given by the voltage difference between charge and discharge potential of the cell and its coulomb efficiency. On module, pack or system level, power demand by electronics and supporting infrastructure can also impact the storage efficiency (study team's own definition, not found in any standards so far). This parameter is expressed in percentage (%).

Note that for this study also definitions on **reparability, dismantlability**, etc. might be needed, they are under development in proposal for new EN standards from CEN CLC JCT10 and preliminary definitions ware already included before in 1.2.5. For the work ongoing see the Annex on standards complementary to this report. Related definitions will be added in later tasks when needed.

1.8 Discussion of the proposed scope of this study

The study aimed at building on the PEF pilot[7] results and therefore on ‘High Specific Energy Rechargeable Batteries for Mobile Applications’ with high capacity, see also section 1.6 on the PEF and functional unit. In order to have a consistent and expected significant scope the study team agreed to electrochemical batteries with internal storage and solid electrodes only[8,9] and the further scoping and focusing explained hereafter. Note that also Tasks 2-5 can according to the MEErP reconsider or reduce the scope for Tasks 6-7 based on their findings. For more information in forecasted market volumes of batteries please read Task 2, it provided the rationale for excluding some applications.

In order to define the scope of the remainder of this study, the following topics were taken into consideration:

- the aim to build on the PEF study for mobile applications and to have a clear single functional unit and a corresponding product group to perform a consistent analysis according the MEErP in Tasks 3 to 6. Considering different applications with different requirements is therefore not an option, it would require different studies.
- Uninterruptable Power Supply systems (UPS) (stationary batteries) were already part of a completed Ecodesign Study (Lot 27). Moreover, UPSs have a complete different functional unit, i.e. provide back-up power during occasional power interrupts, which would lead to an inconsistent study in Tasks 3-6. Therefore, the PEF study for UPS and ‘High Specific Energy Rechargeable Batteries for Mobile Applications’ had a different and incompatible functional unit compared to UPS.
- Industrial back-up batteries (usually, but not always, stationary) are used in for example nuclear power plants, high speed trains, airplanes, offshore platforms, etc. can have each very different requirements (duration of back-up, service life, ability to withstand temperature, shock and vibrations, ability to perform additional services). A unique functional unit would not adequately cover all these segments. Developing use-specific functional units would require a considerable amount of resources, which are not available, and likely would never adequately capture evolving needs.
- Smaller mobile battery systems were also part of previous Ecodesign studies: Computers and servers (Lot 3) and portable machine tools (Lot 5). Moreover, portable batteries are another category in the battery directive.
- The largest volume of lithium batteries (LiB) is expected for EV applications, see Task 2. According to the MEErP this will therefore also define the base cases or reference systems for impact modelling. Hence accordingly the conclusion for Task 3 to 6 will be to focus on EV E-mobility applications.
- Electric bicycles are complex to model in Task 3 because they have hybrid human/electric power and as explained before referring to Task 2, the total EU mass of batteries sold will be relatively low. Hence, they are not relevant for Tasks 3 to 6.

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[7] http://ec.europa.eu/environment/eussd/smgp/ef_pilots.htm

[8] Batteries with external storage are excluded from the scope because the expected niche market (see Task 2) for this application and lack of time to investigate this into detail in this study.

[9] Batteries with liquid electrodes like ceramic batteries are excluded from the scope because they are not used in electric vehicles and their ecodesign and recycling is much less challenging due to the used materials

- We are aware that other industry/agricultural mobile applications exist and might use also use similar rechargeable batteries (forklifts, garden machinery, mobile floor cleaning tools, etc.). However, here again the Task 3-6 modelling could be very complex and accurate data unavailable today and a relative lower volume to EV is expected, for which they will be excluded from Tasks 3-6.
- Note that despite some the proposed focus for Tasks 2-6 content and work, the policy process can be extended where deemed useful in a later stage of policy making following this preparatory study.
- Taking into consideration that the same LiB batteries can render a useful service as an Energy Storage System (ESS) combined with photovoltaic (PV) modules which are in the scope of the Ecodesign Study on photovoltaic Systems[10]. Herein smaller consumers could benefit from further Ecodesign requirements (if any). Also, second life application of EV batteries for ESS could be an option to reduce the carbon footprint, however this still needs to be confirmed if it is technical and economical feasible.
- In their feedback on the draft Task 1 and the first stakeholder meeting several industry federations urged to focus on e-mobility applications because requirements among industrial batteries can be extremely different and each battery technology currently available on the market (lead, lithium, sodium and nickel) can be best suited to serve specific market segments thanks to their different features. This can also be concluded from the introduction in section 1.4.1.
- Taking into account that grid support (mainly ancillary service) and energy storage (mainly photovoltaic energy) function can be very dependent on the local grid circumstances which is not harmonized in the EU (metering intervals, feed in tariffs, grid ancillary services and power reserve market, weather conditions, grid congestion issues, etc.). Therefore, the study will only look at the similar energy storage function but cannot go into the various details of for example grid support (primary reserve, etc.).

Considering all this, the scope herein is: ’High energy rechargeable batteries of high specific energy with solid lithium cathode chemistries for e-mobility and stationary energy storage (if any). Herein batteries are either a pack or a system as defined within this study and in line with the international standards. This does not include power electronics neither heat nor cool supply systems for thermal management which can be part of what the study defined as a battery application system.’

More in detail:

High specific energy is hereby defined by a gravimetric energy density typically above 100 Wh/kg at cell level, this means that several battery technologies are excluded based on this criterium, see Table 4. This is also an elegant and technical way to exclude some types of UPS batteries which have different functional unit and for which weight is of lower importance, see recommendation in section 1.6.

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[10] http://susproc.jrc.ec.europa.eu/solar_photovoltaics/index.html

High capacity means that a total **battery system capacity between 2 and 1000 kWh**. Note that as defined in section 1.5 the 'battery application system' can be a multiple of the 'battery system capacity', e.g. as is the case in large modular energy storage systems for grid support. See also Task 2-3 for market and user data, it appears that few systems above 1000 kWh can be expected due to typical energy use of cars (about 20 kWh/100 km) and houses (about 3500 kWh/year). Battery applications such as grid energy storage that require above 1000 kWh are composed of parallel or multiple smaller systems (<1000 kWh) due to transport and weight constraints. Below 2 kWh is expected a smaller market volume (e.g. cycles), see Task 2, and also ICT (Lot 3) and portable machine tools (Lot 5) having small capacity batteries were already part of previous Ecodesign studies. Below 2 kWh are also the portable batteries which are a separate category in the Batteries Directive(2006/66/EC), see 1.4.3.

Despite this proposed limitation of the scope in Tasks 2-6, in **Task 7 it can be investigated of policy measures can be extended** to a broader scope if the expected impact is unanimously positive.

As a consequence of these energy density and battery system capacity limits, are reducing the scope of this study but **have lithium-ion technologies included**. Given the time constraints in this study this will allow to build on the results from the PEF study for e-mobility available for lithium-ion technology and for which a significant market is expected in the upcoming years (see Task 2).

A battery system and battery application system were previously defined, see 1.5.

As a consequence, the batteries in the proposed scope are according to the definitions of the current Batteries Directive(2006/66/EC) part of the 'the industrial batteries'. Herein 'industrial batteries' are defined as any battery designed for exclusively industrial or professional uses or used in any type of electric vehicle. For more information see section 1.1.12 regarding the Battery Directive.

The proposed scope for this study is thus rechargeable industrial batteries (2006/66/EC) with a high specific density (>100 Wh/kg) and high capacity (2 to 1000 kWh).

1.9 Test standards and/or methods

The general objective of this task is to describe test standards related to the product categories described within the scope of this study. Standards are documents drawn up by consensus and approved by a recognised standardisation body. A test standard describes a method of testing in which no pre-given result is required when performing the test.

The content of this section has been published as a separate annex report due the the extension of the descriptions[11].

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[11] Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage under FWC ENER/C3/2015-619-Lot 1. TASK 1 Scope. Annex: Analysis of available relevant performance standards & methods in relation to Ecodesign Regulation for batteries and identification of gaps. January 2019.

Complementary to the Annex information in related standards can be also be found in: https://www.batterystandards.info/[12], the public document of the MAT4BAT project Deliverable 5a 'List of relevant regulations and standards' [43] and the JRC technical report on 'Standards for the performance assessment of electric vehicles batteries' [12].

1.10 Existing legislation

According to the MEErP methodology, EU legislation, Member State legislation and third country legislation relevant to the product group should be screened and analysed.

The most interesting battery regulations can be summarized in the following list:

- Regulation on CE marking
- Regulations on transport of batteries
- European battery directive
- Directive on restrictions of hazardous substances (RoHS)
- Regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)
- The battery capacity labelling regulation
- The UNECE vehicle regulation
- Ecodesign Directive (ED)
- The Energy Labelling Regulations (ELR)
- The Framework Directive on type-approval for motor vehicles
- The End of Life of Vehicles (ELV) Directive
- The Waste of Electrical and Electronic Equipment (WEEE) Directive

1.10.1 Regulation on CE marking

Regulation (EC) No 765/2008 [13] on CE marking creates the premise of the internal European Union market. It established the legal basis for accreditation and market surveillance and consolidated the meaning of the CE marking. Therefore, it is of relevance for battery manufacturers. Amongst others it defines the responsibilities of the manufacturer, i.e.:

- carry out the applicable conformity assessment or have it carried out, for example verify compliance with applicable European Directives;
- draw up the required technical documentation;
- draw up the EU Declaration of Conformity (EU DoC);
- accompany the product with instructions and safety information;

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[12] This website is dedicated in supporting a way through standards on rechargeable batteries and system integration

[13] REGULATION (EC) No 765/2008 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 9 July 2008 setting out the requirements for accreditation and market surveillance relating to the marketing of products and repealing Regulation (EEC) No 339/93

- satisfy the following traceability requirements:
  - Keep the technical documentation and the EU Declaration of Conformity for 10 years after the product has been placed on the market or for the period specified in the relevant Union harmonisation act.
  - Ensure that the product bears a type, batch or serial number or other element allowing its identification.
  - Indicate the following three elements: his (1) name, (2) registered trade name or registered trade mark and (3) a single contact postal address on the product or when not possible because of the size or physical characteristics of the products on its packaging and/or on the accompanying documentation.
- affix the conformity marking (CE marking and where relevant other markings) to the product in accordance with the applicable legislation, e.g. the collection symbol for batteries (see the Batteries Directive below).
- ensure that procedures are in place for series production to remain in conformity.
- Where relevant, certify the product and/or the quality system.

This is applicable to all battery products and devices that use batteries. When a device with an original battery is converted with for example a Li-ion battery retrofit kit the full CE marking procedure needs to be redone including new technical documentation, EU DoC, serial number, etc. A complete guide on the implementation of EU product rules is given in the Blue Guide: Commission notice 2016/C 272/01[14].

1.10.2 European Agreement concerning the international carriage of dangerous goods by road (ADR)

The transport of dangerous goods and articles in Europe is arranged in the ADR by UNECE (ECE/TRANS/257)[15]. Batteries fall under class 8 (corrosive products) or, for lithium and Li-ion batteries under class 9 (miscellaneous). For lithium (ion) batteries a specific section exists (§2.2.9.1.7) with exigencies to these batteries:

- Lithium cells and batteries have to pass ‘Manual of Tests and Criteria, part III, sub section 38.3’.
- Cells and batteries must have a safety venting device or being designed that no violent rupture can occur.
- Each cell and battery are equipped with an effective means preventing external short circuit.
- Each battery with cells or strings of cells in parallel are equipped with an effective means preventing a dangerous current in the opposite direction, e.g. by diodes or fuses.
- Cells and batteries must be manufactured under a production quality management system.

Table A in the ADR prescribes the needed marking, the special provisions and the packaging possibilities. Chapter 6 prescribes the packaging tests and pass criteria.

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[14] https://ec.europa.eu/growth/content/%E2%80%98blue-guide%E2%80%99-implementation-eu-product-rules-0_fi

[15] https://www.unece.org/fileadmin/DAM/trans/danger/publi/adr/adr2017/ADR2017E_web.pdf

For lithium batteries a distinct category is made for damaged or defective cells or batteries, defined as that they do not conform to the type tested according to the provisions of the Manual of Tests and Criteria.

1.10.3 Manual of Tests and Criteria, part III, subsection 38.3

All lithium (ion) batteries that are transported, irrespective of the transport way, have to fulfil the UN38.3 regulation by the United Nations [40]. It prescribes 8 test methods and test criteria that battery cells and batteries have to fulfil before delivery.

The international organisations for the transport modes have their own regulation for the transport of dangerous goods being:

- ICAO: Dangerous goods (DGR), and Li-ion by airplane
- UNECE: Dangerous goods by road: European Agreement concerning the International Carriage of Dangerous Goods by Road, ADR
- UNECE: European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways, ADN
- IMO: Dangerous goods by ship: International Maritime Dangerous Goods Code, IMDG
- CIT: Dangerous goods by train: Regulation concerning the International Carriage of Dangerous Goods by Rail, RID.

1.10.4 European battery directive

Directive 2006/66/EC is the main European regulation on batteries. The primary objective is to minimise the negative impact of batteries on the environment. It advocates a high collection and recycling rate for waste batteries and accumulators in the European member states to achieve a high level of environmental protection and material recovery throughout the Community.

Producers have to finance the costs of collecting, treating and recycling all collected batteries minus the profit made by selling the materials recovered.

Note that the Batteries Directive is currently under review[16].

1.10.4.1 Scope

The Batteries Directive discriminates three battery applications:

- Portable battery: any battery, button cell, battery pack or accumulator that:
    - is sealed;
    - can be hand-carried; and
    - is neither an industrial battery or accumulator nor an automotive battery.
- automotive battery or accumulator: any battery or accumulator used for automotive starter, lighting or ignition power;

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[16] https://ec.europa.eu/info/consultations/public-consultation-evaluation-batteries-directive_en

- industrial battery or accumulator: any battery or accumulator designed for exclusively industrial or professional uses or used in any type of electric vehicle.

1.10.4.2 Labelling

The directive prescribes an additional label to the CE marking. All batteries, accumulators and battery packs are required to be marked with the separate collection symbol (crossed-out wheeled bin) either on the battery or its packaging depending on size. In if the battery contains more heavy metals than prescribed (see below), their chemical symbols have to be added.

Figure 9: Obligatory labelling for batteries

1.10.4.3 Heavy metals

Batteries are not allowed to contain more than 0.0005% of mercury by weight; and portable batteries not more than 0.002% of cadmium by weight. Exceptions are emergency and alarm systems, emergency lighting and medical equipment.

If batteries contain more than 0.0005% mercury, more than 0.002% cadmium or more than 0.004% lead, they must be marked below the crossed-out dustbin sign with the chemical symbol for the metal concerned: Hg, Cd or Pb.

1.10.4.4 Collection rates for portable equipment

EU member states should achieve the following minimum collection rates:

- 25 % by 26 September 2012;
- 45 % by 26 September 2016.

1.10.4.5 Disposal

The EU member states shall prohibit the disposal in landfills or by incineration of waste industrial and automotive batteries. However, residues of any batteries and accumulators that have undergone both treatment and recycling may be disposed of in landfills or by incineration.

1.10.4.6 Treatment

Treatment has minimally to include removal of all fluids and acids. Treatment and any storage, including temporary storage, at treatment facilities shall take place in sites with impermeable surfaces and suitable weatherproof covering or in suitable containers.

1.10.4.7 Recycling

Recycling processes must achieve the following minimum recycling efficiencies:

- recycling of 65% by average weight of lead-acid batteries and accumulators, including recycling of the lead content to the highest degree that is technically feasible while avoiding excessive costs;
- recycling of 75% by average weight of nickel-cadmium batteries and accumulators, including recycling of the cadmium content to the highest degree that is technically feasible while avoiding excessive costs; and
- recycling of 50% by average weight of other waste batteries and accumulators.

This means that Li rechargeable batteries must be recycled for at least 50% by average weight.

According to EC regulation 493/2012 the recycling process stops at the production of output fractions. Herein 'output fraction'(Art. 2 (5)) means the mass of materials that are produced from the input fraction as a result of the recycling process, as defined in an Annex (I) without undergoing further treatment, that have ceased to be waste or that will be used for their original purpose or for other purposes, but excluding energy recovery. The mass of the output fractions concerns the dry matter of the elements or compounds expressed in tons per calendar year.

The elements that are incorporated in the alloys, CO_2 emission and/or slags can be included in the recycling efficiency. This concerns mostly oxygen. Carbon can also be used as a reducing agent and therefore CO_2 emission from the battery recycling can be accounted as recycled if it has been used as a reducing agent. An independent scientific authority must certify and publish the recycling efficiency for these cases. The percentage of oxygen and carbon in the output materials are indicated as a percentage. The total recycling rate can be expressed e.g. as 60% from which 20% as functional recycling in alloys and 15% O_2 in the slags.

The recycled materials of batteries include metal alloys and slag that can be used further without extra treatment. A possible plastic fraction can be partly recycled and partly thermally valorised. The light fraction due to the separator material that may be formed during the recycling process can be disposed for final treatment. If black mass is formed out of the electrolyte substances, then it can be used in hydro metallurgic processes and/or thermal processes.

Closely related EU legislation on hazardous waste are:

- Council Directive 67/548/EEC[17] on classification, packaging and labelling of dangerous substances determines the substances that are considered dangerous and give provisions on classification, packaging and labelling
- Directive 2000/53/EC on end-of-life vehicles[18]. It prohibits the use of mercury, lead, cadmium and hexavalent chromium in vehicle materials and components. It has

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[17] Council Directive 67/548/EEC of 27 June 1967 on the approximation of laws, regulations and administrative provisions relating to the classification, packaging and labelling of dangerous substances.

[18] Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles

no additional clauses for battery materials. Batteries must be removed for depollution of end-of-life vehicles.

- Directive 2012/19/EU on Waste Electrical and Electronic Equipment (WEEE)[19]. It sets recycling rates for this type of equipment, including selective treatment of batteries included in electrical and electronic equipment.

Note that related to recycling the European Commission has defined a list of Critical Raw Materials[20] (CRM). Raw materials are crucial to Europe's economy and access to certain raw materials is a growing concern within the EU and across the globe. To address this challenge, the European Commission has created a list of critical raw materials (CRMs) for the EU, see Table 7, which is subject to a regularly review and update.

Table 7 2017 list of Critical Raw Materials

2017 CRMs (27)			
Antimony	Fluorspar	LREEs	Phosphorus
Baryte	Gallium	Magnesium	Scandium
Beryllium	Germanium	Natural graphite	Silicon metal
Bismuth	Hafnium	Natural rubber	Tantalum
Borate	Helium	Niobium	Tungsten
Cobalt	HREEs	PGMs	Vanadium
Coking coal	Indium	Phosphate rock	

*HREEs=heavy rare earth elements, LREEs=light rare earth elements, PGMs=platinum group metals

1.10.4.8 Member state implementation

Most of the EU members states have national legislation for implementing the Batteries Directive (2006/66/EC). It is related with the chemical restrictions, recycling and collection of batteries and accumulators found in different electrical applications. Table 6 shows a list of the different legislations implemented in specific member states.

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[19] Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE)

[20] http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_nl

Table 8: Member state legislation on batteries and accumulators [45].

Austria	Regulation of the Federal Minister for Agriculture and Forestry on prevention of waste, and the collection and treatment of end-of-life batteries and accumulators
Belgium	Flemish regulations on waste prevention and waste management VLAREA Arrête royal relative aux piles et accumulateurs ainsi qu'aux déchets de piles et d'accumulateurs
Bulgaria	Ordinance on the requirements for placing on the market batteries and accumulators and treatment and transportation of waste batteries and accumulators
Cyprus	The regulations on solid and hazardous wastes (batteries or accumulators)
Czech Republic	Act No. 185/2001, on waste and amending some other laws (Directive 2006/66/EC)
Denmark	Executive order on batteries and accumulators and waste batteries and accumulators
Estonia	Handling requirements for used batteries and accumulators
Finland	Decree on batteries and accumulators
France	Decree on the placing on the market of batteries and accumulators and on the disposal of waste batteries and accumulators and amending the environmental code
Germany	The introduction to circulation, recovery and environmentally-friendly disposal of batteries and accumulators
Greece	Decree on waste management from batteries and accumulators
Hungary	Government regulation No. 181/20098 on the take-back of batteries and accumulators
Ireland	Waste management (batteries and accumulators) regulations 2008 (S.I. No 268 of 2008)
Italy	Recepimento della direttiva 2006/66/CE del parlemento europeo e del cosiglio del 6 settembre 2006, elativa a pille e accumulatori e ai rifiuti di pile e accumulatori e che abroga la direttiva 91/157/CEE
Latvia	Waste management law
Lithuania	Law on waste management of the republic of Lithuania
Luxembourg	Loi du 19 décembre 2008 relative aux piles et accumulateurs ainsi qu'aux déchets de piles et d'accumulateurs
Malta	Batteries and accumulators regulations, 2011
Netherlands	Besluit van 4 juli 2008, houdende regels met betrekking tot de mededeling inzake het afvalbeheer en het gebruik van bepaalde gevaarlijke stoffen in batterijen en accu's (Besluit beheer batterijen en accu's 2008)
Norway	Regulation on changes to regulation on recycling processing of waste (Waste regulation)
Poland	The law of 2007 on batteries and accumulators as well as waste batteries and accumulators
Portugal	Decree law 6/2009 transposing the battery directive
Romania	Government decision draft on batteries and accumulators, and waste batteries and accumulators (April 2008)
Slovakia	Slovakian law – Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators
Slovenia	Decree on batteries and accumulators and waste batteries and accumulators
Spain	Royal decree 106/2008 of 1 February 2008, on batteries and accumulators and environmental waste management
Sweden	Proposal for implementation of Directive 2006/66/EC of the European Parliament and of the Council, of 6 September 2006, on batteries and accumulators, and waste batteries and accumulators
United Kingdom	Document on the Implementation of the Batteries and Accumulators and Waste Batteries and Accumulators Directive (2006/66/EC) – Waste Battery Collection and Recycling Provisions

1.10.5 Directive on the Restriction of Hazardous Substance (RoHS)

The RoHS recast Directive 2011/65/EU[21] restricts the use of hazardous substances in electrical and electronic equipment. The objective of these schemes is to increase the recycling and/or re-use of such products. It also requires heavy metals such as lead, mercury, cadmium, and hexavalent chromium and flame retardants such as polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE) to be substituted by safer alternatives. Batteries are currently not in the scope of this directive; however it might apply to some parts of a battery system such as the battery management system.

1.10.6 Regulation on capacity labelling of portable secondary and automotive batteries

The Commission Regulation 1103/2010 on rules as regards capacity labelling of portable secondary (rechargeable) and automotive batteries and accumulators pertains the capacity marking requirements of portable rechargeable batteries including specific requirements related to its minimum size and location. The capacity label shall include both the numeral and its units expressed in Ah or mAh. The capacity label is a marking, which has to appear either on the battery label, the battery casing and/or the packaging. The capacity of portable secondary (rechargeable) batteries and accumulators shall be determined on the basis of IEC/EN 61951-1, IEC/EN 61951-2, IEC/EN 60622, IEC/EN 61960 and IEC/EN 61056-1 standards depending on chemical substances contained therein.

Battery standards may contain additional labelling prescriptions about the used battery materials, the power capability and e.g. recycling issues.

1.10.7 UNECE Electric vehicle regulation

The Economic Commission for Europe of the United Nations (UNECE) has developed the regulation UNECE R100, Battery electric vehicle safety, within committee ECE/TRANS/WP.29 [46]. It concerns safety requirements for road vehicles with an electric power train and a maximum design speed exceeding 25 km/h. This regulation comprises safety tests regarding vibration, thermal shock, mechanical shock, fire resistance and charge protection. It is applicable to complete battery systems and battery packs [47].

Today electric vehicles must specify the battery capacity often only indirectly in a driving range, which is related to standard driving cycles.

Under the UNECE vehicle regulation two driving profiles to assess the CO_2 emissions of vehicles have been developed. These are the New European Driving Cycle (NEDC - E/ECE/324/Rev.2/Add.100/Rev.3) [48] and the Worldwide Harmonised Light Vehicle Test Procedure (WLTP - ECE/TRANS/WP.29/GRPE/2018/19) driving profiles [49]. While these driving profiles have been mainly developed for the assessment of tail pipe emissions of conventional vehicles they can be also be implemented in the context of Electric Vehicles. Electric Vehicle manufactures are implementing these driving cycles to inform the consumer of the total driving range that these vehicles can deliver. These driving cycles are not being executed to establish the capacity of individual batteries but the driving range that a battery system of an Electric Vehicle can deliver all the energy stored is consumed.

Furthermore under the UNECE regulation additional safety aspect have to be considered in relation to Electric Vehicles in UN R100.02 [48]. It aims to protect against electric shock and

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[21] Title here as from previous examples…

therefore: direct contact in connectors and during service of the vehicle, indirect contact and isolation resistance. The UNECE regulation provides also safety in terms of accumulation of gas, functional safety and determination of hydrogen emissions. It will be transposed in the future by the regulation GTR 20 encompassing ECE/TRANS/180/Add.20 [50] and ECE/TRANS/180/Add.20/Appendix I [51].

1.10.8 Regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)

Regulation (EC) No 1907/2006 on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)[22] is regulating the use of chemicals in Europe [52]. REACH addresses the production and use of chemical substances and their potential impacts on human health and the environment. It requires all companies manufacturing or importing chemical substances into the European Union in quantities of one ton or more per year to register these substances with the European Chemicals Agency (ECHA). The ECHA databases contain over 120000 unique substances/entries at the start of 2016 [53].

One of the obligations is to inform customers about the ‘Substances of Very High Concern’ (SVHC) that are listed on the ‘Candidate List’ and contained in products in concentrations higher than 0.1% weight by weight per article. These materials may be found in batteries, probably as an electrolyte solvent. A further obligation for these substances is to inform the customer, if necessary, about how to safely use the product. The authorisation procedure aims to assure that the risks from Substances of Very High Concern are properly controlled and that these substances are progressively replaced by suitable alternatives while ensuring the good functioning of the EU internal market.

The Candidate List of substances of very high concern for Authorisation [54] contains at least two substances known for use in Li-ion batteries:

- 1,2-dimethoxyethane or ethylene glycol dimethyl ether (EGDME, $C_4H_{10}O_2$) [55]: electrolyte solvent, very persistent and very bio-accumulative (vPvB)
- 1,3-propanesultone or 1,2-oxathiolane, 2,2-dioxide ($C_3H_6O_3S$) [56]: electrolyte fluid in lithium ion batteries, carcinogenic

According to the REACH regulation batteries are identified as articles with no intended release of the substances they contain. Battery producers are users of chemicals [57]. Providing a Safety Data Sheet is not mandatory for articles and users of chemicals [58].

1.10.9 The European Ecodesign Directive (2009/125/EC) and its implementing regulations

The Ecodesign Directive provides consistent EU-wide rules for improving the environmental performance of products, such as household appliances, information and communication technologies The Directive sets out minimum mandatory requirements for the energy efficiency of these products and/or on providing information.

Important content related to battery applications: In Article 1 on ‘Subject-matter and scope’ it says that it ‘This Directive shall not apply to means of transport for persons or goods’. Therefore, it does for example exclude Electrical Vehicles as a product itself and products that

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[22]

are exclusively used for cars, such as tyre labels that have their own Regulation (EC) No 1222/2009 and also batteries which are exclusively for vehicles. This is a legal matter but could pose challenges to convert the outcomes of this study into policy based on the Ecodesign Directive. Note however that due to the Vehicle-to-Grid (V2G) technology, EV batteries might also be used as electricity storage for buildings and have a therefore different nature than the solely transport-related one.

So far two EU Ecodesign Regulations are currently in preparation that may cover battery systems:

Commission Regulation (EU) No 617/2013 with regard to Ecodesign requirements for computers and computer servers includes requirements on the extraction and replacement of batteries. The review may include requirements on battery durability (proxy of indication on number of loading cycles that batteries can withstand). A review study of the ecodesign requirements for this product group has been completed in July 2018 [59].

Potential Commission Regulation and/or Voluntary Initiative within the framework of the Ecodesign Directive 2009/125/EC with regard to Uninterruptible Power Supplies (UPS): The status is that a preparatory study has been carried out (Lot 27: Uninterruptible power supplies). The proposed measures are based on UPS efficiency with a material resource bonus, hence taking battery efficiency and materials into account. So far there is no Ecodesign Directive implementing measure yet. However, a voluntary agreement (not under the Ecodesign Ddirective) has been in place for abut ten years, namely the Code of Conduct for AC Uninterruptible Power Systems [60].

Note that parallel to this study an Ecodesign Study on Photovoltaic systems is ongoing[23], that also includes battery storage.

It is the purpose of this study to consider further Implementing Measures (IM) for batteries within the framework of the Ecodesign Directive.

1.10.10 The EU Energy Labelling Framework Regulation (2017/1369)

This EU Regulation sets a framework for energy labelling, simplifying and updating the energy efficiency labelling requirements for products sold in the EU.

Important content related to battery applications:

- In their recitals it says that ‘As the energy consumption of means of transport for persons or goods is directly and indirectly regulated by other Union law and policies, it is appropriate to continue to exempt them from the scope of this Regulation, ...'
- In Article 1 on ‘Subject-matter and scope’ it says that it ‘does not apply to: (a) second-hand products, unless they are imported from a third country; (b) means of transport for persons or goods’.

As a conclusion, it does for example exclude Electrical Vehicles as a product itself. It is however unclear whether or not this also applies to components for vehicles such as batteries. This is a legal matter, which goes beyond the scope of this study.

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[23] http://susproc.jrc.ec.europa.eu/solar_photovoltaics/index.html

1.10.11 The framework Directive on type-approval for motor and other vehicles

The technical harmonisation of motor vehicles in the EU is based on the Whole Vehicle Type-Approval System (WVTA)[24]. Under the WVTA, a manufacturer can obtain certification for a vehicle type in one EU country and market it EU-wide without further tests.

It is based on:

- A framework Directive on type-approval for motor vehicles motor vehicles (2007/46/EC)
- Regulation (EU) 2018/858 on the approval and market surveillance of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles, amending previous regulation
- Regulation for two and three-wheeled vehicles and quadricycles (168/2013/EU)
- Regulation for non-road mobile machinery emissions (Regulation (EU) 2016/1628)

Within WVTA the concept of type approval of components is used which might be relevant to this study:

A ‘whole vehicle’ is made up of large numbers of components and systems, each of which must conform to corresponding requirements. Suppliers of relevant parts however must ensure that their products meet those requirements. Type approval makes a distinction between ‘components for vehicles’ - such as lighting components, glazing, rear view mirrors, etc - and ‘systems for vehicles’, which determine compliance of many components together, such as for braking, steering, crash performance and emissions.

1.10.12 The End of Life of Vehicles (ELV) Directive

Directive 2000/53/EC on end-of life vehicles aims at making dismantling and recycling of ELVs more environmentally friendly. It sets clear quantified targets for reuse, recycling and recovery of the ELVs and their components. It also pushes producers to manufacture new vehicles without hazardous substances (in particular lead, mercury, cadmium and hexavalent chromium), thus promoting the reuse, recyclability and recovery of waste vehicles.

The Commission has an obligation to review the ELV Directive by 31 December 2020.

1.10.13 The Waste of Electrical and Electronic Equipment (WEEE) Directive

Directive 2012/19/EU (WEEE) was issued in 2012 as a recast of Directive 2002/96/EC.

The aim of this directive is expressed by its article 1: ‘This Directive lays down measures to protect the environment and human health by preventing or reducing the adverse impacts of the generation and management of waste from electrical and electronic equipment (WEEE) and by reducing overall impacts of resource use and improving the efficiency of such use.’

The directive puts the responsibility for handling of WEEE on the producers of such equipment. They shall finance the collection and treatment of their WEEE in a harmonised way that avoids false competition. Producers will shift payments to the consumers under the principle that the 'polluter pays’, avoiding costs for the general taxpayer.

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[24] http://ec.europa.eu/growth/sectors/automotive/technical-harmonisation/eu_en

In WEEE:

- Annex VII requires that batteries have to be removed from any separately collected WEEE. For specific treatment reference is made to the Batteries Directive.
- Annex VIII requires that batteries in sites for treatment of WEEE are stored in appropriate containers.
- In its recitals reference is made to the batteries directive that contains more specific requirements for batteries.

1.10.14 Directive on harmonisation of laws on Low Voltage equipment (LVD)

Directive 2014/35/EU regarding Low Voltage electrical equipment (LVD) was issued in February 2014 and repeals the existing directive 2006/95/EC with effect from April 2016. The purpose of this Directive is to ensure that electrical equipment on the market fulfils the requirements providing for a high level of protection of health and safety of persons, and of domestic animals and property, while guaranteeing the functioning of the internal market. The Directive applies to electrical equipment designed for use with a voltage rating between 50 and 1000 V for alternating current and between 75 and 1500 V for direct current. These voltage ratings refer to the voltage of the electrical input or output, not to voltages that may appear inside the equipment. For electrical equipment within its scope, the directive covers all health and safety risks, thus ensuring that electrical equipment will be used safely and in applications for which it was made. For most electrical equipment, the health aspects of emissions of electromagnetic fields are also under the domain of the Low Voltage Directive.

1.10.15 Regulation (EU) No 333/2014 to reduce car CO_2 emissions

Regulation (EU) No 333/2014 amending Regulation (EC) No 443/2009 sets targets to reduce CO_2 emissions from new passenger cars by 2021. By 2021, phased in from 2020, the fleet average to be achieved by all new cars is 95 grams of CO_2 per kilometre. This means a fuel consumption of around 4.1 l/100 km of petrol or 3.6 l/100 km of diesel. Emission limits are set according to the mass of vehicle, using a limit value curve. There are penalty payments for excess emissions. Manufacturers can group together and act jointly to meet the emissions target. The cars Regulation gives manufacturers additional incentives to produce vehicles with extremely low emissions (below 50 g/km). Super-credits will also apply in the second stage of emission reductions, from 2020 to 2022.

The European Commission is currently working on a proposal for setting targets after 2020: https://ec.europa.eu/clima/policies/transport/vehicles/proposal_en.

The proposed framework combines CO_2 targets for 2025 and 2030 with a technology-neutral incentive mechanism for zero- and low-emission vehicles in order to give the market a clear signal for investment in clean vehicles. Herein are defined:

- **zero-emission vehicles** such as battery electric or fuel cell vehicles
- **low-emission vehicles** having tailpipe emissions of less than 50 g CO_2 per km – these are mainly plug-in hybrid vehicles equipped with both a conventional and an electric engine

Important herein worth noting that for defining CO_2 emissions only exhaust emissions are taken into account, based on how data is reported according to the worldwide harmonized light vehicles test procedure (WLTP) or previously the New (1997) European Driving Cycle (NEDC).

The CO_2 targets of this regulation are based on measurements at the tailpipe to evaluate the in-use emissions performance. This is the so-called 'tank to-wheel' approach, rather than a well-to-wheel or life-cycle analysis approach. These other approaches look further along the emissions chain, e.g. energy involved in producing the fuel/energy used, energy from making the vehicle or its end-of-life treatment. Nevertheless, these are important issues for this study, so far CO_2 emissions from electric vehicles (EV) were not taken into account as there is no consistent methodology in use for such an approach. Hence in the current approach electric vehicles have attributed 0 g CO_2/kWh, in other words it is currently CO_2 emission targets at the tail-pipe used in Regulation (EU) No 33/2014 and not the CO_2-eq GWP targets from life-cycle analysis (LCA).

Hence, this Regulation does not take into account indirect CO_2 emissions that will be modelled later on in this study.

1.10.16 The car labelling Directive (Directive 1999/94/EC)

The aim is to help drivers choose new cars with low fuel consumption, EU countries are required to ensure that relevant information is provided to consumers, including a label showing a car's fuel efficiency and CO_2 emissions. It is complementary to the Regulation (EU) No 333/2014 to reduce car CO_2 emissions, see 1.10.15.

Here again the CO_2 label is based on measurements at the tailpipe to evaluate the in-use emissions performance or the so-called 'tank to-wheel' approach, rather than a well-to-wheel or life-cycle analysis approach. Therefore, electric vehicles have attributed 0 g CO_2/kWh, in other words it is currently based on CO_2 emission at the tail-pipe but not the CO_2-eq GWP targets from life-cycle analysis (LCA).

1.10.17 Weight and dimension limits in road transportation

In Europe regular road transport must comply with certain rules regarding to weights and dimensions for road safety reasons and to avoid damaging roads, bridges and tunnels. This is implemented through the Directive (EU) 2015/719 for the indirect impact on the maximum weight and size laying down for certain road vehicles the maximum authorised dimensions and the maximum authorised weights. This directive limits regular road transport to 40 tonnes (incl. trailer), 2.6-meter width, 4-meter height (incl. trailer) and 12-meter length. As an indirect consequence, in Europe battery application systems as defined in this task for use in applications that require large storage capacity such as grid support are unlikely to become larger. For large storage application most likely a set of parallel battery systems will be installed.

1.10.18 Relevant examples of legislation outside the EU

Looking at the international landscape, different countries have implemented legislation dealing with the recycling and collection of battery materials. This can be related to chemical restrictions (mercury, nickel etc.) during manufacturing of batteries and procedures that have to be followed for the recycling of the battery materials. In Annex A of IEC 60086-6 ED1 Primary batteries - Part 6 Guidance on environmental aspects a list of found international legislations has been included.

Table 9: International legislation related to the recycling and restrictions of chemicals in batteries

China	Restriction of the Use of Certain Hazardous Substances in Electrical and 669 Electronic Products (China RoHS 2) A national standard: Recycling Of Traction Battery Used In Electric Vehicle-dismantling -specification (GB/T 33598-2017)". Manufacturers are responsible for recycling and must set up a traceability systems[25] and have a maintenance network
Taiwan	Waste Disposal Act
Japan	Act on Preventing Environmental Pollution of Mercury
	Act on the Promotion of Effective Utilization of Resources
Republic of Korea	Enforcement Decree of the Act on the promotion of saving and recycling of 726 resources
	ELECTRICAL APPLIANCES AND CONSUMER PRODUCTS SAFETY CONTROL 735 ACT
Singapore	Environmental Protection and Management Act
Vietnam	Decision No.16/2015/QĐ-TTg of the Prime Minister
Brazil	CONAMA resolution No.401 of Nov.4, 2008
Colombia	Resolution 1297/2010 - Secondary batteries of following HS code and primary batteries
Israel	Environmental Treatment of Electrical and Electronic Equipment and Batteries Law, 854 5772-2012
Canada	Products Containing Mercury Regulations (SOR/2014-254)
Quebec	Regulation respecting the recovery and reclamation of products by enterprises
British Columbia	Recycling Regulation, B.C. Reg. 449/2004, Environmental Management Act
Manitoba	Regulation 16/2010, Household Hazardous Material and Prescribed Material 872 Stewardship Regulation
USA	Mercury-Containing and Rechargeable Battery Management Act
	New York State Rechargeable Battery Law

1.10.19 Summary and conclusion on legislation for batteries in the scope of this study

The main findings of this review are that the outcomes of this study could:

- Result in Implementing Measures in the framework of the Ecodesign Directive (2009/125/EC), but might require an amendment because means of transport are exempted
- Provide useful input for a future review of the Car Labelling Directive (D1999/94/EC) in the case that full life cycle emissions should be considered instead of tail pipe emissions.
- Define a label for the Energy Labelling Regulation (EU) 2017/1369 for a battery as standalone product, but might require some amendments because means of transport are currently exempted or without amendment for batteries that are not exclusively for mobility.
- Contribute to the review and impact of the Battery Directive (2006/66/EC).

1.11 Other initiatives

Hereafter is a selection of other government supported initiatives that could be relevant for the study.

1.11.1 Product Environmental Footprint

The European Commission services are working on building the single market for green products and therefore also the life cycle environmental performance of products and organisations[26].

There are two methods to measure environmental performance throughout the lifecycle, the Product Environmental Footprint (PEF) and the Organisation Environmental Footprint (OEF).

Two pilot studies were done[27] related to batteries, one on ‘Batteries and accumulators’ and another on ‘Uninterruptible Power Supply’.

They will provide useful data to this study.

1.11.2 Nordic Swan ecolabelling for primary batteries

The Nordic Swan is a voluntary official ecolabel in Denmark, Norway, Sweden and Iceland. For batteries it focuses on portable primary batteries. Since the market for primary batteries is extensive and since they have differences in environmental and quality properties, the Nordic Ecolabelling is capable to differentiate and to determine the best ones in terms of environmental and quality properties.

The ecolabel prescribes much lower maximum values for toxic metals than the Batteries Directive does. It bans the use of PVC. Clear information on the possible application type must be given and the ecolabel discerns 3 discharge power levels.

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[26] http://ec.europa.eu/environment/eussd/smgp/policy_footprint.htm

[27] http://ec.europa.eu/environment/eussd/smgp/ef_pilots.htm#pef

1.11.3 Nordic Swan ecolabelling for rechargeable batteries and portable chargers

The Nordic Swan Ecolabel focuses on capacity and durability of batteries to ensure long battery life thereby reducing the resource consumption. At the same time, batteries and portable chargers must meet recognized quality and safety standards.

The requirements include:

- Threshold values for heavy metals in batteries.
- No use of PVC and a number of flame-retardants in plastic.
- CSR policy to ensure responsible use and sourcing of limited raw materials and “conflict free” minerals.
- Electrical-, safety- and quality testing of batteries/cells, portable- and battery chargers.
- Nickel metal hydride (NiMH) batteries and cells must be fully charged when leaving the production site.
- Recyclable design of the portable charger.

1.11.4 Green Public Procurement in the EU

In 2008, the European Commission adopted a Communication on GPP (COM400, 2008), which, as part of the Sustainable Production and Consumption Action Plan, introduced a number of measures aimed at supporting GPP implementation[28] across the EU. Its key features are:

- EU GPP criteria
- Helpdesk
- Studies aimed at monitoring GPP implementation

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Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage under FWC ENER/C3/2015-619-Lot 1

TASK 1 Scope

Annex Analysis of available relevant performance standards&methods in relation to Ecodesign Regulation for batteries and identification of gaps.

Scope (Definitions, Standards and Legislation) – For Ecodesign and Energy Labelling

VITO, Fraunhofer, Viegand Maagøe

In cooperation with JRC

January 2019

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Contents

ABBREVIATIONS

Abbreviations	Descriptions
ADR	European Agreement Concerning the International Carriage of Dangerous Goods by Road
AND	European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways
BEV	Battery Electric Vehicle
BMS	Battery Management System
Cd	Cadmium
CE	European Conformity
CIT	International Rail Transport Committee
CPA	Statistical Classification of Products by Activity
CPT	Cordless Power Tools
CRM	Critical Raw Materials
DC	Direct Current
DG	Directorate General
DoC	Declaration of Conformity
DOD	Depth of Discharge
EC	European Commission
ECHA	European Chemicals Agency
ED	Ecodesign Directive
EDLC	Electrical Double-Layer Capacitor
EGDME	1, 2-dimethoxyethane or ethylene glycol dimethyl ether
ELR	Energy Labelling Regulation
ELV	End of Life of Vehicles
EOL	End of Life
ESS	Electrical Energy Storage Systems
EU	European Union
EV	Electric Vehicle
FU	Functional Unit
HEV	Hybrid Electric Vehicle
Hg	Mercury
HREEs	Heavy rare earth elements
IATA	International Air Transport Association
ICT	Information and Communications Technology
IEC	International Electrotechnical Commission
IM	Implementing Measure
IMDG	International Maritime Dangerous Goods Code
IMO	International Maritime Organization
ISO	International Organization for Standardization
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory, which is the data collection and modelling part of an LCA
LCIA	Life Cycle Impact Assessment. In the LCIA, the environmental impact of the LCA model is analysed
LCO	Lithium-ion Cobalt Oxide

Abbreviations	Descriptions
LFP	Lithium-Ion Phosphate
LiB	Lithium ion Battery
Li-Cap	Lithium-ion Capacitor
LMNO	Lithium-Ion Manganese Nickel Oxide
LMO	Lithium-Ion Manganese Oxide
LREEs	Light rare earth elements
LTO	Lithium-Ion Titanate Oxide
LVD	Low Voltage Directive
MEErP	Methodology for Ecodesign of Energy related Products
NACE	Statistical Classification of Economic Activity
NCA	Lithium Nickel Cobalt Aluminium
NiCd	Nickel-Cadmium
NiMH	Nickel-Metal hydride
NMC	Lithium-ion Nickel Manganese Cobalt Oxide
OCV	Open Circuit Voltage
Pb	Lead
PBB	Polybrominated biphenyls
PBDE	Polybrominated diphenyl ethers
PCM	Protection Circuit Module
PEF	Product Environmental Footprint
PGMs	Platinum Group metals
PHEV	Plug-in Hybrid Electric Vehicle
PRODCOM	Production Communautaire
PTC	Positive Thermal Coefficient
PV	Photovoltaic
REACH	Regulation on the registration, evaluation, authorisation and restriction of chemicals
RID	International Carriage of Dangerous Goods by Rail
RoHS	Restriction of hazardous substances
RRR	Recyclability, Recoverability, Reusability
SOC	State of Charge
SVHC	Substances of Very High Concern
TMS	Thermal Management System
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UPS	Uninterruptible Power Supply
vPvB	Very persistent and very bio accumulative
WEEE	Waste electrical and electronic equipment
WLTP	Worldwide harmonized light vehicles test procedure
WVTA	Whole Vehicle Type-Approval System

General introduction of this annex

The general objective of this annex is to dentify gaps in the available relevant standards in relation to Ecodesign Regulation for batteries. If important gaps exist to obtain critical ecodesign parameters, then transitional measurement methods need to be developed. The test standards are related to the product categories described within the scope of this study, being high energy rechargeable batteries of high specific energy with lithium chemistries for e-mobility and stationary energy storage (see Task 1 "Scope"). Standards are documents drawn up by consensus and approved by a recognised standardisation body. A test standard describes a method of testing in which no pre-given result is required when performing the test.

This task is done in cooperation with JRC and is included as a separate annex to Task 1 (scope).

The standards that have been analysed in detail are:

• IEC 62660-1:2018	Secondary lithium-ion cells for the propulsion of electrical road vehicles - Performance Testing.
• ISO 12405-4:2018	Electrically propelled road vehicles --Test specification for lithium-ion traction battery packs and systems -- Part 4: Performance testing
• DOE-INL/EXT-15-34184 (2015)	U.S. DOE Battery Test Manual for Electric Vehicles
• DOE-INL/EXT-07-12536 (2008)	Battery test manual for plug-in hybrid electric vehicles
• SAE J1798:2008	Recommended Practice for Performance Rating of Electric Vehicle Battery Modules
• ISO/DIS 18243: 2017	Electrically propelled mopeds and motorcycles -- Test specification and safety requirements for lithium-ion battery system
• IEC 62620: 2014	Secondary lithium cells and batteries for use in industrial applications
• IEC 61427-2: 2015	Secondary cells and batteries for renewable energy storage Part 2 On grid applications
• IEC 62984-3-2:2017	High Temperature Secondary Batteries – Part 3: Sodium-based batteries – Section 2: Performance requirements and tests
• BVES Effizienzleitfaden (2017)	BVES Effizienzleitfaden
• ANSI/CAN/UL 1974:2018	Standard for evaluation for repurposing batteries
• Nordic Swan Ecolabel (2018)	About Nordic Swan Ecolabelled Rechargeable batteries and portable chargers
• IEC 60086-6 (2017)	Primary batteries: Guidance on environmental aspects
• IEC/TS 62933-4 (2017)	Electrical Energy Storage (EES) Systems - Guidance on environmental issues
• IEC 63218 (under dev.)	Secondary Li-ion, Ni-Cd, and Ni-MH cells and batteries for portable applications - Guidance on environmental aspects

A summary of the contents concerning test methods are given in this annex with help of tables. These standards are about performance testing as needed for ecodesign regulation. Safety tests have been kept out of the scope.

Complementary detailed information about the standards included in this annex and concerns with them can also be found on/in:

- https://www.batterystandards.info/ [1],
- the public document of the MAT4BAT project Deliverable 5.1 'List of relevant regulations and standards' [1],
- the JRC technical report on 'Standards for the performance assessment of electric vehicles batteries' [2],
- the testing document 'White Paper on Test methods for improved battery cell understanding' that was developed by a cooperation between European battery projects [3],
- the JRC report 'Putting science into standards - Driving towards decarbonisation of transport: safety, performance, second life and recycling of automotive batteries for e-vehicles', 2016 [4],
- the JRC technical report 'Sustainability assessment of second life application of automotive batteries (SASLAB)', 2018. [5],
- and of course in the respective standards.

These documents also give information on battery safety and safety tests, what is less the subject of ecodesign.

After this general introduction, this annex covers the following sections:

- Section 1 gives the summary of the identified gaps of relevant battery standards.
- Section 2 starts with a short introduction on standards and standardisation bodies followed sub-sections with lists of battery standards per standardisation committee.
- Section 3 provides a more detailed overview including descriptions of relevant standards by subject, being: measurement and testing, electric vehicle applications, other applications, environment related topics, reuse of batteries, and functioning during use phase.

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[1] This website is dedicated in supporting your way through standards on rechargeable batteries and system integration.

1. Identified gaps of relevant battery standards

This section summarises the identified gaps of relevant standards in relation to Ecodesign Regulation for batteries. The structure of this summary follows the structure of the tasks considered within the Methodology for Ecodesign of Energy-related products (MEErP). The gaps come from the analysis on standards in chapter 3 and from gaps given in the above mentioned reports, as far as they relate to ecodesign issues.

For defining the scope, related to Task 1:

- It can be concluded that all definitions for the scope can be done according to IEC/ISO standards, except Calendar life, Specific power / Gravimetric power density and Volumetric Power density.

Concerning performance metrics on product life time and efficiency related to Task 3:

- The performance metrics such as energy content and internal resistance are defined in the standards. However, in each standard and for each application (even within one standard since it can cover several applications) the exact methodology is dissimilar. Also, several methodologies can be given for the same metrics. This means that the capacity (in Ah) can be based on e.g. a 1 h, 5 h or 8 h discharge period or even on a discharge with a specific current profile. Resistance values may be derived from a pulse test, a jump in discharge current, but also from an AC signal.
- Most standards have test clauses to express the capacity in Ah. This unit is prescribed by the European regulation 1103/2010 on capacity labelling of portable secondary and automotive batteries (*i.e.* starter battery, not electric vehicle battery). Few standards prescribe the determination of energy content expressed in kWh, like the proposed functional unit, especially for standards outside automotive.
- The energy involved in heat and cooling of the battery system is not determined in standards.
- The capacity tests in the standards ignore that cells can be charged at several current rates. This is, however, of interest for e.g. quick charging and regenerative braking. It must be noted that charging is mostly not allowed in the same temperature range as discharging if no active heating is present (i.e. only above 0°C).
- The heating and cooling of the battery is within the study’s system boundary. However, the needed energy is outside the boundary and will be an arbitrary value. It must be noted that the test standards do not measure this value, what could have been used as a reference.
- For cycle life tests (repeated imposition of a test profile on the battery expressed in current or power) many profiles exist. 14 have been identified in the relevant standards. Each application has a profile and dissimilar standards may have a different profile. The profiles found are always a simplification of real profiles like the battery would undergo during e.g. a WLTP test.
- Most cycle life tests are applied at 25°C but also one at 30 and one at 45°C. One test standard mentions that the cooling system has to be switched on. The reason for the testing temperatures are not given in the standards. [2]
- Cycle life tests do not take into account temperature profiles, like a series of temperature in weekly consecution such as -10°C, 25 and 45°C. Dissimilar charging and discharging temperatures are not considered. Cycle life tests are not combined with calendar life tests. Few standards incorporate calendar life examination anyway. [2]

- The influence of mechanical stresses like vibrations and shocks, so mechanical ageing, is not considered in the relevant standards. [4]
- In European battery development projects often an ageing test programme is performed with a swarm of test conditions being a combination of calendar life testing and cycle life tests with simple profiles. These conditions allow to derive the ageing behaviour comprehensively and goes therefore beyond single use cases. This generic approach is not found in current test standards. [3] [4]
- Several standards give end of life criteria, defining when the battery is not useful anymore. This is mostly related to the specific, application dependent, test cycle: if the profile imposed as cycle life test cannot be performed anymore since the battery voltage hits upper and or lower limit almost immediately, or e.g. that the battery becomes too hot during the cycling, then this is considered as an end of life state.
- No clear definition of SOH exists and it is differently used over applications and manufacturers. Battery degradation is a combination of phenomena as capacity fade, power fade, efficiency reduction, rise in cooling demand and negative incidents. A more elaborate approach to tackle SOH is therefore needed. Even if SOH only refers to capacity fade then still the calculation method has to be clarified since the nominal capacity can be taken or the capacity related to the needed power. [4]
- The indicators for SOH should be openly available from the BMS [4]. Alternatively, a traceability and tracking system for battery packs must be conceived.
- End of life (EOL) information: the BMS has currently no prescribed role in it, although it could give information on remaining capacity, actual power capability (being limited by either the battery resistance or the battery cooling capability) and negative events that happened. This information is of interest for the possibility to repair modules in a battery system and for repurposing batteries to a second life application. The standard ANSI/CAN/UL1974 provides a list with information that a BMS should provide to understand the battery health.
- The standard ANSI/CAN/UL1974 on repurposing of batteries introduces the calendar expiration date. A battery should not be used longer than this date. This date must be provided by the manufacturer. Current battery standards do not require this information. It must be stated that the battery life is much dependent on the use conditions such as the total time being at 100% SOC. Unlike primary batteries such a date is currently not given on secondary batteries.
- SOH determination by advanced techniques like electrochemical impedance measurement can be treated in standards as additional indicators [4].

For material efficiency aspects (life time, repair, recycling, ...), related to Task 4/5:

- There are no voted standards currently and work is in progress within CEN/CLC/JTC 10– 'Energy-related products-Material Efficiency Aspects for Ecodesign’.

For carrying out environmental life cycle assessments (LCA), related to Tasks 5/6:

- There are two ISO standards for drafting LCA studies (ISO 14040 and ISO 14044). However, they leave LCA practitioners with an array of choices that can affect the execution and results of an LCA. A tighter framework is available throuht the CEN/TC 350 EN 15804 standardand through the Product Environmental Footprint (PEF) methodology . However, the first mentioned is specifically for the construction sector, and the latter is not a standard but a harmonised European method. Nevertheless, there is a standard under development that can possibly fill the gap for batteries: prEN 50693 'Method for quantitative eco design via life cycle assessment and environmental declarations through product category rules for EEE'.

- Unified guidelines or harmonized approaches for performing LCA do not exist and different analyses may yield conflicting results when second use applications are considered, due to variability in assumptions, scope of the application and scenarios (e.g. considerations for recycling, costs and energy involved in manufacturing) [4].
- Most software and databases are proprietary which could hamper to include LCA results such as a carbon footprint in EC Regulation. The following LCA methods and tool are not standards but can be interesting in order to overcome proprietary issues:
    - openLCA is an open source and free software for LCA. It is developed and hosted by GreenDelta, an independent sustainability consulting and software company in Berlin, Germany. It is sustained by a network of partners, contributors, supporters and a user community. openLCA can offer free databases for use in openLCA and other datasets can be directly imported in case the datasets are in EcoSpold or ILCD format (common LCA dataset formats). It is highly likely that there are no LiB datasets in openLCA.
    - There is a lack of test cases and/or standards to test whether LCA software is calculating correctly. Within the LCA community it is a well-known problem that using a different LCA software can lead to different results even when calculating the same model and using the same dataset.
    - The Life Cycle Data Network is hosted by the EC/JRC and aims to provide a globally usable infrastructure for the publication of quality assured LCA dataset (i.e. LCI datasets and LCIA method datasets) (http://eplca.jrc.ec.europa.eu/). It aspires to include the Environmental Footprint (EF) datasets for representative products and a benchmark (http://eplca.jrc.ec.europa.eu/EF-node/). So far, the datasets for LiB are not publicly available yet.
    - The GREET model of Argonne National Lab is a model for "Greenhouse gases, Regulated Emissions, and Energy use in Transportation". It is available in excel format and .NET format. The aim is to get a full life cycle carbon emission impact estimate from well to wheels for fuels and raw material mining to vehicle disposal for automobiles (https://greet.es.anl.gov/). It includes recent carbon footprint data for LiB. This public domain model is available free of charge for anyone to use.

For re-sales and repurposing of batteries:

- For a profitable second use of batteries, additional costs as for testing, disassembly and retrofitting need to be minimised [4]. The original battery design and the BMS have a high impact on this. Since a BMS designed for an EV application would probably not be suitable for a second use application, the possibility of uploading adapted firmware must be considered. These issues are not in nowadays standards. Test methods to assess battery reliability, safety and performance at the end of first life use are absent. Criteria and guidelines to determine the suitability for a relevant second use can be developed. Standardised interfaces for hardware and software, including connectors, would support this minimised cost approach [4].
- Use information on the first life application, beyond the remaining capacity, is necessary. The standard ANSI/CAN/UL1974 identifies the information need. This information is

however probably not reachable, partly since it is not stored, partly since a BMS is probably not accessible by third-parties. Open BMS information that includes sufficient use history information can help. A traceability system of battery packs can lead to a similar functionality.

- For repurposing and recycling activity, standardised battery module sizes and pack sizes can help. Size standardisation is currently only at cell level (ISO/PAS 19295: 2016; DIN 91252:2016).

For recycling of batteries:

- Explicit information and guidance on battery recycling is lacking in current standards.
- Little information is available on the material contents of batteries by labelling standards with IEC 62902 being the most important one. The argument is that it should not be too visible which Li-ion battery has most value for recycling. However, a database or traceability system can fulfil this information gap.
- Standards that define battery marking including the principal active materials (i.e IEC 62620, IEC 61960) need to anticipate new active materials like a silicon based anode.
- Harmonised calculation methods for the recycling efficiency to avoid data misinterpretation is welcomed. This should include environmental aspects like waste styreams, incineration with energy recovery and final landfilling or elimination. [4]
- Harmonised quantification of key indicators as CO_2 footprint, recycling percentage, toxicity and recycling cost is needed [4].

2. Overview of relevant standards according to their standardization bodies

2.1. Introduction to standards and standardization bodies

Standards are not written by a government, but by standardisation organisations. These can be public and private. Typically, they refer to product performance or quality assurance. Standards are voluntarily, except if a specific standard is prescribed in a national regulation, which occurs rarely. If standards exist for a certain product group, it is recommendable to investigate if a product complies with it. Standards give a raised confidence if it the standard is about product design and safety. Standards can also lead to better insight in the performance of products by prescribing performance tests.

In Europe a special category of standards exists: the *harmonised standards*. These are commissioned by the European Commission to comply with specific directives, like the machine directive, gas appliances directive and of course the Ecodesign directive. The General product safety directive 2001/95/EC [2] encourages explicitly to use harmonised standards, since products designed accordingly are assumed to be safe.

The harmonised standards are made by the European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC). Often CEN and CENELEC take over standards by the International Electrotechnical Committee (IEC) and the International Standards Organisation (ISO) and add clauses to bring the standards in accordance with the European rules on e.g. environmental protection, safety and consumer protection. The complete list of harmonised standards is can be found online[3]. The use of these standards remains voluntary, but manufacturers then have an obligation to prove that their products meet the essential requirements written in each applicable directive.

Standards are made with dissimilar aims and can mix several objectives. These can be:

– design

– performance tests

– safety design

– safety tests

– environmental protection

– classification

– guidance

– recommendation.

A standard can thus be found that guides the battery user in the different types of batteries and installation methods. A standard can explain how to design a battery installation, probably stressing safety aspects whereas other standards can prescribe performance tests and safety tests and often refer to standards with test methods that work out specific test conditions.

Closely related to batteries are standards that involve:

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[2] https://eur-lex.europa.eu/legal-content/NL/TXT/PDF

[3] https://ec.europa.eu/growth/single-market/european-standards/harmonised-standards_en

- functional safety
- test methods.

Standards can cover different life cycle stages being:

- design
- production
- transport
- installation
- use
- return.

Standardisation on batteries is much broader than the legislation and many bodies are developing standards. The worldwide standardisation organisations that include battery standardisation are:

- International Electrotechnical Commission, IEC
- International Standardisation Organisation, ISO

At European level the European Committee for Electrotechnical Standardization, CENELEC, is involved regarding batteries.

At national level there are also active organisations (e.g. China[4], Japan Electric Vehicle Association Standards (Japan), VDE (Germany), DIN (Germany), ANSI (United States of America)).

Also, commercial organisations and associations develop standards on batteries (e.g. Underwriters Laboratory, UL, Telcordia, SAE, DNV GL, Ellicert, BATSO).

For standards on batteries for electric vehicle standards a work division has been made between IEC, ISO, CEN and CENELEC. IEC TC 21 and SC21A develop standards from cell to pack level. ISO TC22 works on system level. This is visible for example in ISO 14205 series 'Electrically propelled road vehicles — Test specification for lithium-ion traction battery packs and systems'. In the scope it states that ISO 12405 specifies test procedures for lithium-ion battery packs and systems which are connected to the electric propulsion system of electrically propelled vehicles. For the specifications for battery cells, the series refer to IEC 62660-1 to 3 'Secondary lithium-ion cells for the propulsion of electric road vehicles'.

At European level there are two counter parts. For IEC TC21 and SC21A, there is committee (CENELEC) CLC/TC21. This committee has as objectives: to implement IEC/TC 21/SC 21A documents into CENELEC standards; to prepare Product Standards, general requirements and methods of testing included; to prepare Safety Standards and associated Codes of Practice; to consider Environmental Requirements (EC Rules) for the products.

The counterpart for ISO TC 22 is CEN/TC301 'Road vehicles'. It is very explicit on their relation: "Preparation of road vehicle European Standards answering essentially to European mandates. Since the automotive industry is acting globally, the international level (ISO/TC 22 Road vehicles) shall have top priority for any other standardization projects."

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[4] http://www.eu-china-standards.cn

2.2. Standards from IEC committees on batteries

An overview of well-known standards and relevant for the Ecodesign preparatory study that are published under each per committee is given here. Additional information on standards under development by the committees is also given.

2.2.1. IEC TC21 Secondary cells and batteries

The scope of this committee is to provide standards for all secondary cells and batteries related to product, safety, testing, and safe application.

- IEC 61427 series - Batteries for renewable energy storage

They contain:

  - Part 1: Photovoltaic off-grid application
  - Part 2: On-grid applications

- IEC 62485 series - Safety requirements for secondary batteries and battery installations (with parts for Li-ion, lead-acid, …)

They contain:

  - Part 1: General safety information
  - Part 2: Stationary batteries
  - Part 3: Traction batteries (planned, no document)
  - Part 4: Valve-regulated lead-acid batteries for use in portable appliances (planned, no document)
  - Part 5: Safe operation of stationary lithium-ion batteries
  - Part 6: Safe operation of lithium-ion batteries in traction applications

- IEC/EN 60952 series - Aircraft batteries
- IEC/EN 60896 series - Stationary lead-acid batteries
- IEC/EN 60254-1 - Lead-acid traction batteries
- IEC/EN 61056 series - General purpose lead-acid batteries (valve-regulated types)
- IEC 61982 series Secondary batteries (except lithium) for the propulsion of electric road vehicles

They contain:

  - Performance and endurance tests (no part number)
  - Part 4: Safety requirements of nickel-metal hydride cells and modules

- IEC 62660 series - Secondary lithium-ion cells for the propulsion of electric road vehicles

They contain:

  - Part 1: Performance testing
  - Part 2: Reliability and abuse testing for lithium- ion cells
  - Part 3: Safety requirements

- IEC 62932 series - Flow battery systems for stationary applications
- IEC 62984 series - High Temperature Batteries

They contain:

- Part 1: General aspects, definitions and tests
- Part 2: Safety requirements and tests of cells and batteries
- Part 3: Sodium-based batteries – Performance requirements and tests

- IEC 61429 - Marking of secondary cells and batteries with the international recycling symbol ISO 7000-1135. (This standard applies to lead-acid batteries (Pb) and nickel-cadmium batteries (Ni-Cd).)
- IEC 62902 - Marking symbols for secondary batteries for the identification of their chemistry. (This standard applies to lead acid (Pb), nickel cadmium (Ni-Cd), nickel metal hydride (Ni-MH), lithium ion (Li-ion), secondary lithium metal (Li-metal).)

2.2.2. IEC SC21A Batteries with alkaline and other non-acid electrolytes

IEC SC21A prepares standards regarding product and test specifications for all secondary cells and batteries of sealed and vented designs containing alkaline or other non-acid electrolytes, being lithium batteries.

IEC/EN 62133 series	Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications.
IEC 62620	Secondary lithium cells and batteries for use in industrial applications
IEC 62619	Safety requirements for secondary lithium cells and batteries for use in industrial applications
IEC 61960 series	Secondary lithium cells and batteries for portable applications
IEC/EN 61951 series	Portable sealed rechargeable single cells (NiCd, NiMH)
IEC/EN 60622	Sealed nickel-cadmium prismatic rechargeable single cells
IEC/EN 60623	Vented nickel-cadmium prismatic rechargeable single cells
Under development	Secondary lithium-ion, nickel cadmium, and nickel metal hydride cells and batteries for portable applications – Guidance on environmental aspects (IEC 63218)
Under development	Safety requirements for secondary lithium cells and batteries for use in electrical energy storage systems (IEC 63056)
Under development	Secondary lithium batteries for use in road vehicles not for the propulsion (IEC 63118)
Under development	Safety requirements for secondary lithium batteries for use in road vehicles not for the propulsion (IEC 63057)

2.2.3. IEC TC35 Primary cells and batteries

They are out of scope for rechargeable Li-ion batteries, except their transport standard:

IEC/EN 62281	Safety of primary and secondary lithium cells and batteries during transport

It is almost a copy of UN38.3 except small differences in test preparations. A comparison is found in the table on safety tests on BatteryStandards.info: https://www.batterystandards.info/sites/batterystandards.info/files/safety_tests_detailed.pdf .

IEC 60086 series	Primary batteries Interesting can be Part 6: Guidance on environmental aspects.

2.2.4. IEC TC120 Electric energy storage (EES) systems

This committee works on standardisation in the field of grid integrated EES Systems. It focusses on system aspects on EES Systems rather than energy storage devices.

IEC 62933-1	Electrical Energy Storage (EES) systems - Terminology
IEC 62933-2	Electric Energy Storage (EES) systems - Unit parameters and testing methods of electrical energy storage (EES) system - Part 1: General specification
IEC 62933-3	Planning and installation of electrical energy storage systems
IEC/TS 62933-4	Electrical Energy Storage (EES) Systems - Guidance on environmental issues
IEC/TS 62933-5	Safety considerations related to the integrated electrical energy storage (EES) systems

2.2.5. IEC TC69 Electric road vehicles and electric industrial trucks

The scope of this committee is on the preparation of international standards for road vehicles, totally or partly electrically propelled from self-contained power sources, and for electric industrial trucks.

IEC 62576	Electric double-layer capacitors for use in hybrid electric vehicles - Test methods for electrical characteristics
IEC 61851 series	Electric vehicle conductive charging system; under development are communication protocols
IEC 61980 series	Electric vehicle wireless power transfer (WPT) systems
IEC TS 62763	Pilot function through a control pilot circuit using PWM (pulse width modulation) and a control pilot wire
IEC 62840 series	Electric vehicle battery swap system

2.2.6. IEC TC113 Nanotechnology standardization for electrical and electronic products and systems

IEC TC113 works on standardisation of the technologies relevant to electrotechnical products and systems in the field of nanotechnology.

IEC TS 62607 series	Nanomanufacturing - Key control characteristics
IEC 62565 series	Nanomanufacturing - Material specifications
IEC/TS 62876 series	Nanotechnology - Reliability
ISO/TS 80004 series	Nanotechnologies - Vocabulary

Concerning battery materials, some standards on nano-enabled energy storage are:

IEC TS 62607-4 series	Nanomanufacturing - Key control characteristics

It concerns:

- Part 4-1: Cathode nanomaterials for nano-enabled electrical energy storage - Electrochemical characterisation, 2-electrode cell method
- Part 4-2: Physical characterization of nanomaterials, density measurement

Part 4-3: Nano-enabled electrical energy storage - Contact and coating resistivity measurements for nanomaterials

Part 4-4 Thermal Characterization of Nanomaterials, Nail Penetration Method

Part 4-5 Cathode nanomaterials - Electrochemical characterisation, 3-electrode cell method

Part 4-6: Nano-enabled electrical energy storage devices - Determination of carbon content for nano electrode materials, infrared absorption method

Part 4-7: Nano-enabled electrical energy storage - Determination of magnetic impurities in anode nanomaterials, ICP-OES method

Under development	Nanomanufacturing – Part 4-8 Nano-enabled electrical energy storage devices - water content for electrode nanomaterials by Karl Fischer Method (NWP IEC TS 62607-4-8)

2.2.7. Other battery related IEC standards

IEC 60364-5-57 ED1	Low-voltage installations - Part 5 Selection and erection of equipment - Clause 57 Erection of stationary secondary batteries

2.2.8. IEC TC 111 Environmental standardization for electrical and electronic products and systems

This committee prepares the necessary guidelines, basic and horizontal standards, including technical reports, in the environmental area, in close cooperation with product committees of IEC. It liaises ISO/TC 207 (mentioned later).

IEC 62430	Environmentally Conscious Design (ECD) - Principles, requirements and guidance

2.3. Standards from ISO committees

2.3.1. ISO TC22 Road vehicles

This committee has several subcommittees dealing with the application of batteries in electric drivetrains.

SC 37 Electrically propelled vehicles

ISO 12405 series	Electrically propelled road vehicles -- Test specification for lithium-ion traction battery packs and systems

They contain:

- (Part 1: High-power applications: obsolete and replaced by part 4 in 2018)
- (Part 2: High-energy applications: obsolete and replaced by part 4 in 2018)
- Part 3: Safety performance requirements
- Part 4: Performance testing

ISO 6469 series	Electrically propelled road vehicles -- Safety specifications
ISO/TR 8713	Electrically propelled road vehicle – Vocabulary
ISO/IEC PAS 16898	Electrically propelled road vehicles - Dimensions and designation of secondary lithium-ion cells
ISO 18300	Electrically propelled road vehicles -- Specifications for lithium-ion battery systems combined with lead acid battery or capacitor

ISO/PAS 19295:2016	Electrically propelled road vehicles -- Specification of voltage sub-classes for voltage class B
ISO 20762	Electrically propelled road vehicles – Determination of power for propulsion of hybrid electric vehicles
Under development	ISO/DIS 21782 series Electrically propelled road vehicles -- Test specification for electric propulsion components. They contain: – Part 1: General – Part 2: Performance testing of motor system – Part 3: Performance testing of motor and inverter – Part 6: Operating load testing of motor and inverter
Under development	ISO/DIS 19363 Electrically propelled road vehicles -- Magnetic field wireless power transfer -- Safety and interoperability requirements
Under development	ISO/DIS 21498 Electrically propelled road vehicles -- Electrical tests for voltage class B components

SC 38 Motorcycles and mopeds

ISO 13064-1:2012	Battery-electric mopeds and motorcycles -- Performance -- Part 1: Reference energy consumption and range
ISO 18243	Electrically propelled mopeds and motorcycles – tests and safety requirements Li-ion battery systems
Under development	ISO/AWI 23280 Electrically propelled mopeds and motorcycles -- Test method for performance measurement of traction motor system

SC 32 Electrical and electronic components and general system aspects

ISO 19453 series	Road vehicles – Environmental conditions and testing for electrical and electronic equipment for drive system of electric propulsion vehicles

They contain:

- Part 1: General
- Part 2: Electrical loads
- Part 3: Mechanical loads
- Part 4: Climatic loads
- Part 5: Chemical loads

Under development	ISO 19453 Road vehicles – Environmental conditions and testing for electrical and electronic equipment for drive system of electric propulsion vehicles: Part 6: Traction battery packs and systems

2.3.2. ISO TC207 Environmental management

This committee works on standardisation in the field of environmental management systems and tools in support of sustainable development. It has several working groups and subcommittees including Life cycle assessment.

SC 5 Life cycle assessment

- ISO 14040:2006: Environmental management – Life cycle assessment – Principles and framework
- ISO 14044:2006: Environmental management – Life cycle assessment – Requirements and guidelines

2.4. Specific standards from CEN and CENELEC committees

2.4.1. CENELEC CLC/TC21X Secondary cells and batteries

This committee has as objectives: to implement IEC/TC 21/SC 21A documents into CENELEC standards; to prepare Product Standards, general requirements and methods of testing included; to prepare Safety Standards and associated Codes of Practice; to consider Environmental Requirements (EC Rules) for the products.

EN 50604-1:2016	Secondary lithium batteries for light EV (electric vehicle) applications - Part 1: General safety requirements and test methods
EN 50272 series	Safety requirements for secondary batteries and battery installations. *Note: this standard will be replaced by IEC 62485 series.*
EN 50342 series	Lead-acid starter batteries

2.4.2. CEN/TC301 Road vehicles

This committee is involved in the preparation of road vehicle European Standards answering essentially to European mandates. As counterpart for ISO TC 22 that committee has priority for any other standardization projects.

EN 1987 series	Electrically propelled road vehicles - Specific requirements for safety

For batteries is of interest:

- Part 1: on board energy storage

2.4.3. CENELEC CLC/TC111x Environment

CLC/TC111x deals with environmental aspects for electrical and electronic products and systems. It enhances CENELEC's environmental links with the European legal framework, particularly in the context of standardization aspects of EU environmental regulations and directives. It assists product committees in the elaboration of environmental requirements of product standards.

prEN 50693	Method for quantitative eco design via life cycle assessment and environmental declarations through product category rules for EEE **(under development)**
FprEN 50614	Requirements for the preparing for re-use of waste electrical and electronic equipment **(under development)**

2.4.4. CEN-CENELEC Joint Technical Committee 10 on Energy-related products – Material Efficiency Aspects for Ecodesign

CEN/CLC/JTC 10 is a Joint Technical Committee between CEN and CENELEC in response to the EU Standardization Mandate/543 for Material Efficiency aspects. All standards are in development. They will have numbers EN 4555X.They must be horizontal and generic: not product specific. These standards could serve as a voluntary reference point when designing all kinds of products.

CLC/prTR 45550	Definitions related to material efficiency (under drafting)
CLC/prTR 45551	Guide on how to use generic material efficiency standards when writing energy related product specific standardization deliverables (under drafting)
prEN 45552	General method for the assessment of the durability of energy-related products (under drafting)
prEN 45553	General method for the assessment of the ability to re-manufacture energy related products (under drafting)
prEN 45554	General methods for the assessment of the ability to repair, reuse and upgrade energy related products (under drafting)
prEN 45555	General methods for assessing the recyclability and recoverability of energy related products (under approval)
prEN 45556	General method for assessing the proportion of re-used components in an energy related product (under approval)
prEN 45557	General method for assessing the proportion of recycled content in an energy related product (under approval)
prEN 45558	General method to declare the use of critical raw materials in energy related products (under approval)
prEN 45559	Methods for providing information relating to material efficiency aspects of energy related products (under approval)

2.5. Standards from national bodies

E_VDE-AR-E_2510-50	Sicherheitsanförderungen Stationäre Li-ionspeicher Safety requirements for stationary battery energy storage systems with lithium batteries
E_VDE-AR-E_2510-2	Stationäre_Speicher_ans_NS-Netz About the safe connection of batteries to the low voltage grid
DIN 91252	Electrically propelled road vehicles - Battery systems - Design specifications for Lithium-Ion battery cells (this standard specifies cell formats)

2.6. Standards from private and governmental bodies

UL 1642	UL Standard for Safety of Lithium Batteries
UL 2580	Batteries for Use in Electric Vehicles
UL 2271	Batteries For Use In Light Electric Vehicle (LEV) Applications

UL 2580	Batteries For Use In Electric Vehicles
UL 1973	Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications (the scope of UL 1973 includes batteries for use as auxiliary power in recreational vehicles and for temporary energy storage system applications that are mobile but used as stationary energy storage.)
ANSI/CAN/UL 1974	Standard for evaluation for repurposing batteries
SAE 2288	Life Cycle Testing of Electric Vehicle Battery Modules
SAE J2344	Guidelines for Electric Vehicle Safety
SAE J2289	Electric-Drive Battery Pack System Functional Guidelines
SAE J2464	Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing
SAE J2929	Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-based Rechargeable Cells
SAE J2950	Recommended Practices (RP) for Shipping Transport and Handling of Automotive-Type Battery System - Lithium Ion
SAE J2997	Standards for battery secondary use (**under development**)
SAE J2758	Determination of the maximum available power from a rechargeable energy storage system of hybrid electric vehicle (**under development**)
Ellicert Batteries	Certification scheme for battery cells and packs for rechargeable electric and hybrid vehicles – General requirements relating to certification – Application to Lithium based elements
BATSO 01	Manual for evaluation of energy systems for Light Electric Vehicle (LEV) - Secondary Lithium Batteries
BATSO 02	Manual for evaluation of energy systems – Secondary Lithium Batteries (stationary applications)
BVES Effizienzleitfaden für PV-Speichersysteme V1.0.4 (2017)	From 'Bundersverband Energiespeicher' in Germany. It provides test methods to determine the energy efficiency of home solar storage systems. It discerns the efficiency and energy losses of the inverter(s) and the battery separately.
DOE-INL/EXT-15-34184	Battery test manual for electric vehicles
DOE-INL/EXT-07-12536	Battery test manual for plug-in electric vehicles.

Nordic Swan Ecolabel Primary Batteries	The Nordic Swan is a voluntary official ecolabel in the Scandinavian countries, Denmark and Iceland.
Nordic Swan ecolabelling for rechargeable batteries and portable chargers	The Nordic Swan Ecolabel focuses on capacity and durability of batteries. Batteries and portable chargers must meet recognized quality and safety standards.
Recharge PEFCR	Product environmental footprint category rules for high specific energy rechargeable batteries for mobile applications. *Note: a PEFCR is a guideline based on the harmonised PEF method.*

3. Overview of relevant standards per topic

3.1. Measurement and test standards

The assessment of the performance of batteries has been dealt with by multiple international organizations, as elaborated in the previous chapter. Depending on the type of application specialized standards have been developed. Although different standards have been created it is commonly found that the same type of testing topics are applied on the battery with different test conditions. This can involve the prescribed current to discharge a battery or the current profile and depth of discharge in a cycle-life test. The testing method independently of the application can be separated into four main categories. These are related with the:

- Characterization tests: electrical and energy performance of the system under different load profiles. For the Ecodesign preparatory study this is of main importance.
- Ageing tests: the behaviour of the system throughout the lifetime that it is being operated. For the Ecodesign preparatory study this is of main importance.
- Safety/Abuse tests: assessment of the safety of the system under different stress conditions for safe utilization and transportation of the system. For the Ecodesign preparatory study this is of low importance.
- Material testing: characterization of the materials incorporated in the system. This category is found in environmentally related standards, on the determination of heavy metals for instance, and are found as individual standards by IEC TC113 on nanotechnology.

3.2. Relevant standards for EV application

The characterization tests and ageing tests are mainly being implemented in the context of Electric Vehicle applications. In the following list the main international standards dealing with the assessment of the electrical performance of high specific energy batteries in Electric Vehicle applications are listed:

- IEC 62260-1:2010: Secondary lithium-ion cells for the propulsion of electric road vehicles;
- IEC 61982:2012: Secondary batteries (except lithium) for the propulsion of electric road vehicles - Performance and endurance tests
- ISO 12405-4:2018: Electrically propelled road vehicles -- Test specification for lithium-ion traction battery packs and systems -- Part 4: Performance testing;
- DOE-INL/EXT-15-34184: Battery test manual for electric vehicles;
- DOE-INL/EXT-07-12536: Battery test manual for plug-in electric vehicles;
- SAE 2288 Life Cycle Testing of Electric Vehicle Battery Modules;
- SAE J1798:2008: Recommended Practice for Performance Rating of Electric Vehicle Battery Modules.

A summary of the different test procedures that are included in these standards is dealt with in section 3.6, specifically by Table 1.

3.3. Relevant standards for other applications

- IEC 61427-2 Batteries for renewable energy storage Part 2 On-grid

This standard contains endurance tests for the following applications:

  - frequency-regulation service
  - load-following service
  - peak-power shaving service
  - photovoltaic energy storage, time-shift service

It also describes methods to determine battery properties and electrical performance, being:

  - energy content at +25 °C ambient temperature
  - energy efficiency during endurance tests at +25 °C ambient temperature
  - energy efficiency during endurance tests at the minimum and maximum ambient temperature
  - waste heat generated during endurance tests at the maximum ambient temperature
  - energy requirements during periods of idle state at +25 °C ambient temperature

- IEC 62620 Secondary lithium cells and batteries for use in industrial applications

This standard is applicable for industrially used batteries. This covers a broad range of applications:

  - Stationary applications: telecom, uninterruptible power supplies (UPS), electrical energy storage system, utility switching, emergency power and similar applications.
  - Motive applications: fork-lift truck, golf cart, AGV, railway, and marine, excluding road vehicles.

It contains performance tests:

  - Discharge performance at +25 °C (rated capacity)
  - Discharge performance at low temperature
  - High rate permissible current
  - Charge (capacity) retention and recovery
  - Cell and battery internal resistance: AC and DC resistance

It contains two endurance tests:

  - Endurance in cycles
  - Endurance in storage at constant voltage (permanent charge life)

This standard discerns 4 battery categories:

  - High energy (S; <C/8)
  - Energy (E; <C/2)
  - Medium rate discharge (M; <3.5C)
  - High rate (H; >3.5C)

- IEC 62933-2 Electric Energy Storage (EES) systems - Unit parameters and testing methods of electrical energy storage (EES) system - Part 1: General specification

This standard is applicable on the following stationary applications: Frequency regulation, Fluctuation reduction, Voltage regulation, Peak shaving / Peak shifting, Back-up power. It prescribes performance tests for them.

It covers also test methods for the following unit parameters:

- Actual energy capacity
- Input and output power rating
- Round trip energy efficiency
- Expected service life
- System response
- Auxiliary power consumption
- Self-discharge of EESS
- Voltage range
- Frequency range

- IEC 62984-3-2:2017 High Temperature Secondary Batteries – Part 3: Sodium-based batteries – Section 2: Performance requirements and tests

- ISO/DIS 18243 Electrically propelled mopeds and motorcycles -- Test specification and safety requirements for lithium-ion battery system

- ISO 13064-1:2012 Battery-electric mopeds and motorcycles -- Performance -- Part 1: Reference energy consumption and range

The contents relevant for ecodesign of these standards (except the last one) are covered by Table 2 in section 3.6.

3.4. Environment related standards

3.4.1. Battery specific

IEC 63218	Secondary Lithium ion, Nickel Cadmium, and Nickel Metal Hydride cells and batteries for portable applications - Guidance on environmental aspects (**under development**). It describes environmental aspects of batteries and restriction of environmental hazardous materials, especially heavy metals. It also contains an environmental impact assessment and it identifies product environmental aspects. Annex A of the standard gives an overview of battery specific laws and regulations worldwide.
IEC/TS 62933-4	Electrical Energy Storage (EES) Systems - Guidance on environmental issues. It describes three aspects to identify environmental issues, namely life-cycle thinking, system aspects with respect to environment and storage technology

	independency. It also gives environmental guidelines on substance leakage, vibration, earth leakage current, weather conditions and life form invasion.
IEC 61429	Marking of secondary cells and batteries with the international recycling symbol ISO 7000-1135. This symbol must be added on batteries.
IEC 62902	Marking symbols for secondary batteries for the identification of their chemistry). For Pb, NiCd, NiMH, Li-ion and Li-metal a marking by colour code is developed. Also, the ISO 7000-1135 recycling symbol must be added if no other recycling symbol is applied on the battery.
IEC 60086-6	Primary batteries - Part 6 Guidance on environmental aspects It sets requirements on heavy metal contents for Hg, Pb and Cd. It sets hazardous waste criteria based on toxicity, ignitability, reactivity and corrosivity. It gives an environmental assessment based on reduction, reuse, recycle, raw material use, manufacturing and disposal. As annex it provides on overview on battery specific laws and regulations worldwide.
Nordic Swan Ecolabel Primary Batteries	The Nordic Swan is a voluntary official ecolabel in the Scandinavian countries, Denmark and Iceland. For batteries it focuses on portable primary batteries. Since the market for primary batteries is extensive and since they have differences in environmental and quality properties, the Nordic Ecolabelling is capable to differentiate and to determine the best ones in terms of environmental and quality properties. The ecolabel prescribes much lower maximum values for toxic metals than the Battery Directive does. It bans the use of PVC. Clear information on the possible application type must be given and the ecolabel discerns 3 drain (discharge) levels.
Nordic Swan ecolabelling for rechargeable batteries and portable chargers	The Nordic Swan Ecolabel focuses on capacity and durability of batteries to ensure long battery life thereby reducing the resource consumption. At the same time, batteries and portable chargers must meet recognized quality and safety standards. The requirements include: • Threshold values for heavy metals in batteries. • No use of PVC and a number of flame-retardants in plastic. • CSR policy to ensure responsible use and sourcing of limited raw materials and “conflict free” minerals. • Electrical-, safety- and quality testing of batteries/cells, portable and battery chargers. • Nickel Metal Hydride (NiMH) batteries and cells must be fully charged when leaving the production site. • Recyclable design of the portable charger.

3.4.2. Material efficiency

As stated in the Mandate M/543 [6]: 'horizontal and generic, not product specific, European standards on material efficiency aspects could serve as a voluntary reference point when designing all kinds of products beyond the scope of Directive 2009/125/EC and its implementing measures'. This activity was taken by CEN and CENELEC as part of the Joint TC 10: CEN/CLC/JTC 10–'Energy-related products-Material Efficiency Aspects for Ecodesign'. The list of standards under preparation (foreseen to be published in 2019) is given in section 2.4.4.

One of the reasons for the relative lack of Ecodesign requirements related to material efficiency in the implementing measures adopted so far is the absence of adequate metrics. The aim of this new workgroup is to:

- Define parameters and methods relevant for assessing durability, upgradability and ability to repair, re-use and re-manufacture of products;
- Address the ability to access/remove certain components, consumables or assemblies from products to facilitate repair or remanufacture or reuse;
- Address reusability/recyclability/recoverability indexes or criteria;
- Address the ability to access/remove certain components or assemblies from products to facilitate their extraction at the end-of-life for ease of treatment and recycling;
- Establish a method to assess the proportion of re-used components and/or recycled materials in products;
- Address the use and recyclability of Critical Raw Materials to the EU, listed by the European Commission; and
- Address the documentation and/or marking regarding information relating to material efficiency of the product taking into account the intended audience.

Proposed standards and status can be found on the CEN server[5].

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[5] https://standards.cen.eu/dyn/www/f?p=204:22:0::::FSP_ORG_ID,FSP_LANG_ID:2240017,25&cs=1D4156C3D679EE526A476E8463ACFAA98

3.4.3. Life Cycle Assessment (LCA) standards and methodologies

ISO standards

The following two ISO standards are available that provide a general (conceptual) methodological framework for LCA:

- ISO 14040:2006: Environmental management – Life cycle assessment – Principles and framework
- ISO 14044:2006: Environmental management – Life cycle assessment – Requirements and guidelines

These ISO standards prescribe the steps in which an LCA must be performed. However, they also leave LCA practitioners with an array of choices that can affect the execution and results of an LCA.

CENELEC standard (under development)

The following standard is under development:

- prEN 50693 Method for quantitative eco design via life cycle assessment and environmental declarations through product category rules for EEE (under development)

CEN standards

Within the construction sector, voluntary horizontal standardised methods are developed under the responsibility of CEN/TC 350 for the assessment of the sustainability aspects of new and existing construction works and to draft environmental product declarations (EPDs) of construction products. Compared to the two ISO standards, the EN standard prescribe a tighter framework for executing an LCA. The specific standard regarding LCA of construction products is:

- EN 15804:2012+A1:2013: Sustainability of construction works – Environmental production declarations – core rules for the production category of construction products

In some European countries (e.g. Belgium, the Netherlands, and Germany) there are national annexes and/or product category rules applicable to the EN 15804 standard with additional country-specific rules for drafting EPDs in case a manufacturer wants to register their EPD(s) in the national EPD database.

PEF methodology

In addition to the above-mentioned standards, the Product Environmental Footprint was developed by the Institute for Environment and Sustainability (IES) of the Joint Research Centre (JRC), a Directorate General of the EC upon mandate of the EC Directorate General Environment (DG ENV). The PEF is a harmonised methodology for the calculation of the environmental performance of products (i.e. goods and/or services, not within a specific sector) from a life cycle perspective. The PEF methodology is published as:

- European Commission (2013). ANNEX II Product Environmental Footprint (PEF) Guide, in: 2013/179/EU: Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. *Official Journal of the European Union*, L 124, Volume 56, 4 May 2013[6].

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[6] http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32013H0179

Note: the PEF Guide is not a standard, but a common method of which the pilot phase was finished in 2018 based on those tests the EC is currently exploring how to use the PEF methods in policies.

During the pilot phase, stakeholders of several product groups had the possibility to sign up and to follow the development of Product Environmental Footprint Category Rules (PEFCRs). One of these product groups was the product group of 'Rechargeable batteries'. The association Recharge chaired the Technical Secretariat of the batteries PEF pilot. The final PEFCR for "high specific energy rechargeable batteries for mobile applications" was published in February 2018[7]. The PEFCR is applicable for rechargeable single cells or/and batteries used in the following equipment or vehicle:

- E-mobility (e.g., e-bikes, ELV, PHEV, cars, bus/trucks), excluding charging unit,
- Information & Communication Technologies (e.g., tablets and phones, computers, cameras, games), including charging unit,
- cordless power tools (e.g., drills, electric screwdrivers), including charging unit.

Alignment EN standards and PEF

Regarding the CEN/TC 350 standards, DG Environment and DG Growth drafted a first proposal for an amendment of Mandate M/350 on 5 October 2015. The amendment aims to solve, or at least reduce to the maximum extent possible, the differences between the requirements included in the CEN/TC 350 standards and those included in the PEF methodology, in order to align the CEN/TC 350 standards and the PEF as much as possible. The amendment of the CEN/TC 350 standards, the EN 15804 in particular, is still going on (1/2019).

LCA software, models and datasets

Ecodesign EcoReport 2014

This project needs to introduce data regarding lithium-ion batteries for an efficient and correct environmental LCA study for the ecodesign and ecolabelling of these systems. Currently the Ecodesign EcoReport 2014 Excel-based tool is used to calculate the environmental impacts in MEErP format. The EcoReport tool is suitable for not too complex products that can be modelled with the standard materials in the EcoReport, but not for complex products like batteries that are composed of complex chemistries and substances. Another limitation of the EcoReport is that it was developed from 2011 to 2014 and it includes outdated data to calculate the environmental impact.

openLCA software

There are more up-to-date and flexible (but also more complex) software on the market for LCA calculations. openLCA is a free and open source LCA software that can be used for modelling and calculating LCAs, like PEF [8]. It is developed and hosted by GreenDelta, an independent sustainability consulting and software company in Berlin, Germany. It is sustained by a network of partners, contributors and a user community. openLCA can offer free databases for use in openLCA and other datasets can be directly imported in case the datasets are in EcoSpold or ILCD format (common LCA dataset formats). It is highly likely that there are no LiB datasets in openLCA.

Note: this is not a standard but can be seen as an open harmonised method for LCA calculations. It would likely be too complex and would lack the needed flexibility for a standard.

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[7] http://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_Batteries.pdf

[8] https://www.openlca.org/project/pef/

Using LCA software

An identified gap regarding LCA standards and software is the lack of test cases and/or standards to test whether LCA software is calculating correctly. Within the LCA community it is a well-known problem that using a different LCA software can lead to different results even when calculating the same model and using the same dataset.

The EC/JRC Life Cycle Data Network data sets

Note: This is not a standard, this open data network with harmonized sets of data is a more flexible approach that can benefit from frequent updates.

The Life Cycle Data Network is hosted by the EC/JRC and aims to provide a globally usable infrastructure for the publication of quality assured LCA dataset (i.e. LCI datasets and LCIA method datasets)[9]. It aims to include the Environmental Footprint (EF) datasets for Representative products and a Benchmark [10]. So far, the datasets for LiB are not publicly available yet.

The GREET model of Argonne National Lab

Note: This is not a national standard but a public supported and available method.

The GREET model stands for “Greenhouse gases, Regulated Emissions, and Energy use in Transportation” model. It is available in excel format and .NET format. The aim is to get a full life cycle carbon emission impact estimate from well to wheels for fuels and raw material mining to vehicle disposal for automobiles [11]

For a given vehicle and fuel system, GREET separately calculates the following:

- Consumption of total resources (energy in non-renewable and renewable sources), fossil fuels (petroleum, natural gas, and coal together), petroleum, coal, natural gas and water.
- Emissions of CO2-equivalent greenhouse gases - primarily carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O).
- Emissions of seven criteria pollutants: volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxide (NOx), particulate matter with size smaller than 10 micron (PM10), particulate matter with size smaller than 2.5 micron (PM2.5), black carbon (BC), and sulphur oxides (SOx).

It includes recent carbon footprint data for LiB. This public domain model is available free of charge for anyone to use. It is sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE).

3.5. Standards on reuse of batteries

- SAE J2758 Determination of the maximum available power from a rechargeable energy storage system of hybrid electric vehicle (under development).

This standard started in 2012 but no information is found about it.

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[9] http://eplca.jrc.ec.europa.eu/

[10] http://eplca.jrc.ec.europa.eu/EF-node/

[11] https://greet.es.anl.gov/

- ANSI/CAN/UL 1974:2018 Standard for evaluation for repurposing batteries

This standard covers the sorting and grading process of battery packs, modules and cells and electrochemical capacitors that were originally and used and configured for other purposes, such as electric vehicle propulsion, and that are intended for a repurposed use application.

A basic requirement is that the cells, modules and auxiliary equipment must fulfil the requirements of the envisaged application as given in standards. Also, the battery should not be used longer than the *calendar expiration date*. This date must be provided by the manufacturer. The history of the battery has to be tracked with emphasis on previous misuse situations and on information coming from the BMS on the battery's state of health. The battery must be visually, also including disassembly, without damage, unless it is minor.

The standard prescribes a routine test analysis comprising:

- Incoming open circuit voltage (OCV) measurement;
- Incoming high voltage isolation check;
- Capacity check;
- Internal resistance check;
- Check of BMS controls and protection components;
- Discharge/charge cycle test;
- Self-discharge.

The repurposing manufacturer shall have a system for grading cells, modules and battery packs/systems for repurposing. This must ensure that the new battery combination is balanced and appropriately matched to prevent performance and safety problems in the final assembly.

Finally, marking including mention of 'UL1974' must be provided.

3.6. Standards on functioning during use phase

An ecodesign study needs to know the behaviour of its subject during use phase. Therefore, test methods must exist for parameters like nominal capacity, energy, internal resistance and ageing behaviour. Since one standard can give several test methods for the same parameter there can exist the nominal capacity and additional capacities as function of C-rate and temperature. This holds for other parameters as well. It is not necessarily about a test method, but it can also involve a criterion like the end of life criterion and information agreements like information that is given to determine the state of health, marking of a battery and BMS communication.

The parameters that should be found in standards are:

- nominal capacity and the corresponding C_n-rate, including the reference temperature
- Other capacities
- Energy
- Other energies
- Charge method
- Quick charge
- Power

- Other power
- Internal resistance
- Energy efficiency
- Additional energy efficiency
- Self-discharge at storage
- Charge retention for transport
- Non-load loss
- Energy for heating and cooling
- Cycle life test
- Calendar life test
- Efficiency of life test
- SOH definition(s)
- EOL criterion / lifetime
- EOL information
- Calendar expiration date
- Marking method
- BMS prescriptions
- BMS communication

Apart from these topics, it must be clear what application(s) a standard envisages and for what battery (sub)type it is directed (also called ‘chemistry’). Most standards can be used from cell level up to system level and not necessarily only for Li-ion. Some standards only direct themselves at cell level for a certain application. This means that already at cell level performance criteria can be given.

An analysis of the above topics for the identified standards with performance tests is given in Table 1 (on page 40) and Table 2 (on page 42). Per topic and standard a short description of each test clause is given, if the topic is covered. Table 1 focusses on automotive standards and Table 2 on other applications.

In Table 1 the following standards are given:

- IEC 62660-1: 2018 Secondary lithium-ion cells for the propulsion of electrical road vehicles - Performance Testing.
- ISO 12405-4: 2018 Electrically propelled road vehicles --Test specification for lithium-ion traction battery packs and systems -- Part 4: Performance testing
- DOE-INL/EXT-15-34184 (2015) U.S. DOE Battery Test Manual for Electric Vehicles
- DOE-INL/EXT-07-12536 (2008) Battery test manual for plug-in hybrid electric vehicles
- SAE J1798: 2008 Recommended Practice for Performance Rating of Electric Vehicle Battery Modules

In Table 2 are given:

- ISO/DIS 18243: 2017 Electrically propelled mopeds and motorcycles -- Test specification and safety requirements for lithium-ion battery system
- IEC 62620: 2014 Secondary lithium cells and batteries for use in industrial applications
- IEC 61427-2: 2015 Secondary cells and batteries for renewable energy storage Part 2 On grid applications
- IEC 62984-3-2:2017 High Temperature Secondary Batteries – Part 3: Sodium-based batteries – Section 2: Performance requirements and tests
- BVES Effizienzleitfaden (2017) BVES Effizienzleitfaden
- ANSI/CAN/UL 1974:2018 Standard for evaluation for repurposing batteries

The performance metrics such as energy content, internal resistance and cycle life test are defined in the standards as can be seen from Table 1 and Table 2. However, in each standard and for each application (even within one standard since it can cover several applications) the exact methodology is dissimilar. Also, several methodologies can be given for the same metrics.

Several standards give end of life criteria. This is mostly related to the specific test cycle: that it cannot be performed anymore within the allowed voltage limits or e.g. that the battery becomes too hot. In test manuals from the US Department of Energy application specific end of life criteria are given. These are copied in Figure 1 and Figure *2*.

Standard IEC 61427-2 On-grid applications prescribes test profiles for its 4 applications. This is interesting for application-based criteria. The cycles are reproduced in Figure 3. However, no End of Life criteria are given. The battery is considered at the end of life when the user does not accept the behaviour anymore. Real tests results according to these profiles are not available.

Conclusions that can be drawn are:

Concerning performance metrics on product life time and efficiency related to Task 3:

- The performance metrics such as energy content and internal resistance are defined in the standards. However, in each standard and for each application (even within one standard since it can cover several applications) the exact methodology is dissimilar. Also, several methodologies can be given for the same metrics. This means that the capacity (in Ah) can be based on e.g. a 1 h, 5 h or 8 h discharge period or even on a discharge with a specific current profile. Resistance values may be derived from a pulse test, a jump in discharge current, but also from an AC signal.
- Most standards have test clauses to express the capacity in Ah. This unit is prescribed by the European regulation 1103/2010 on capacity labelling of portable secondary and automotive batteries (*i.e.* starter battery, not electric vehicle battery). Few standards prescribe the determination of energy content expressed in kWh, like the proposed functional unit, especially for standards outside automotive.
- The energy involved in heat and cooling of the battery system is not determined in standards.
- The capacity tests in the standards ignore that cells can be charged at several current rates. This is, however, of interest for e.g. quick charging and regenerative braking. It must be noted that charging is mostly not allowed in the same temperature range as discharging if no active heating is present (i.e. only above 0°C).
- The heating & cooling of the battery is within the study's system boundary. However, the needed energy is outside the boundary and will be an arbitrary value. It must be noted that the test standards do not measure this value, what could be used as a reference.
- For cycle life tests (repeated imposition of a test profile on the battery expressed in current or power) many profiles exist. 14 have been identified in the relevant standards. Each application has a profile and dissimilar standards may have a different profile. The profiles found are always a simplification of real profiles like the battery would undergo during e.g. a WLTP test.
- In European battery development projects often an ageing test programme is performed with a swarm of test conditions being a combination of calendar life testing and cycle life tests with simple profiles. These conditions allow to derive the ageing behaviour comprehensively and goes therefore beyond single use cases. This generic approach is not found in current test standards. [3] [4]
- Several standards give end of life criteria, defining when the battery is not useful anymore. This is mostly related to the specific, application dependent, test cycle: if the profile imposed as cycle life test cannot be performed anymore since the battery voltage hits upper and or lower limit almost immediately, or e.g. that the battery becomes too hot during the cycling, then this is considered as an end of life state.
- The following topics appear to be empty:
    - Charge method (only the charge method by the manufacturer)
    - Quick charge (except IEC 62984-3-2 for high temp. sodium batteries)
    - Energy for heating and cooling
    - Efficiency of life test

  - SOH definition(s)
  - EOL information (except IEC 62620 prescribes to write the cycle life test result in the battery marking)
  - Calendar expiration date
  - Marking method (except IEC 62620)
  - BMS prescriptions
  - BMS communication
- No clear definition of SOH exists and it is differently used over applications and manufacturers. Battery degradation is a combination of phenomena as capacity fade, power fade, efficiency reduction, rise in cooling demand and negative incidents. A more elaborate approach to tackle SOH is therefore needed. Even if SOH only refers to capacity fade then still the calculation method has to be clarified since the nominal capacity can be taken or the capacity related to the needed power. [4] The tables show that this topic is empty.
- EOL information: the BMS has currently no prescribed role in it, although it could give information on remaining capacity, actual power capability (being limited by either the battery resistance or the battery cooling capability) and negative events that happened. This information is of interest for the possibility to repair modules in a battery system and for repurposing batteries to a second life application. The standard ANSI/CAN/UL1974 provides a list with information that a BMS should provide to understand the battery health.
- The indicators for SOH should be openly available from the BMS [4]. Alternatively, a traceability and tracking system for battery packs must be conceived.
- The standard ANSI/CAN/UL1974 on repurposing of batteries introduces the calendar expiration date. A battery should not be used longer than this date. This date must be provided by the manufacturer. Current battery standards do not require this information. It must be stated that the battery life is much dependent on the use conditions such as the total time being at 100% SOC.
- SOH determination by advanced techniques like electrochemical impedance measurement can be treated in standards as additional indicators [4].

For re-sales and repurposing of batteries:

- For a profitable second use of batteries, additional costs as for testing, disassembly and retrofitting need to be minimised [4]. The original battery design and the BMS have a high impact on this. Since a BMS designed for an EV application would probably not be suitable for a second use application, the possibility of uploading adapted firmware must be considered. These issues are not in nowadays standards. Test methods to assess battery reliability, safety and performance at the end of first life use are absent. Criteria and guidelines to determine the suitability for a relevant second use can be developed. Standardised interfaces for hardware and software, including connectors, would support this minimised cost approach [4].
- Use information on the first life application, beyond the remaining capacity, is necessary. The standard ANSI/CAN/UL1974 identifies the information need. This information is however probably not reachable, partly since it is not stored, partly since a BMS is probably

not accessible by third-parties. Open BMS information that includes sufficient use history information can help.

- For repurposing and recycling activity, standardised battery module sizes and pack sizes can help. Size standardisation is currently only at cell level (ISO/PAS 19295: 2016; DIN 91252:2016).

Table 1: Test conditions and criteria on information necessary for ecodesign in relevant standards for EV application.

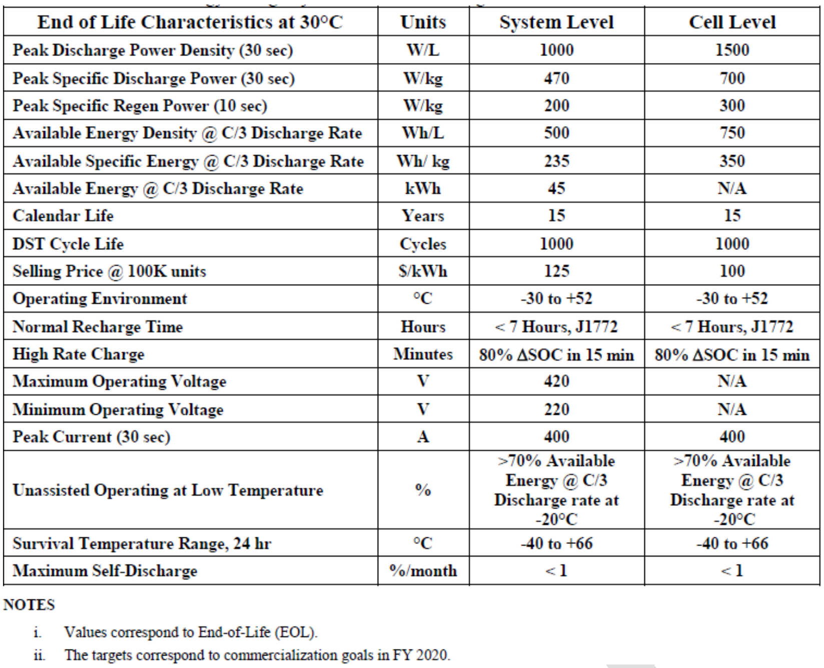
	EV application						
Reference	IEC 62660-1:2010		ISO 12405-4:2018		DOE-INL/EXT-15-34184(2015)	DOE-INL/EXT-07-12536 (2008)	SAE J1798:2008
Title	Secondary lithium-ion cells for the propulsion of electrical road vehicles - Performance Testing.		Electrically propelled road vehicles --Test specification for lithium-ion traction battery packs and systems -- Part 4: Performance testing		U.S. DOE Battery Test Manual for Electric Vehicles	Battery test manual for plug-in hybrid electric vehicles	*Recommended Practice for Performance Rating of Electric Vehicle Battery Modules*
Refined application	Cells for the propulsion of BEV	Cells for the propulsion of HEV	HEV & FCV	BEV & PHEV	BEV	PHEV	BEV
Chemistry	Li-ion	,,	Li-ion	,,	Generic	cell to system level	Generic
Level (cell, module, pack, system)	Cell	,,	Pack, system	,,	cell to system level		module
C_n-rate method (incl. temp.)	1/3 I_t at 0, 25, 45°C; additional tests possible and proposed	1 I_t at 0, 25, 45°C; additional tests possible and proposed	1C, 10C and max. discharge at -18, 0, 25, 40°C.	C/3, 1C, 2C and max. discharge at -18, -10, 0, 25, 40°C.			1C, C/2, C/3 at 45, 25, 0 and -20°C.
nominal capacity	(No, manufacturer value)	(No, manufacturer value)	1C (1 hour discharge capacit	1C (1 hour discharge capacity)	C_3, including check that the capacity deviates <10% from rated capacity.	–	–
Other capacities	See C_n-rate method, and Dynamic discharge capacity at 25 and 45°C.	See C_n-rate method.	See C_n-rate method.	,,		Discharge at highest possible rate from (HPPC) pulse test; discharge with 10kW (or scaled if a battery size factor is applied). Both at 30°C	From C_n-rate method; Dynamic discharge at 25°C
Energy	1/3 I_t at 25°C X U_{avg}	1 I_t at 25°C X U_{avg}			From C/3 discharge		From C_n-rate method
Other energies			See C_n-rate method.	See C_n-rate method.			
Charge method	As declared by manufacturer	,,	As declared by manufacturer	,,	Charging procedure by manufacturer including a default rest period.		By manufacturer
Quick charge				1C, 2C and max.current.	3.2C or defined by manufacturer for 15 min. to reach at least 80% SOC.		
Power	10s pulses at maximum allowed discharge rate followed by maximum allowed charge rate; SOC: 80, 50, 20%; Temp.: 25°C. For 50% SOC also at 40, 0 and-20°C.	,,	18s discharge and 10s charge pulses at max. possible current; 80, 65, 50, 35, 20% SOC; 40, 25, 0, -10 and -18°C	18s discharge pulse at max. possible current followed by 102s at 3/4 of previous current and 20s charge pulse at the latter current; 90, 70, 50, 35, 20% SOC; 40, 25, 0, -10, -18 and -25°C	30s discharge pulse at max. allowed current and 10s harge pulse at 3/4 of this power from 90 to 10% SOC at 30°C (Hybrid Pulse Power Capability test).	10s discharge pulse at max. allowed current and 10s charge pulse at 3/4 of this power from 90 to 10% SOC at 30°C (Hybrid Pulse Power Capability test).	Peak power pulses over 90% DoD at 25°C
Other power	If maximum pulse rate is not given: 10s pulses, both for discharge and charge. Rates: 1/3, 1, 2 and 5 I_t ; SOC: 80, 50, 20%; Temp.: 40, 25, 0,-20°C	If maximum pulse rate is not given: 10s pulses, both for discharge and charge. Rates: 1/3, 1, 5 and 10 I_t ; SOC: 80, 50, 20%; Temp.: 40, 25, 0,-20°C			Previous pulse test at 52, 0, -10, -20 and -30°C. Discharge pulse with 1C and with 3/4 of max.allowed current, at 30°C; peak power test: no rests periods between pulses.	Previous pulse test at temperatures between 52 - 30°C, mainly to test thermal management.	
Internal resistance	Slope of voltage-current characteristic from 10s pulse at max. pulse discharge current	,,	From pulses	,,	From pulses	From pulses	From pulses

	EV application						
Reference	IEC 62660-1:2010		ISO 12405-4:2018		DOE-INL/EXT-15-34184(2015)	DOE-INL/EXT-07-12536 (2008)	SAE J1798:2008
Energy efficiency	Charge-discharge (1/3 I_t) cycle with SOC window 0-100% at	Charge-discharge (1 I_t) cycle with SOC window 0-100% at	Based on a series of pulses at 65, 50 and 35% SOC at	Based on fast charge rates within requirements by		From pulses: based on 100 efficiency test profiles.	
Additional energy efficiency	Charge-discharge cycle with SOC window 0-70% & 0-80% at	Charge-discharge (1 I_t) cycle					
Self discharge at storage	Store cell at 100% SOC and 45°C for 42 days, repeated 3 times.	Store cell at 50% SOC and 45°C for 42 days, repeated 3 times.			30 days at initially 50% SOC and 30°C.	Partly discharged battery at 30°C for a period that should cover 5% capacity	30 days at 100% SOC and at 45 and 25°C
Charge retention for transport	Store cell at 50% SOC and 45°C for 28 days.	,,	30 days at initially 50% SOC. All battery system terminals disconnected. At 45°C.	,,			
Non-load loss			30 days at initially 80% SOC; BCU powered by auxiliary device. This is energy is reported. At 25 and 40°C.	30 days at initially 100% SOC; BCU powered by auxiliary device. This is energy is reported. At 25°C and 40°C.			
Energy for heating&cooling							
Cycle life test	Repeated Dynamic discharge tests for 28 days, repeated 6 times.	Repeated discharge rich and charge rich profiles between 30 and 80% SOC and 45°C for six months.	Repeated discharge rich and charge rich profiles between 30 and 80% SOC at 25°C. Systems only! Cooling must operate.	Repeated Dynamic discharge tests between 20 (or other agreed limit) and 100% SOC. Systems only! Cooling must operate.	Repeated Dynamic stress test at 30°C. Increased temperature allowed.	Repeated Charge-Depleting Cycle Life Test Profile and Charge-sustaining Cycle Life Test Profile; different for minimum and maximum PHEV battery.	
Calender life test					3 or up to 7 temperatures. Highest one such that battery does not age within 2 years. SOC at most challenging level. A daily calendar life test profile is applied.	3 or up to 7 temperatures. Highest one such that battery does not age within 2 years. SOC at most challenging level. A daily calendar life test profile is applied.	
Efficiency of life test							
SOH definition(s)							
EOL criterion / lifetime	80% of initial capacity; temperature too high	80% of initial capacity.	Cycle life test conditions cannot be maintained; the parameter checks are not possible anymore; or in accordance with manufacturer.	,,	Dynamic stress test cycle cannot be performed within voltage limits, intended to be over 1000 DST cycles, 15 years, specific energy and power requirements.	Cycle life test conditions cannot be maintained; the parameter checks are not possible anymore; or in accordance with manufacturer. 300,000 cycles are intended for charge-sustaining mode and 5000 cycles for charge-depleting mode.	
EOL information							
Battery expiration date							
Marking method							
BMS prescriptions							
BMS communication							

Table 2: Test conditions and criteria on information necessary for ecodesign in relevant standards for other applications.

	Motorcycle	*Industrial*				*On-grid*						*Repurposing*
Reference	ISO/DIS 18243: 2017	IEC 62620: 2014				IEC 61427-2: 2015				IEC 62984-3-2:2017	BVES Effizienz-leitfaden (2017)	ANSI/CAN/UL 1974 (2018)
Title	Electrically propelled mopeds and motorcycles -- Test specification and safety requirements for lithium-ion battery system	Secondary lithium cells and batteries for use in industrial applications				Secondary cells and batteries for renewable energy storage Part 2 On grid applications				High Temperature secondary Batteries – Part 3: Sodium-based batteries – Section 2: Performance requirements and tests	BVES Effizienzleitfaden	Standard for evaluation for repurposing batteries
Refined application	Moped and motorcycle	High energy (S; <C/8)	Energy (E; <C/2)	Medium rate discharge (M; <3.5C)	High rate (H; >3.5C)	Frequency regulation service	Load-following service	Peak-power shaving service	PV energy storage / time shift service	Stationary (& on-board (except propulsion))	PV energy storage	All applications but with 2nd life batteries
Chemistry	Li-ion	Li-ion	,,	,,	,,	Generic	,,	,,	,,	Na-based	Generic	Generic
Level (cell, module, pack, system)	pack and system	Cell up to system	,,	,,	,,					pack, system		
C_n-rate method (incl. temp.)	C/3, 1C, 2C and maximum allowed rate at at 40, 25, 0 and <=-10°C.	1/n I_t at 25°C.	1/5 I_t at 25°C.	1/5 I_t and 1/I_t at 25°C.	1/5 I_t and 1/I_t and 5 I_t at 25°C.					C_8 and max. allowed discharge rate		According to standard of 2nd life application
nominal capacity	C_3 or defined by manufacturer	C_n	C_5	C_5	C_5					C_8 (8 hour discharge)		According to standard of 2nd life application
Other capacities	By C_n-rate method.	By C_n-rate method. Also at 10, 0, -10 and -20°C, until capacity is <70% of rated one.	By C_n-rate method. Also at 10, 0, -10 and -20°C, until capacity is <70% of rated one.	By C_n-rate method. 1/I_t capacity >95% C_5 capacity. Also at 10, 0, -10 and -20°C, until capacity is <70% of rated one.	By C_n-rate method. 5/I_t capacity >90% C_5 capacity. Also at 10, 0, -10 and -20°C, until capacity is <70% of rated one.					By C_n-rate method.		
Energy										By C_8 method		Constant power discharge according to repurposing manufacturer
Other energies												
Charge method	As recommended by manufacturer, but within 8h.	As declared by manufacturer								C_8		As declared by repurposing manufacturer
Quick charge										Yes up to allowed voltage		
Power	18s discharge pulse at max.possible rate followed by 102s pulse at 3/4 rate and 20s charge pulse at latter rate. 90 to 20% SOC; 40, 25, 0 and -10°C.			5s discharge pulse of min.6I_t at 100%SOC.	5s discharge pulse of min.20I_t at 100%SOC.							
Other power												
Internal resistance	From pulses.	1kHz AC resistance; DC resistance by jump in current at 50%SOC.	,,	,,	,,							From step in current specified by repurposing manufacturer at 90 and 20% SOC

	Motorcycle	*Industrial*				*On-grid*						*Repurposing*
Reference	ISO/DIS 18243	IEC 62620				IEC 61427-2				IEC 62984-3-2:2017	BVES Effizienzleitfaden	ANSI/CAN/UL 1974
Energy efficiency										Yes, including energy loss for auxiliaries	Yes	
Additional energy efficiency												
Self discharge at storage		28 days at 25°C and initially 100% SOC.	,,	,,	,,							1 day
Charge retention for transport	30 days at initially 50% SOC. All battery system terminals disconnected. At 45°C.											
Non-load loss	30 days at initially 100% SOC; BCU powered by auxiliary device. This is energy is reported. At 25°C and 40°C.											
Energy for heating&cooling												
Cycle life test	1C discharges down to voltage limit by manufacturer at 25°C.	500 cycles with 1/n I_t and 25°C.	500 cycles with 1/5 I_t and 25°C.	,,	,,	Specific cycle at 25, min. and max. ambient temp.	,,	,,	,,	300 cycles; max. 3% capacity loss		
Calender life test		90 days at max.voltage for standby applications.										
Efficiency of life test						Yes, at min. and max. ambient temp.	,,	,,	,,			
SOH definition(s)												
EOL criterion / lifetime	80% of initial capacity.	Capacity > 60% after 500 cycles. Capacity >85% for standby applications.	,,	,,	,,	As acceptable	,,	,,	,,			
EOL information		In marking	,,	,,	,,							
Battery expiration date												
Marking method		Yes										Yes, with repurposed capacity
BMS prescriptions												Prescription of beeded parameters from BMS
BMS communication												



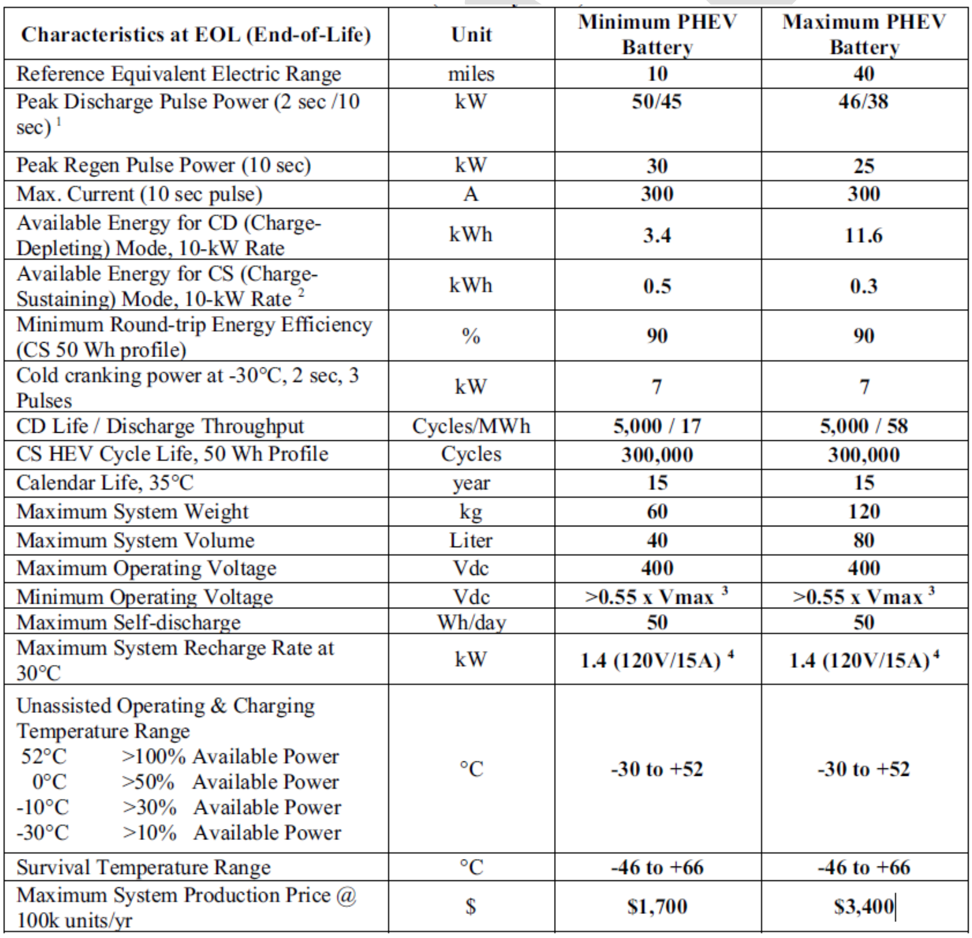
End of Life Characteristics at 30°C	Units	System Level	Cell Level
Peak Discharge Power Density (30 sec)	W/L	1000	1500
Peak Specific Discharge Power (30 sec)	W/kg	470	700
Peak Specific Regen Power (10 sec)	W/kg	200	300
Available Energy Density @ C/3 Discharge Rate	Wh/L	500	750
Available Specific Energy @ C/3 Discharge Rate	Wh/ kg	235	350
Available Energy @ C/3 Discharge Rate	kWh	45	N/A
Calendar Life	Years	15	15
DST Cycle Life	Cycles	1000	1000
Selling Price @ 100K units	$/kWh	125	100
Operating Environment	°C	-30 to +52	-30 to +52
Normal Recharge Time	Hours	< 7 Hours, J1772	< 7 Hours, J1772
High Rate Charge	Minutes	80% ΔSOC in 15 min	80% ΔSOC in 15 min
Maximum Operating Voltage	V	420	N/A
Minimum Operating Voltage	V	220	N/A
Peak Current (30 sec)	A	400	400
Unassisted Operating at Low Temperature	%	>70% Available Energy @ C/3 Discharge rate at -20°C	>70% Available Energy @ C/3 Discharge rate at -20°C
Survival Temperature Range, 24 hr	°C	-40 to +66	-40 to +66
Maximum Self-Discharge	%/month	< 1	< 1

NOTES

i. Values correspond to End-of-Life (EOL).

ii. The targets correspond to commercialization goals in FY 2020.

Figure 1: End of life criteria as defined in DOE-INL/EXT-15-34184(2015) U.S. DOE Battery Test Manual for Electric Vehicles.



Characteristics at EOL (End-of-Life)	Unit	Minimum PHEV Battery	Maximum PHEV Battery
Reference Equivalent Electric Range	miles	10	40
Peak Discharge Pulse Power (2 sec /10 sec)[1]	kW	50/45	46/38
Peak Regen Pulse Power (10 sec)	kW	30	25
Max. Current (10 sec pulse)	A	300	300
Available Energy for CD (Charge-Depleting) Mode, 10-kW Rate	kWh	3.4	11.6
Available Energy for CS (Charge-Sustaining) Mode, 10-kW Rate[2]	kWh	0.5	0.3
Minimum Round-trip Energy Efficiency (CS 50 Wh profile)	%	90	90
Cold cranking power at -30°C, 2 sec, 3 Pulses	kW	7	7
CD Life / Discharge Throughput	Cycles/MWh	5,000 / 17	5,000 / 58
CS HEV Cycle Life, 50 Wh Profile	Cycles	300,000	300,000
Calendar Life, 35°C	year	15	15
Maximum System Weight	kg	60	120
Maximum System Volume	Liter	40	80
Maximum Operating Voltage	Vdc	400	400
Minimum Operating Voltage	Vdc	>0.55 x Vmax[3]	>0.55 x Vmax[3]
Maximum Self-discharge	Wh/day	50	50
Maximum System Recharge Rate at 30°C	kW	1.4 (120V/15A)[4]	1.4 (120V/15A)[4]
Unassisted Operating & Charging Temperature Range 52°C >100% Available Power 0°C >50% Available Power -10°C >30% Available Power -30°C >10% Available Power	°C	-30 to +52	-30 to +52
Survival Temperature Range	°C	-46 to +66	-46 to +66
Maximum System Production Price @ 100k units/yr	$	$1,700	$3,400

Figure 2: End of life criteria as defined in DOE-INL/EXT-07-12536 (2008) Battery test manual for plug-in hybrid electric vehicles.

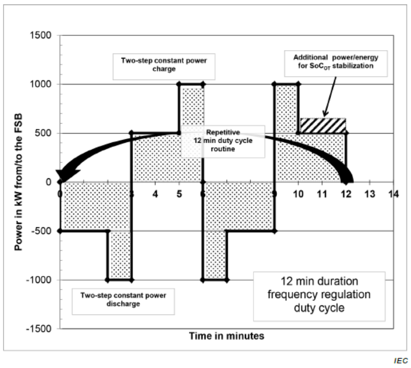


Figure 6 – Frequency regulation service test routine profile (6.2) – Profile a

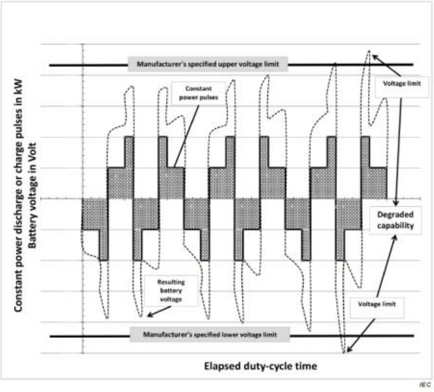


Figure 9 – Schematic view of the evolution of battery voltage over time during cycling with constant power discharge and charge pulses

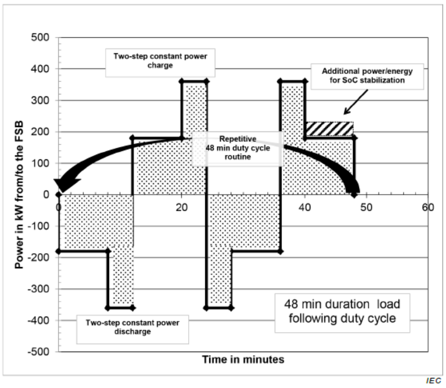


Figure 10 – Load-following service test routine profile (6.3) – Profile a

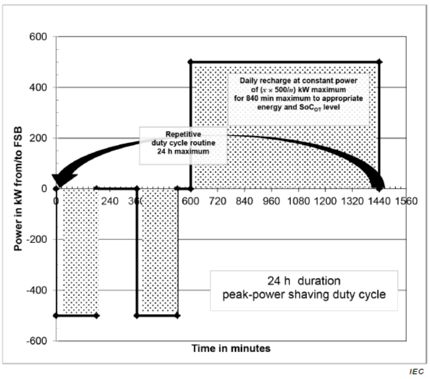


Figure 13 – Daily peak-power shaving service test routine profile (6.4)

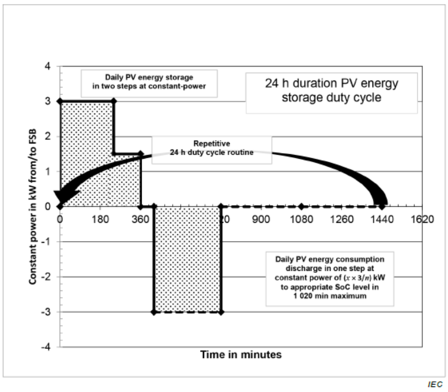


Figure 14 – Daily photovoltaic energy storage time-shift service test routine (6.5) – 3 kW

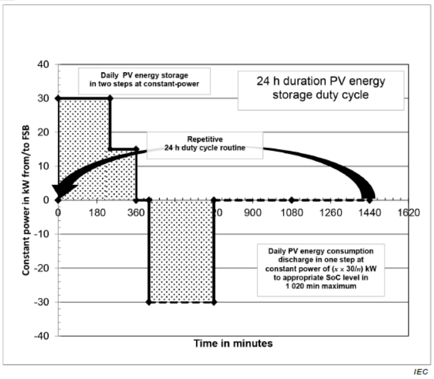


Figure 15 – Daily photovoltaic energy storage time-shift service test routine (6.5) – 30 kW

Figure 3: Test profiles for the 4 applications in IEC 61427-2 On-grid applications. Variants in profiles with different SOC stabilisation methods are not given here.

3.7. Ecodesign topics outside use phase

Performance prescriptions during the use phase are only one aspect of the information that ecodesign needs and on which it can put criteria. A limited list is given in Table 3 for the following standards:

- Nordic Swan Ecolabel (2018) About Nordic Swan Ecolabelled Rechargeable batteries and portable chargers
- IEC 60086-6 (2017) Primary batteries: Guidance on environmental aspects
- IEC/TS 62933-4 (2017) Electrical Energy Storage (EES) Systems - Guidance on environmental issues
- IEC 63218 (under dev.) Secondary Li-ion, Ni-Cd, and Ni-MH cells and batteries for portable applications - Guidance on environmental aspects

The performance test standards as given in the previous tables do not cover these topics.

Gaps for the recycling phase can be derived with help of the table.

- Explicit information and guidance on battery recycling is lacking in current standards.
- Little information is available on the material contents of batteries by labelling standards with IEC 62902 being the most important one. The argument is that it should not be too visible which Li-ion battery has most value for recycling. However, a database or traceability system can fulfil this information gap.
- Standards that define battery marking including the principal active materials (i.e IEC 62620, IEC 61960) need to anticipate new active materials like a silicon based anode.
- Harmonised calculation methods for the recycling efficiency to avoid data misinterpretation is welcomed. This should include environmental aspects like waste styreams, incineration with energy recovery and final landfilling or elimination. [4]
- Harmonised quantification of key indicators as CO_2 footprint, recycling percentage, toxicity and recycling cost is needed [4].

Table 3: Other topics that are needed for an ecodesign study.

===

Category	*Topic*	*Standard / label*			
	Reference	Nordic Swan Ecolabel (2018)	IEC 60086-6 (2017)	IEC/TS 62933-4 (2017)	IEC 63218 (under dev.)
	Title	About Nordic Swan Ecolabelled Rechargeable batteries and portable chargers	Primary batteries: Guidance on environmental aspects	Electrical Energy Storage (EES) Systems - Guidance on environmental issues	Secondary Li-ion, Ni-Cd, and Ni-MH cells and batteries for portable applications - Guidance on environmental aspects
	Aplication	Portable	Portable primary cells and batteries	Electrical energy storage systems	Portable
	Level	Cell up to pack, including charger	Cell up to pack	System	Cell up to pack
Circular economy	Recycle recommendations		Design with ability to separate parts and materials.		
	Disposal recommendations		By marking (collection) on battery and by information on packaging including identification of recyclable parts. Prevent short-circuits.		By marking (collection) on battery including identification Li-ion type. In countries without collection programmes, volantary and co-regulated stewardship programes are encouraged. Prevent short-circuits.
	Dismantling recommendations				
	Minimum technical compatibility with recycling schemes				
	Requirements for repairability				
	Recycling info		Identification of recyclable parts, being electronics and safety devices.		
	Minimum open data BMS				
	Carbon footprint data to be used in applications				
	LCA		LCA according to ISO 14040.		LCA according to ISO 14040.
PEF	Energy & material resources production	yes			
	EOL: collection rate				
	EOL: recycling rate		Minimum 50% by weight.		
	EOL: credits to battery composition				
	Energy & material resources EOL				
	Energy loss over lifetime				
	Waste streams in cycle life stages				
Environment (ecolabel)	Fit for purpose		Determine if rechargeable cells have an environmental advantage.		NiCd remains necessary for low temperatures and emergency equipment.
	Environmental analysis		Assessment needed on reduction, reuse and recycling of materials in design phase, of the manufacturing and of the packaging.	Life cycle thinking; system to environment including leakage, vibration and earth leakage current; environment to system causing malfunction.	Design phase analysis: avoiding inseparable composite materials; minimising number of different materials used; using standardised parts. Assessment needed on reduction, reuse and recycling of materials in design phase, of the manufacturing and of the packaging.
	Energy efficiency requirement				
	Power management	350 cycles for most type of primary battery alternatives. Over 700 for others cells and over 525 for batteries.			
	Limit on hazardous substances	Yes, low, defined amount of mercury, cadmium and lead; arsenic; Requirements on plastic and flame retardants.	Yes, low, defined amount of mercury, cadmium and lead. Exception for button ZnAgO cells and button Zn-air cells.		Yes, low, defined amount of mercury, cadmium (except NiCd) and lead.
	Restriction of substances of very high concern		Check on regulations on banned substances.		Avoid batteries with restricted substances.
	Durability testing for extended lifetime				
	Minimum battery life criterion	60% of initial capacity.			
	Repairability				
	Recyclability				
	Minimum use of recycled material criterion				
	Sourcing of conflict-free minerals				
	Labour condition and human right criterion	yes			
	User instructions				Yes, on transportation, storage, recycling, and disposal.
	Use instructions with environmental advice				Yes on recycle and disposal.
	Use of critical materials	yes, restriction			
	Hazardous waste		Check battery waste on toxicity, ignitability, reactivity and corrosivity by prescribed methods.		
	Marking		Yes, collection symbol		Yes, collection symbol and symbol acc.to IEC 62902. Add Li-ion type to symbol (Cobalt, Manganese, Nickel, Iron).

4. References

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[6] M/543, “COMMISSION IMPLEMENTING DECISION. C(2015) 9096 final. On a standardisation request to the European standardisation organisations as regards ecodesign requirements on material efficiency aspects for energy-related products in support of the implementation,” 2015. Link: http://ec.europa.eu/growth/tools-databases/mandates/index.cfm?fuseaction=search.detail&id=564#

Preparatory Study on Ecodesign and Energy Labelling of Batteries under FWC ENER/C3/2015-619-Lot 1

TASK 2

Markets – For Ecodesign and Energy Labelling

VITO, Fraunhofer, Viegand Maagøe

August 2019

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2. Task 2: Markets

The objective of Task 2 is to present an economic and market analysis on batteries and battery components (particularly LIB) according to the definition presented in 1.2.1. The aims are:

- to provide basic economic information on batteries (according to the definition provided in 1.2.1) (subtask 2.1);
- to provide market size and cost inputs for the EU-wide environmental impact assessment of the product group (subtask 2.2);
- to provide insight into the latest market trends to help assess the impact of potential Ecodesign measures with regard to market structures and ongoing trends in product design (subtask 2.3, also relevant for the impact analyses in Task 3); and finally,
- to provide a practical data set of prices and rates to be used for Life Cycle Cost (LCC) calculations (subtask 2.4).

2.1. Definitions

In the following, several definitions and categories are used:

- Abbreviations for vehicles: combustion powered vehicles (ICE), vehicles utilizing a traction battery (xEV) full electric vehicles (BEV), plugin hybrid electric vehicles (PHEV), hybrid vehicles without option for external charging (HEV), hybrid vehicles making use of a fuel cell as range extender (FCEV).
- Abbreviations for battery markets: Traction batteries, also for auxiliary functions in industrial applications (motive); consumer, computing and communication applications (3C); stationary applications (ESS).
- Market, sales or other volumes in units of battery capacity (kWh, MWh or GWh) or in units of number of battery systems (thousand units: k#, million units: mio#).
- Sales or new installations: Volume (number of units) of battery systems or capacity (GWh) put into operation for the first time (e.g. new vehicles or new storage systems).
- Replacements: Replacement batteries (e.g. packs or cells) for systems already in use (GWh).

Decommissions: Decommissioned batteries (GWh) resulting either from decommissioned systems at their end of life (vehicles, stationary systems) or from broken and replaced batteries.

2.2. Generic economic data

In the MEErP, generic economic data refers to data that is available in official EU statistics (e.g. PRODCOM) and the aim is to identify and report the ‘EU apparent consumption’ which is defined as ‘EU production + EU import – EU export’. Additionally, the average value of each product is verified. The information required for this subtask should be derived from official EU statistics so as to be coherent with official data used in EU industry and trade policy.

2.2.1. Approach to subtask 2

PRODCOM data is publicly available and is a direct source of market information. PRODCOM data does not give any direct information about the total number of installed batteries in use in the EU28 member countries. The data might also not account for batteries imported to or exported from the EU as sub-unit of other products (e.g. batteries in cell phones).

2.2.1.1. Secondary batteries related PRODCOM categories

Several categories on batteries exist within the NACE2 classification (see Table 1), however there is no category for LIB cells, modules or packs. LIB based secondary batteries are included in the composite category 2702300 along with all other, not Pb-based secondary battery technologies.

27201100	Primary cells and primary batteries
27201200	Parts of primary cells and primary batteries (excluding battery carbons, for rechargeable batteries)
27202100	Lead-acid accumulators for starting piston engines
27202200	Lead-acid accumulators, excluding for starting piston engines
27202300	**Nickel-cadmium, nickel metal hydride, lithium-ion, lithium polymer, nickel-iron and other electric accumulators**
27202400	Parts of electric accumulators including separators

Table 1: PRODCOM categories related to batteries [1].

2.2.2. Results of the PRODCOM analysis

The PRODCOM category 27202300 Nickel-cadmium, nickel metal hydride, lithium-ion, lithium polymer, nickel-iron and other electric accumulators is analyzed in more detail for the years 1995, 2000, 2005, 2010, 2015 and 2017 based on Eurostat PRODCOM data obtained online in September 2018 [2].

Figure 1 shows the development of production, import and export volumes in Euro for PRODCOM category 27202300 in the time from 1995 to 2017. The data shows an increase of market volume in all three categories. Since several battery technologies are aggregated in this PRODCOM category, values specific for LIB cannot obtained from this data. Due to the development of the different battery technologies, it is likely that the market values in the 1990s and early 2000s can mainly be attributed to NiMH, NiCd and other technologies. The growth experienced since 2010 in all three market categories is likely to be a result of the development in the LIB market, which can be considered to be the dominant submarket under the battery technologies aggregated under 27202300 today (see and compare section 2.4.3 with a global analysis of different battery technologies).

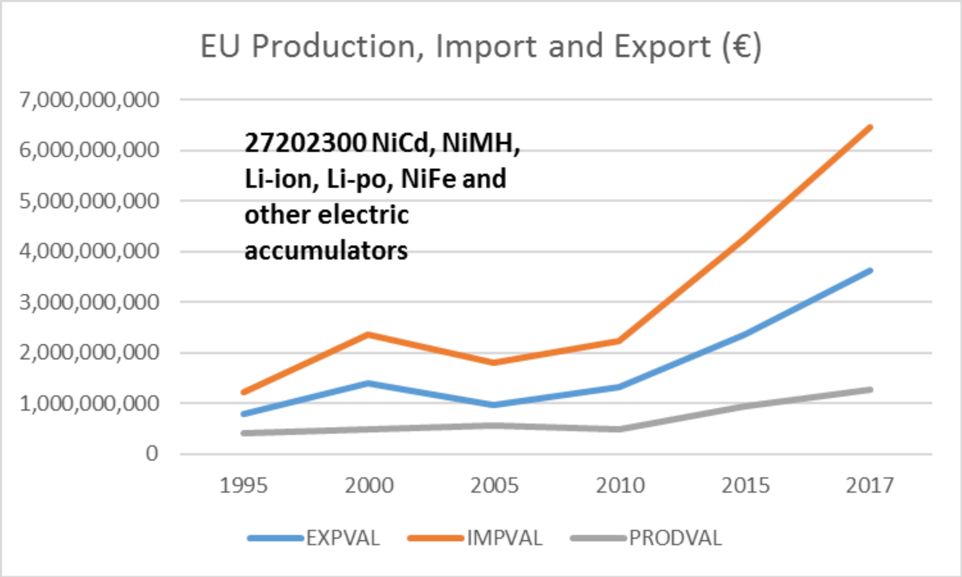


Figure 1: EU production, import and export summarized in PRODCOM category 27202300: Nickel-cadmium, nickel metal hydride, lithium-ion, lithium polymer, nickel-iron and other electric accumulators [2].

Note that no production volumes in terms of units or kWh are available from Eurostat.

The value of batteries integrated into applications or sold as end products in Europe can be assessed by considering the EU consumption value (EU sales and trade), which results from the sum of production and import minus export values (see Figure 2). After a plateau like market behavior between 2000 and 2010, a steep increase of the EU consumption value can be observed. The 2017 value adds up to about 4 billion Euro. Assuming that the majority share of this value can be attributed to LIB with a market price of 300 to 500 €/kWh (assumed mix of higher priced consumer cells and lower priced automotive cells), the value corresponds to a capacity of 8 to 13 GWh. In consideration of its estimated character, this number is in accordance with the data presented in section 2.3.5 (based on a bottom up estimation of the capacity demand by passenger electric vehicles (xEV) and home storage ESS (energy storage systems) markets; 3C (consumer, computing, communication) markets are not considered).

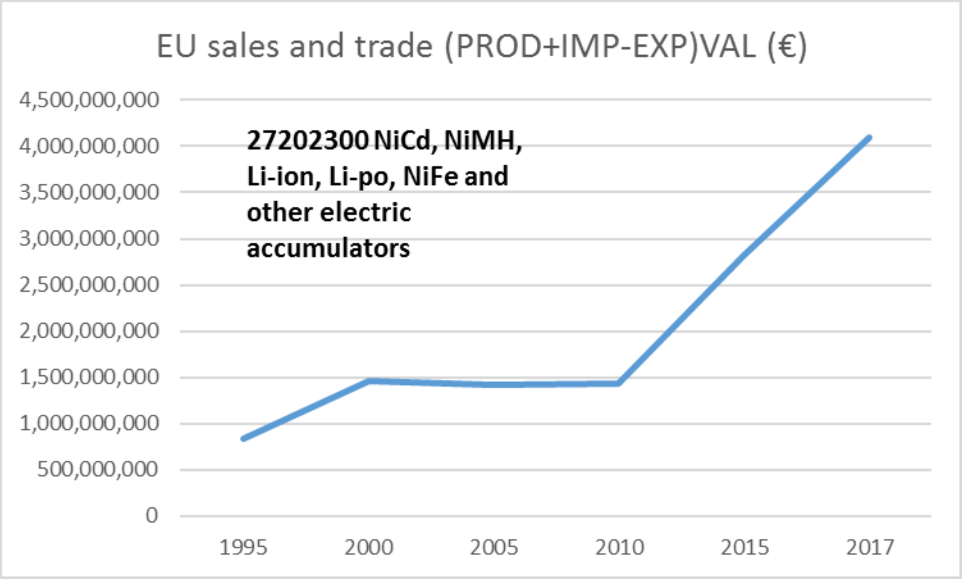


Figure 2: EU sales and trade (PROD+IMP-EXP) summarized in PRODCOM category 27202300 Nickel-cadmium, nickel metal hydride, lithium-ion, lithium polymer, nickel-iron and other electric accumulators [2].

Hence it can be assumed, that the data presented in the PRODCOM database meets the right order of magnitude. Due to the aggregation of battery technologies, the consumption value of LIB alone can however not be assessed by this data. Furthermore, the large price spread for LIB and the dynamic development of prices does not allow to reliably conclude on the demand of battery capacity (GWh). An assessment of market development and installed LIB stock in Europe is given in section 2.3 and 2.4 based on other data sources.

2.3. Market and stock data

2.3.1. General objective of subtask 2.2 and discussion of useful data sources

The objective is to compile market and stock data in physical units for the EU, for each of the product categories defined in Task 1.1, combined with a forecast 2020-2050. Therefore, the following parameters need to be identified:

- Market and installed stock assessment in units of number of systems (battery systems for xEV, battery systems for ESS) and corresponding battery capacity (MWh or GWh).
- Replacement cycles and lifetime data. This data is assumed to be strongly application dependent. At present, there is no comprehensive data available.
-

2.3.1.1. Useful data sources

Several market studies describing the present and future market situation for battery-based applications exist. Most of these studies have a global scope or focus on Asian countries due to the structure of the battery market. Comprehensive studies providing market data for the EU and its member states are not known.

To give an overview about stock and battery markets for the EU28 member states, the following bottom-up sources were utilized to give model estimations:

- Fraunhofer ISI in-house xEV database [3]: The database has been developed in 2014 by Fraunhofer ISI and is updated since on an annual basis. The last update was done in November 2018. It covers global production and sales numbers for xEV models broken down to countries as well as information on battery capacity and range of the vehicles. The database aggregates information provided by Marklines Co, Ltd. [4], the European Automobile Manufacturers Association [5], the EV-sales blog [6] and other online sources (e.g. websites of automotive OEM). The ISI xEV database has been checked against the European Alternative Fuels Observatory [7] and is in well agreement.
- Fraunhofer ISI in-house LIB database [8]: The database covers information on the major industrial players in the Li-ion business from materials to cell production. The development and location of production capacities is frequently updated. Information on performance and cost of commercially available battery cells as well as the meta-analysis of several studies providing forecasts on the respective developments are also covered in the database. Information is collected from several online sources and available product data sheets.
- B3 corporation market studies: B3 corporation provides topical market studies on xEV, ESS and material markets for Li-ion batteries. The market data is updated on an annual basis. B3 studies have a global scope, but occasionally also cover local European markets.
- Additional market studies and databases as discussed in the following sections.

2.3.2. Direct market data on LIB cells

There are few sources providing direct data on battery sales. As compared to the PRODCOM scheme, more detailed data on LIB cells attributed to target applications is given in ProSUM [9] for the years 2000 - 2015. The amount of LIB cells placed on the market is given in units of pieces and weight. The data shows that the majority of cells sold in the EU are rather small cells with an average weight of 40 g/piece in 2000 and 250 g/piece in 2015 (a 18650 format cell has a weight of approximately 50 g). This is also reflected by the high share of cells designated for use in 3C applications (see Figure 3 top, compare also to section 2.4.4 for global data). While this market segment featured moderate yearly growth rates of about 10% between 2010 and 2015, particularly the xEV battery market has been growing strongly (annual growth rate of about 60%).

Figure 3: Top: Weight of battery cells placed on the market in the EU28 and Norway and Switzerland as obtained from [9]. Bottom: Approximated battery capacity for data provided in [9] and comparison with battery demand model (see section 2.3.5).

Assuming an average energy density of 150 Wh/kg in 2010 and 180 Wh/kg in 2015, the data on LIB cell weight given in [9] translates into an estimated total capacity of 15 GWh placed on the market in 2015. Figure 3 (bottom) shows the development of estimated LIB capacity for xEV applications and non-motive industrial applications. In addition, the capacity demand for xEV and ESS as calculated in the frame of the demand and forecast model utilized in the study at hand (EU only) is shown. The model is introduced in sections 2.3.3 and 2.3.4 in more detail. Additional information can be found in section 2.7. With respect to the uncertainties regarding the estimated battery energy density in [9] and the contribution of Norway and Switzerland to the volume of batteries, both data sets are in well agreement.

2.3.3. Market stock and forecast for xEV in Europe

As will be shown in section 2.4, the stock of installed medium or large batteries in Europe is strongly related to the diffusion of electric mobility. In contrast to several Asian countries, xEV sales in Europe predominantly concern passenger cars. Ebuses as well as light and heavy commercial vehicles still do not play a major role in terms of installed capacity, but might become growth markets in the future.

2.3.3.1. Production and sales of BEV

Figure 4 shows the number of produced BEV [3] broken down to their production country from 2010 to 2018. A forecast until 2020 based on the average growth rates between 2016 and 2018 is shown in addition. This production data is a measure for the demand of battery cells in the individual EU28 countries.

Germany, France and the Netherlands lead the field of BEV producers in Europe. On European level, an average yearly growth rate of over 40% can be observed. It is expected that the number of 150000 produced BEV in 2018 will double in 2020.

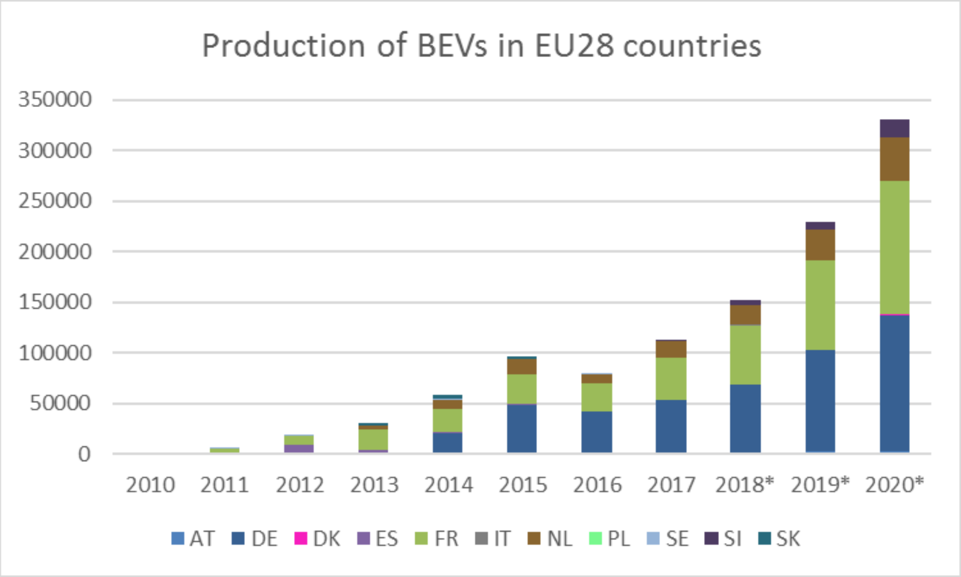


Figure 4: Production numbers for BEVs produced in EU28 countries and forecast until 2020. [3]

In contrast to the production data, the sales numbers for BEV reflect the amount of installed vehicle batteries in the individual EU28 countries. It can be seen in Figure 5, that the distribution in terms of sold vehicles among the EU28 countries is much more even as compared to the production. Germany, France, the United Kingdom and the Netherlands lead the market, however significant sales numbers can also be found in other countries. The level and growth rates of BEV sales is comparable to BEV production. It should however be noted that there is significant trade with other regions of the world, e.g. BEV imports and exports with Asia and North America. Hence, the BEV market cannot be considered as an internal market.

In addition to the EU28 member states, Figure 5 also shows sales numbers for Norway, which significantly contribute to the market volume in the European Economic Area (EEA).

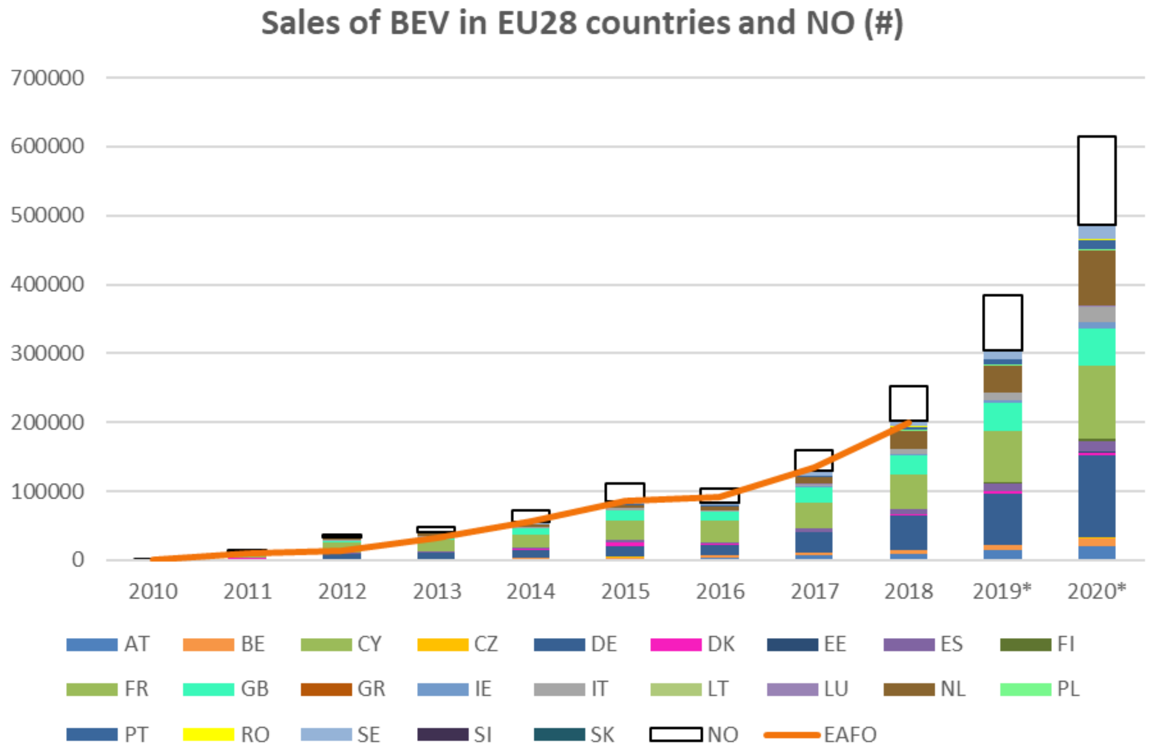


Figure 5: Number of sold BEVs in EU28 member states and Norway and forecast until 2020 [3, 7].

2.3.3.2. Production and sales of PHEV

Similar to section 2.3.3.1, production and sales numbers for PHEV resolved by country are shown in Figure 6 and Figure 7. Although on a comparable level in terms of produced and sold vehicles it must be emphasized that the contribution of PHEVs to the demand for battery capacity is, due to the smaller size of the battery, significantly below the demand generated by BEV. At present, the main production sites for PHEV are located in Germany. Sweden and Slovakia also significantly contribute to the production.

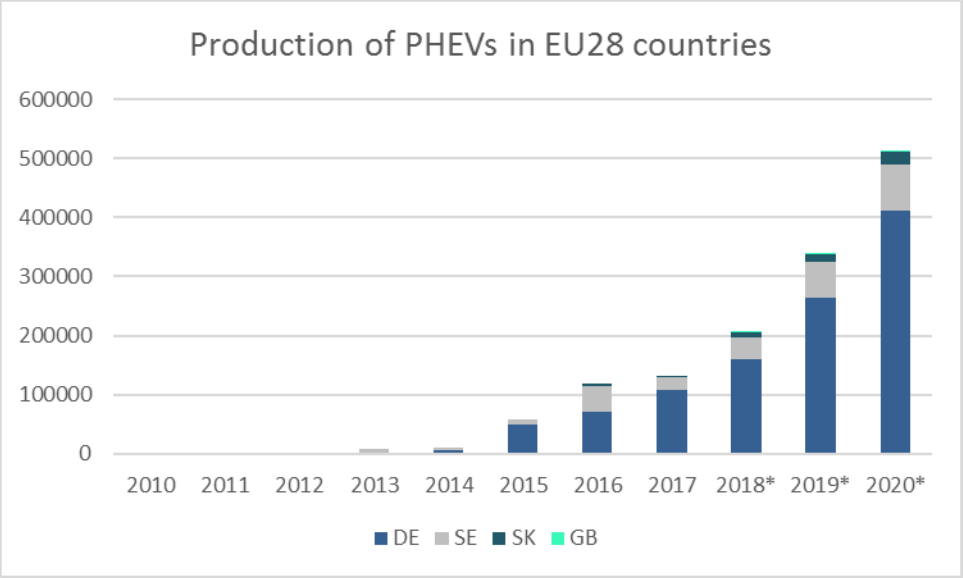


Figure 6: Number of produced PHEV in EU28 member states and forecast until 2020. [3]

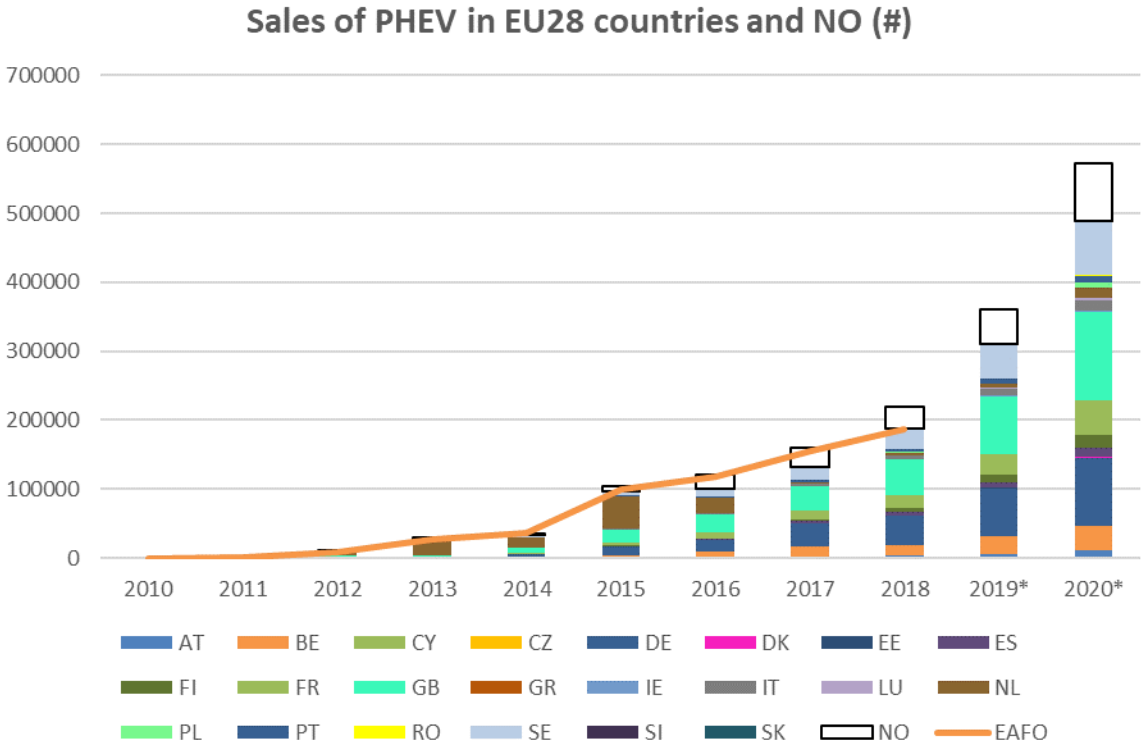


Figure 7: Number of sold PHEV in EU28 member states and Norway and forecast until 2020. [3, 7]

In terms of sales, the largest demand for PHEV is generated in the UK, Germany and Sweden. Interestingly, the share of sold PHEV also produced in the EU is higher as compared to BEV.

2.3.3.3. Forecast passenger xEV sales and stock EU28

The data presented in sections 2.3.3.1 and 2.3.3.2 was used as an input for a forecast model on passenger PHEV and BEV sales in the EU28 (see also [10] and section 2.7).

2.3.3.3.1. Minimum and maximum scenarios

Two different scenarios for the minimum and maximum market diffusion of BEV and PHEV were developed.

In the frame of the forecast model applied, xEV model availability (1, measure for the supply) as well as sales performance (number of sold vehicles per year per model) of xEV models (2, measure for the demand) are major determinants for the future growth of xEV markets. In the minimum scenario, sales numbers until 2025 were derived from (1) existing xEV models and additional models announced by different OEM. A linear forward projection for the sales performance of xEV models was assumed (2). In the maximum scenario it was assumed that OEM will introduce additional models, not yet announced, to the market (1). The sales performance per model was assumed to reach the level of the sales performance of combustion powered cars until 2025 (2). Today, the average sales performance of electric vehicles is significantly below the performance of combustion powered vehicles.

Long-term scenarios are based on the min./max. projection data until 2025 (see section 2.7). It was assumed that extrapolated EU wide sales numbers and growth rates for passenger as well as for light vehicles and buses of all technologies (particularly combustion powered) [5] represent natural boundaries for the growth of xEV markets.

As a third input parameter for min./max. scenarios, the market shares addressable by electric vehicle models and in particular addressable by BEV were included. It was assumed, that the range requirements of long-haul transport (e.g. heavy commercials or touring coaches, see section 2.3.3.4) cannot be met by full battery electric concepts. Hence hybrid (battery and combustion or battery and fuel cell) concepts might have a high market share even in the long term.

The model applied prioritizes the sales of BEV during market ramp-up. BEV will freely diffuse into the market until their addressable market share is reached. Sales of PHEV and HEV will hence decline, once electric vehicles have reached market saturation and there is a direct competition of the three electric drive technologies. The maximum scenario describes fast and deep market penetration of BEV and resulting smaller market shares of PHEV and HEV in the long term. The minimum scenario describes slower market penetration of BEV with a smaller addressable market and resulting higher market shares of PHEV and HEV in the mid to long term.

2.3.3.3.2. Assumptions

The sizes of vehicle markets as well as assumed growth rates are given in Table 2. Minimum and maximum values for the model parameters are given in Table 3.

Market parameter	Value
Passenger vehicle market EU28, 2017 [3, 5]	15 mio vehicles per year
Passenger vehicle market growth rate EU28 [3]	1.3 %

Table 2: Assumptions and input parameters for the xEV market and growth model.

Model parameter	Min. value	Max. value
Share of passenger vehicle market addressable by BEV	60 %	90 %
Share of passenger vehicle market addressable by PHEV	90 %	100 %

Table 3: Assumptions and input parameters for the xEV market and growth model.

At present, there is no sufficient data on the battery and vehicle lifetime of xEV. Vehicle lifetimes were fixed on values for ICE powered vehicles (see section 2.7.1.5). While this might not necessarily be true, differing values would directly influence the overall vehicle market volumes (e.g. shorter lifetime would require higher sales volumes to keep the stock constant). Hence, in the frame of the model applied, vehicle lifetimes were fixed and the overall market volumes for vehicles were adopted from historic data.

Assumptions on battery replacement rates are given in section 2.7.1.4. The assumptions for the stock model are summarized in Table 4.

Model parameter	Value
Passenger xEV lifetime	17 years
Passenger BEV battery replacement rate	10 %
Passenger PHEV battery replacement rate	66 %

Table 4: Assumptions and input parameters for the xEV battery demand and stock model.

2.3.3.3.3. Results: forecast passenger xEV and stock

Historic sales data (2010-2018) for passenger vehicles was aggregated to three segments: (mini) A and B; (comp) C and M; (lux) D, E, F and all SUV segments [11]. Logistic growth functions (see section 2.7.1.2) were fitted to the data for BEV, PHEV and HEV markets. HEV are considered for reasons of consistency. Due to their rather small installed battery capacity, they are not included in overall xEV sales numbers.

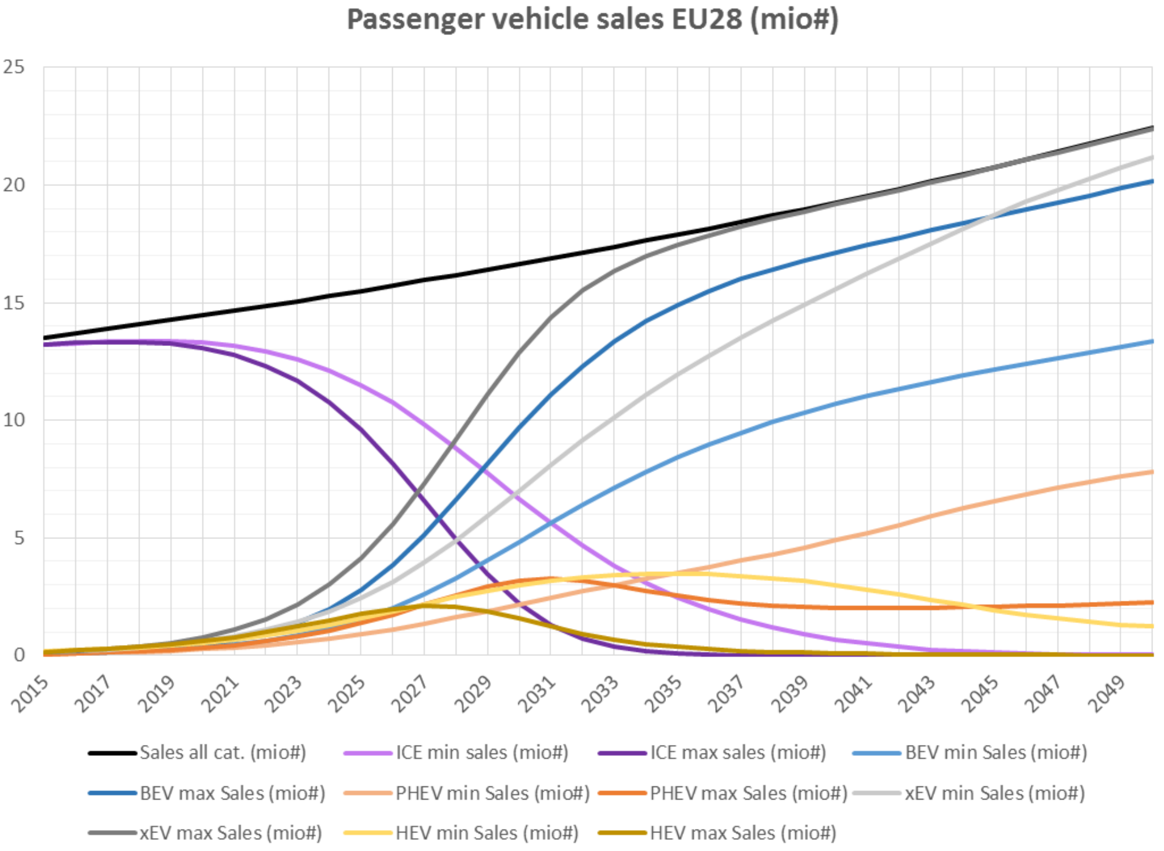
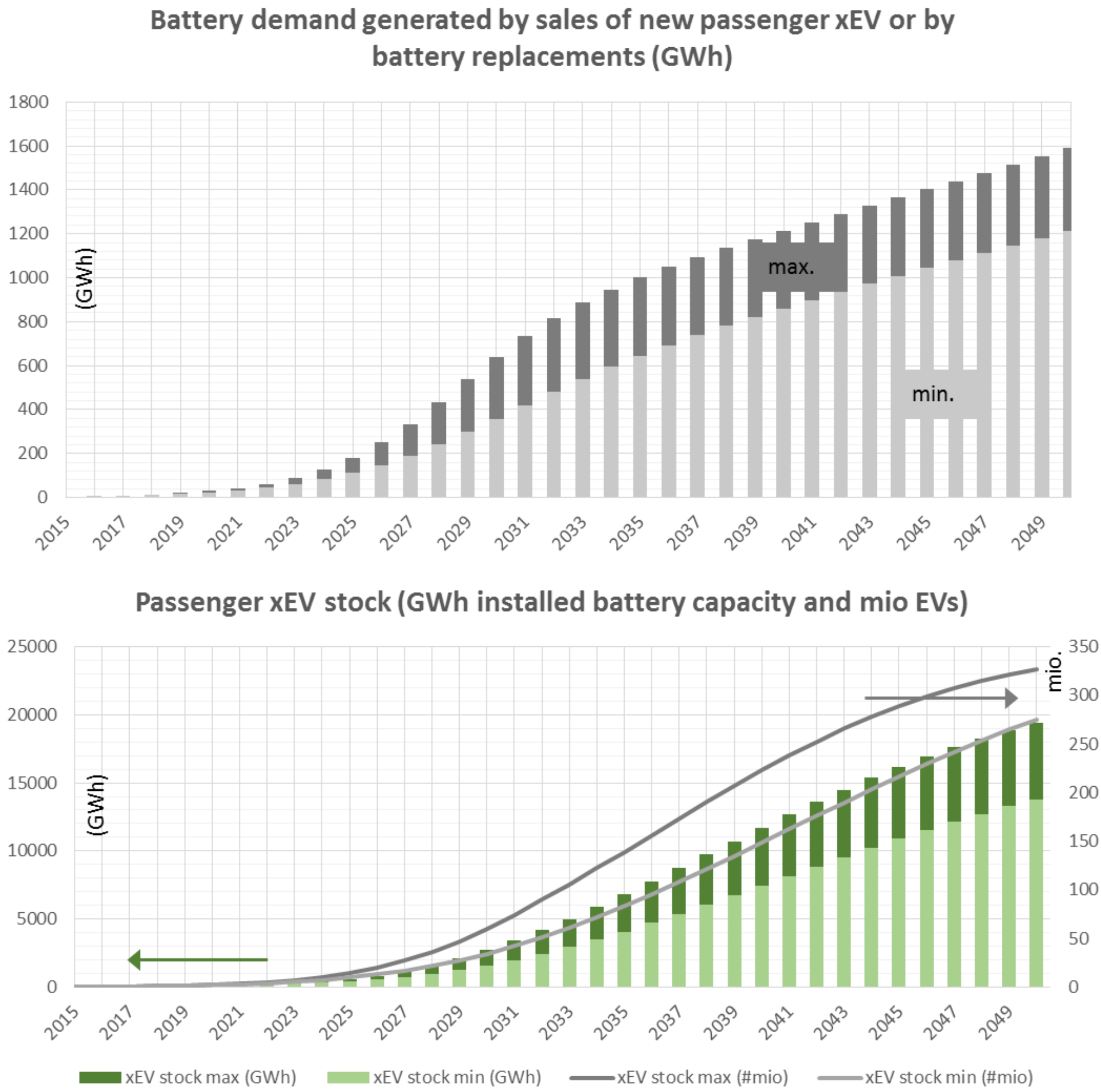


Figure 8: Forecast passenger xEV sales until 2050.

The model and forecast results for passenger vehicles are presented in Figure 8.

Within the model, the major transition to passenger electric vehicles is expected to happen between 2025 and 2035.

The implications of market growth with respect to battery demand – either generated by sales of new vehicles of replacement of batteries – as well as the projected stock of electric vehicles are given in Figure 9.



Battery demand generated by sales of new passenger xEV or by battery replacements (GWh)

Passenger xEV stock (GWh installed battery capacity and mio EVs)

Figure 9: Battery demand generated by passenger xEV and xEV stock.

As noted in section 2.3.3.1, other countries part of the European Economic Area, particularly Norway, will contribute significantly to the market volume of batteries in Europe. With respect to today's sales numbers for passenger electric vehicles in the EEA and in the EU28, the battery demand projected in Figure 9 (EU28) would be 10 to 20% higher if the whole EEA is considered.

2.3.3.4. Sales of commercial vehicles

In contrast to battery electric light commercial EV and eBuses, other commercial or industrial EV segments mostly have rather small market shares. Figure 10 shows sales numbers for electric light commercial vehicles and eBuses for the EU as obtained from [7]. Notably, sales of light commercial EV as well as eBuses are dominated by BEV models. With respect to total market volumes, electric light commercial vehicles and eBuses reached a market share of about 1.2% and 2% in 2018 respectively.

With only few vehicles on the street, electric heavy commercials have a negligible market share.

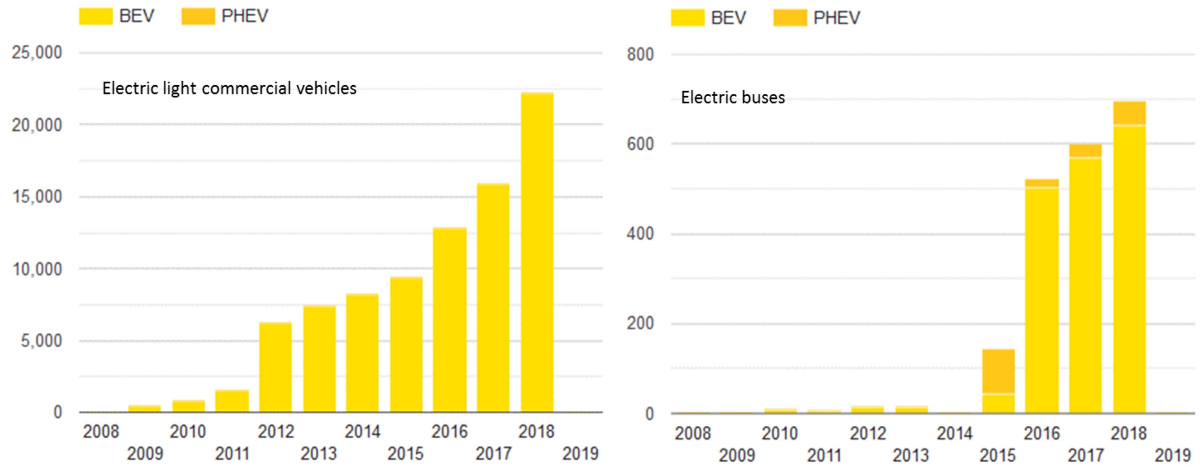


Figure 10: Sales numbers for light commercial vehicles and eBuses in the EU28 as taken from [7].

2.3.3.5. Forecast bus and commercial xEV sales and stock EU28

The sales numbers provided in section 2.3.3.4 were used as input to model the growth of the sub-markets BEV light commercial vehicles and BEV buses. Sales numbers for other sub-markets are comparably low and not sufficient to serve as input for long-term growth models. However, there are market targets for certain segments given by CO_2 or other legislation which allow for an estimate of future market volumes (e.g. procurement of public buses) [12, 13].

Hence, model results presented in section 2.3.3.5.2 should rather be interpreted as estimated scenarios than as forecasts. Minimum and maximum scenarios are used to present a certain range of potential market development.

2.3.3.5.1. Assumptions

The sizes of vehicle markets as well as assumed growth rates are given in Table 5. Minimum and maximum values for the model parameters are given in Table 6.

Market parameter	**Value**
Light commercial vehicle market EU28, 2017	1.8 mio vehicles per year
Heavy commercial vehicle market EU28, 2017	0.33 mio vehicles per year
Medium and heavy bus market EU28, 2017	34 thousand vehicles per year
Commercial vehicle market growth rate EU28	Light: 1.7 %, heavy and bus: 1 %

Table 5: Assumptions and input parameters for the xEV market and growth model.

Model parameter	**Min. value**	**Max. value**
Share of light commercial vehicle market addressable by BEV	65 %	85 %
Share of light commercial vehicle market addressable by PHEV	90 %	100 %
Share of heavy commercial vehicle market addressable by BEV	15 %	25 %
Share of heavy commercial vehicle market addressable by PHEV	70 %	80 %
Share of medium and heavy bus market addressable by BEV	60 %	80 %
Share of medium and heavy bus market addressable by PHEV	90 %	100 %

Table 6: Assumptions and input parameters for the xEV market and growth model.

At present, there is no sufficient data on the battery and vehicle lifetime of xEV. Vehicle lifetimes were fixed to values for ICE powered vehicles (see section 2.7.1.5). Assumptions on battery replacement rates are given in section 2.7.1.4. The assumptions for the stock model are summarized in Table 7.

Model parameter	**Value**
Light commercial xEV lifetime [5]	15.5 years
Heavy commercial xEV lifetime	15 years
eBus lifetime	15 years
Light commercial BEV battery replacement rate	25%
Light commercial PHEV battery replacement rate	30%
Heavy commercial BEV battery replacement rate	80%
Heavy commercial PHEV battery replacement rate	80%
Bus BEV battery replacement rate	80%
Bus PHEV battery replacement rate	80%

Table 7: Assumptions and input parameters for the xEV battery demand and stock model.

Due to their high range requirements, commercial vehicles are candidates for the utilization of fuel cells in battery hybrid concepts (FCEV). The technology was considered as additional path for the time 2030 and later.

2.3.3.5.2. Results forecast passenger xEV and stock

The market diffusion scenarios for light and heavy commercial vehicles and eBuses are shown in Figure 11 and Figure 12 respectively.

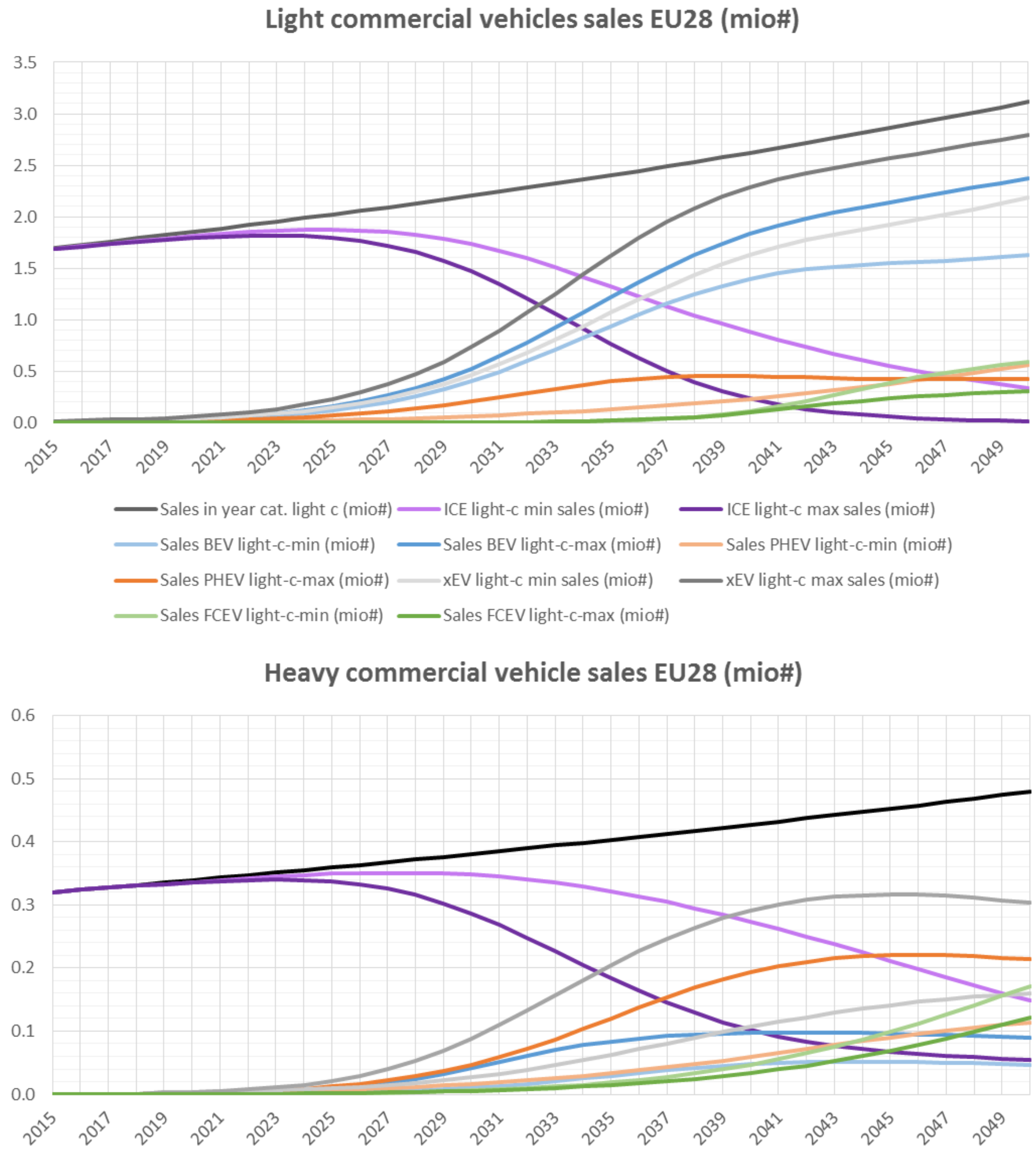


Figure 11: Market diffusion scenarios light and heavy commercial xEV sales until 2050.

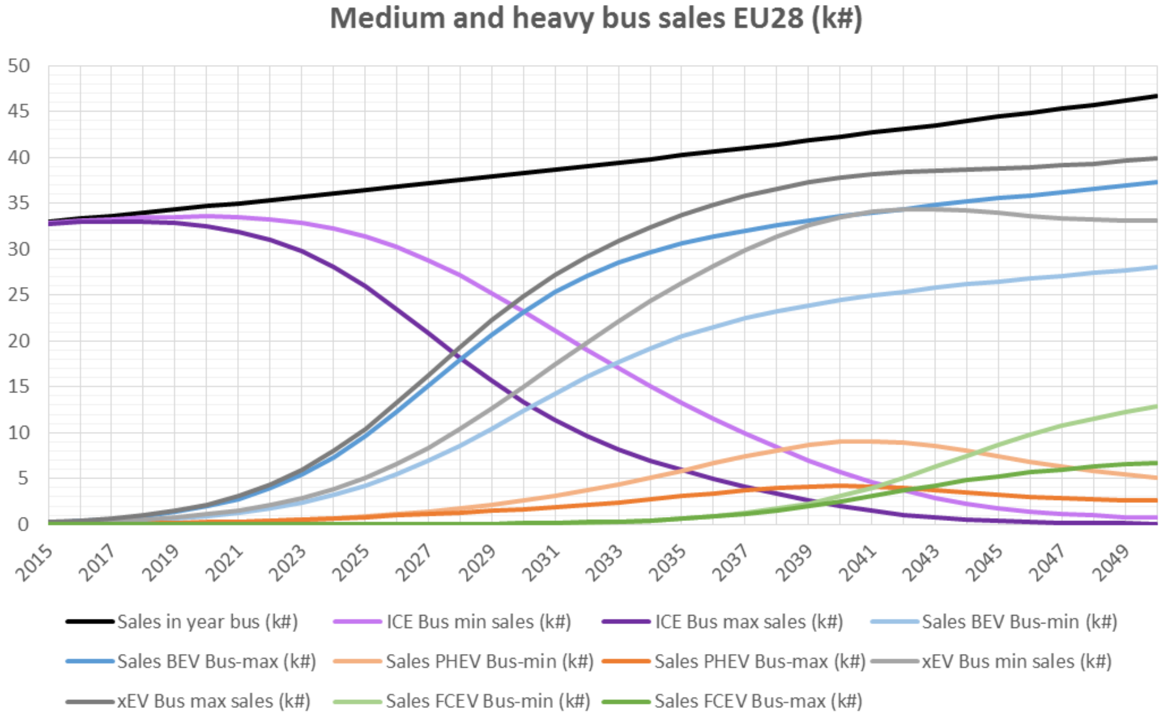


Figure 12: Market diffusion scenarios eBus sales until 2050.

Figure 13 shows the demand for battery capacity resulting from the three markets as well as the calculated EV and battery stock in the EU28.

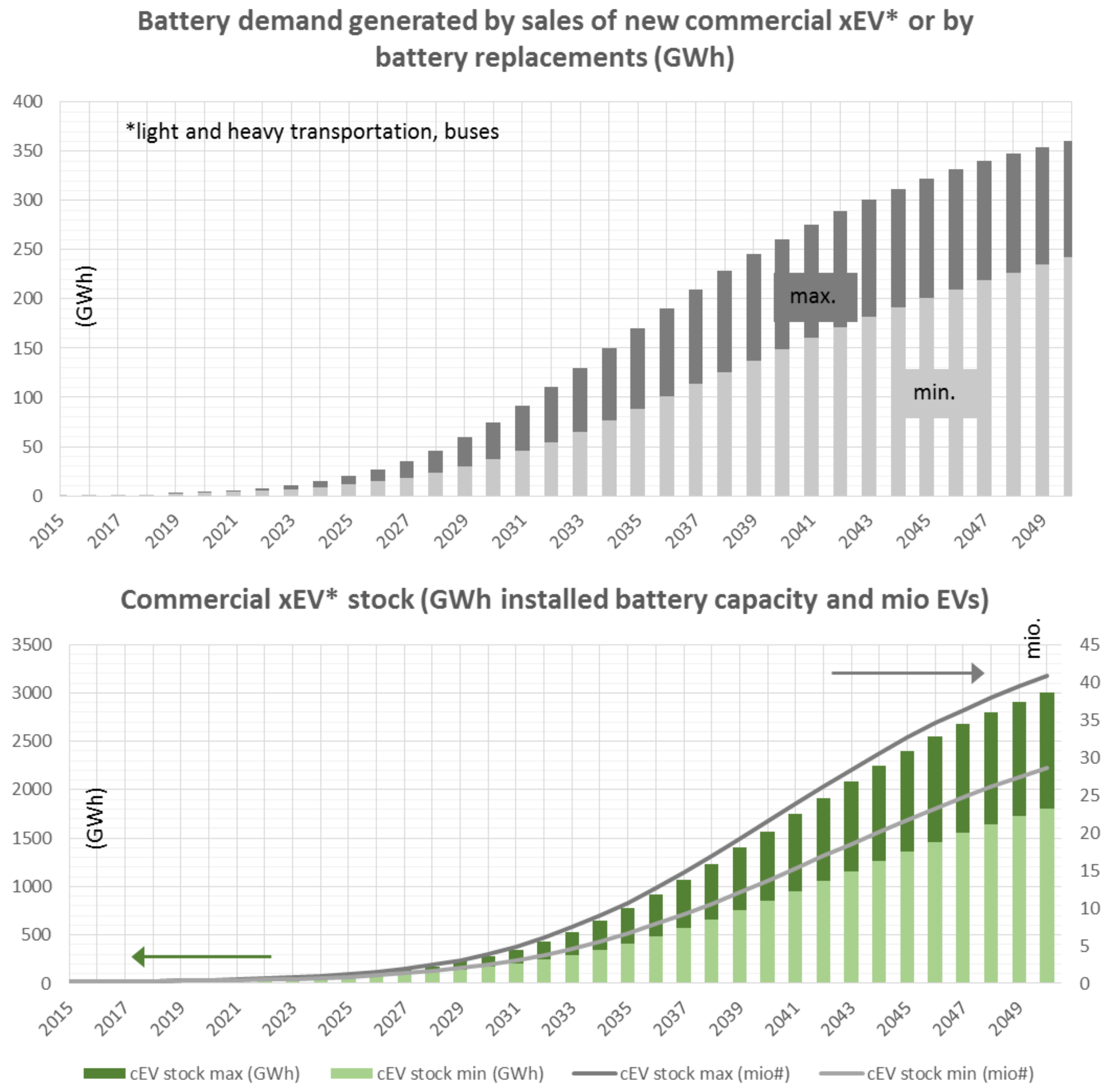


Figure 13: Battery demand generated by commercial xEV and commercial xEV stock.

2.3.4. Market stock and forecast for ESS in Europe

As discussed in Task 1, several stationary applications for batteries exist, ranging from grid support to home storage. As will be shown in section 2.4, the demand for battery capacity generated by ESS applications at present is rather small as compared to 3C and motive markets. There is no systematic registration of large-scale or small-scale stationary storage systems in the EU. Hence, the market stock and volume for respective applications can only be estimated based on indirect data.

2.3.4.1. Photovoltaic installations in the EU

Energy storage systems in combination with photovoltaic installations are one major application for batteries both for private as well as commercial purposes. Due to changes in reimbursement and subsidy policy as well as the physical capability of the energy system to buffer and process high shares of renewable energy, the use of local energy storage systems is becoming more and more popular. There is no data on the share of PV installations equipped with an energy storage system for the EU. However, on regional level, some data is available. According to [14], approximately half of the new PV systems with a peak power below 30 kW installed in Germany in 2017 have been equipped with an energy storage system (amounting to about 30,000 storage systems with a cumulative capacity of 400 MWh).

At present, the installation of storage systems is strongly coupled to new installations of PV systems. As shown in Figure 14 with data on Germany, the retrofit of existing PV installations with storage systems is however expected to contribute significantly to the demand for battery capacity in the PV segment in the future. Within the forecast shown, 50% of the storage systems sold in 2030 might be integrated into already existing PV-systems.

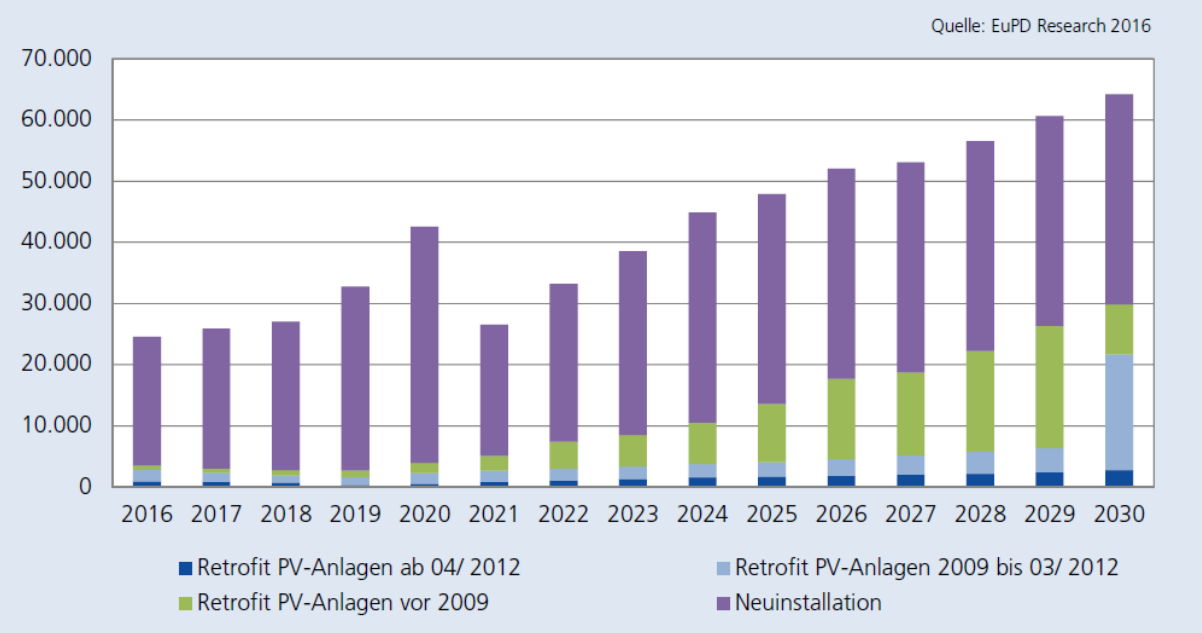


Figure 14: PV installations and retrofit of existing PV installations in Germany. Data and image taken from [15].

An overview about the yearly installed PV power (MW) in the EU28 can be found in [16]. In the years 2010 to 2012, the EU experienced a boom of PV installations, mainly driven by installations in Germany and Italy. Likely as a result of changing subsidy policies, the yearly installed PV power has since then steadily decreased in both countries. On the other hand, countries like the Netherlands and the UK have shown an increase in installations in the last years. In the forecast model applied in [16], a slight increase in new installations is expected until 2021, driven by installations in the UK and Portugal as well as other EU28 member countries, which so far do not have any considerable PV installations. Due to decreasing costs for solar panels and rather stable remuneration rates, this upward trend seems to be justified.

A more recent study in [17] projects higher growth rates of 20% to 50% for solar power installations until 2020. Main drivers are EU 2020 targets for renewable energies which still require significant expansion of renewable electricity generation capacities. The growing economic advantages of electricity self-generation and self-consumption might also trigger more and more private as well as industrial actors to install additional PV (and ESS coupled) capacity.

Particularly in the mid- to longer term, further legislative actions might influence the build-up of solar electricity generation, e.g. if solar installations or other renewable electricity generation would become mandatory for newly built homes.

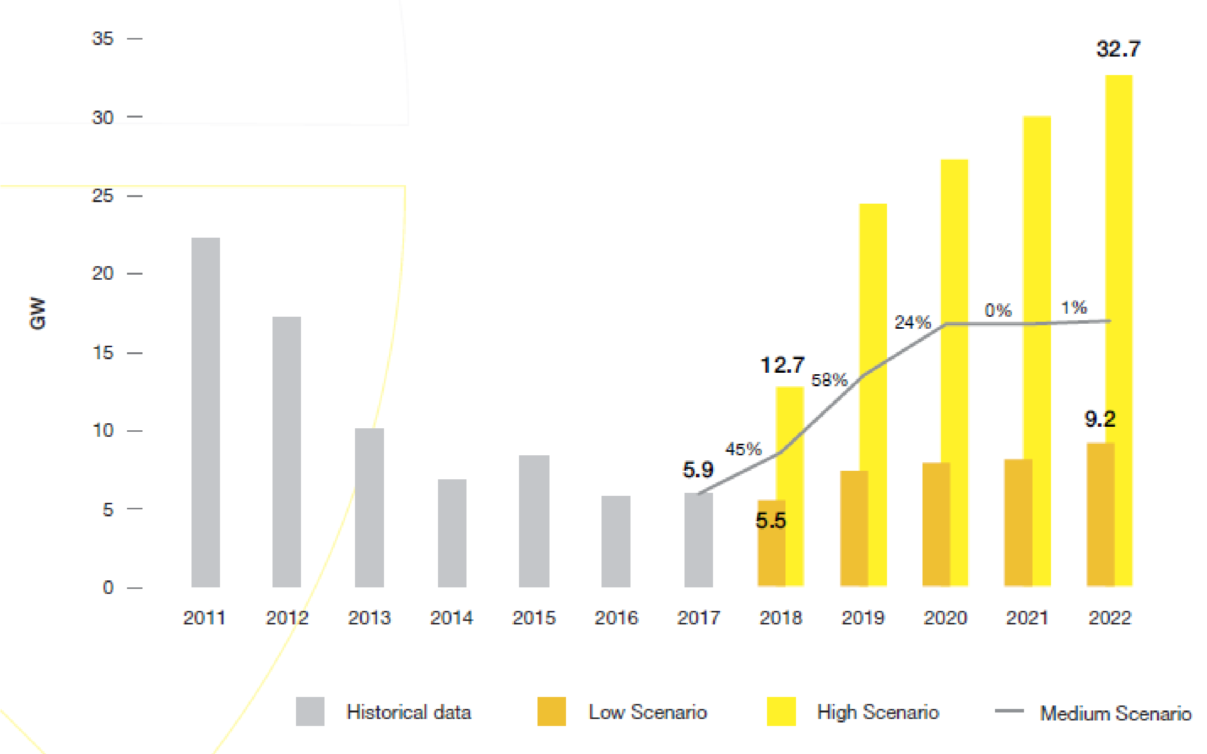


Figure 15: Market development and forecast for PV installations in the EU28. Image taken from [17].

Based on the data given in [14] for Germany, 80% of the installed PV systems (in number of units) can be attributed to small or medium sized installations (average of 10 kWp) directly feeding into the low-voltage grid. In terms of power, these systems amount to about 30% of the installed power. Projections in [17] point to an increase of the share of roof-top installed power in the next years. Suitable energy storage system feature an average battery capacity of 8 to 10 kWh [18].

Concerning installations in Europe, it can be argued that there is a trend towards smaller roof-top systems for more densely populated regions, while in particular in the southern European countries (e.g. Spain, [17]), utility scale solar parks experience a strong upward trend. Since no comprehensive data covering the whole EU is available, only a rough estimation for the demand of battery storage systems and capacity can be made.

Assuming that the number of new smaller roof-top installations (30% of power) as well as the number of new systems equipped with an ESS (50% of installations < 30 kWp) is above average for Germany as compared to the rest of the EU, the market data and forecasts given in [16] and [15] might lead to the range of demand for battery capacity as summarized in Table 8.

Year	Yearly installed PV power EU28 [16, 17] (GW)	Share of power of new installations appropriate for home ESS (%)	Share of new appropriate installations equipped with ESS (%)	Yearly number of systems equipped with ESS	Average capacity per new ESS [14] (kWh)	Yearly demand for battery capacity (MWh)
2017	6 - 8	25	30	45000 - 62000	8.5	400 - 500
2018	9 - 12	24	33	65000 - 90000	9.5	600 - 800
2020	10 - 20	23	40	75000 - 150000	11	800 - 1500

Table 8: Estimation of the demand for battery capacity generated by PV-home ESS systems based on [15] and [16] for the EU28.

Note, that this estimation does not take into account ESS installations for larger scale (>30 kWp) PV-installations.

2.3.4.2. Wind Turbine installations in the EU

Similar to section 2.3.4.1 for PV installations, data and forecasts for wind turbine power installations in the EU28 can be found in [16]. In contrast to PV installations, wind turbine power is almost exclusively attributed to larger scale wind parks delivering power exclusively to the power grid. It can be assumed that the use of small scale ESS for the optimization of private energy consumption is therefore not driven by wind power installations.

Still, the ongoing installation of wind turbine power in the EU28 might become a driver for large scale decentralized energy storage systems, however there is no market data available, which would allow for a battery demand forecast.

2.3.4.3. Large battery ESS projects

The DOE Global Energy Storage Database [19] lists several utility scale ESS projects around the world. Figure 16 shows the cumulated storage capacity (installed stock) for the EU28. Of the 450 MWh capacity installed until 2018 in total, 340 MWh were installed in Germany and 80 MWh in the UK. Since this is not an exhaustive list, it can be considered as lower boundary for the installed stock.

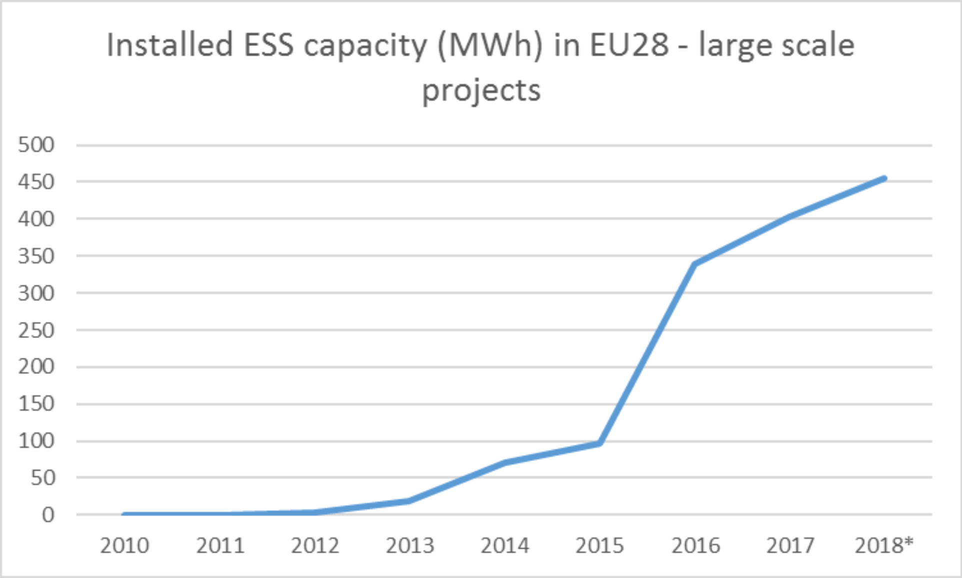


Figure 16: Installed ESS capacity (stock) in large scale projects in EU28. A ratio of 1:1 with respect to installed power and installed energy content (capacity) was assumed [19].

Table 9 gives an overview about larger scale (~MWh) stationary storage systems installed in the EU in 2017 [16]. 80% of these installations are categorized as substation storage, 6% relate to frequency stabilization, 5% to storage of wind-generated energy and 1% to storage of PV-generated energy.

Note that most of these installations are prototype or test facilities, which does not allow to use this split between applications as a template for future market developments. The total installed capacity of 340 MWh in 2017 suggests that the market volume of utility scale ESS is of the same order of magnitude as that of home storage. Note that the installed capacity for 2017 in [19] is only 65 MWh contradicting the data given in [16]. It is however not stated in [16] whether the listed ESS projects are still in construction or already operational.

Purpose	Capacity (MWh)
Wind	16.2
PV	3.1
Frequency	22
Substation	270.4
Other	29.9
All (sum)	**341.6**

Table 9: Utility scale ESS installations in 2017 [16].

2.3.4.4. Forecast ESS sales and stock EU28

The forecast model includes the market development of home storage ESS, utility scale ESS for inner day shift of fluctuating power generation and utility scale ESS for other grid stabilization purposes.

2.3.4.4.1. Minimum and maximum scenarios

For the forecast model it was assumed that both a higher demand for electricity generated by charging of electric vehicles as well as a higher share of fluctuating renewable electricity will necessitate a certain energy storage capacity to stabilize the grid and compensate for the mismatch of renewables production and electricity demand. For inner day peak shift (primarily PV generated electricity) or possibly intra-day peak shift (both wind and PV generated electricity), battery-based storage systems might be one option to fulfil this task.

Accordingly, minimum and maximum scenarios for the demand for ESS were derived from minimum and maximum additional electricity demand resulting from xEV charging[1] (see Figure 17 and min./max. market penetration scenarios for xEV in section 2.3.3.3) and by the rate of build-up of additional renewable and fluctuating electricity generation capacity (see Figure 18 in next section).

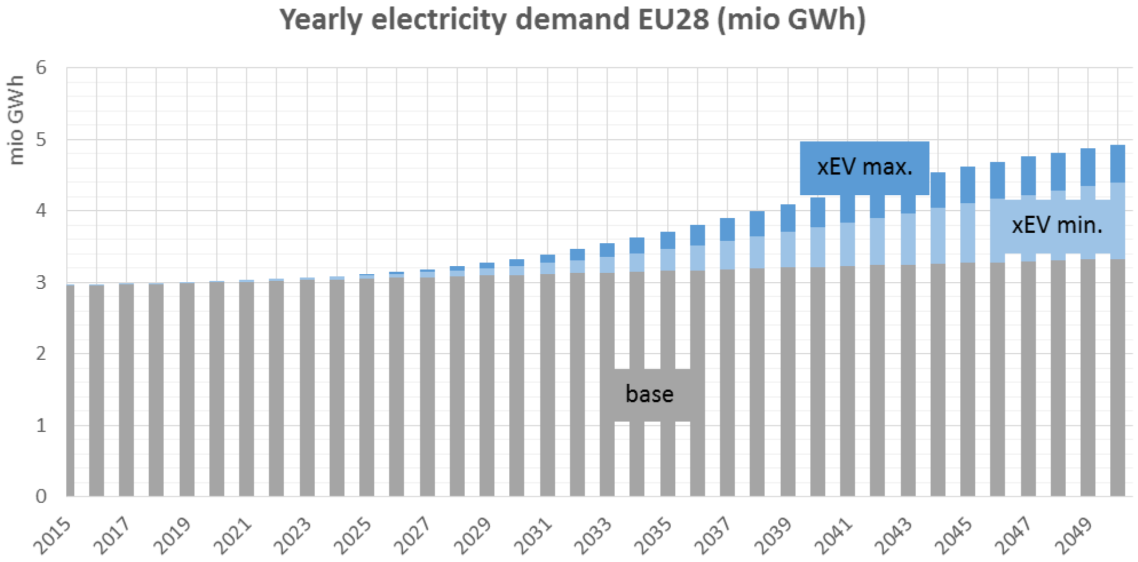


Figure 17: Yearly electricity demand in the EU28 and additional demand resulting from EV charging.

Home storage systems were considered separately. For home storage systems, minimum and maximum scenarios result from different growth rates of PV installations and different shares of PV systems equipped with an ESS.

2.3.4.4.2. Assumptions

The data presented in sections 2.3.4.1, 2.3.4.2 and 2.3.4.3 was used as an input for the forecast model on large scale and home ESS. EU wide sales numbers and growth rates for PV coupled home storage systems were extrapolated from the data presented in section 2.3.4.1.

In a broader picture, the generation of electricity by renewable and fluctuating sources necessitates a certain flexibility of the grid. Today, daily imbalances are met primarily by

---

[1] Assuming yearly travelled distances of 12,000 km (0.18 kWh/km) for passenger vehicles, 20,000 (0.25 kWh/km) and 65,000 km (1.2 kWh/km) for light and heavy commercial vehicles and 45,000 km (0.7 kWh/km) for buses. Combined charger / battery efficiency of 80%.

dispatching conventional power plants, e.g. after sunset. For the model it was assumed that the ability to match electricity demand and generation will not be possible by the deployment of highly flexible fossil-fuel based power plants alone. Above a certain threshold of the share of fluctuating electricity sources in the grid, some ESS buffer capacity might be necessary to efficiently use renewables and avoid high over capacities. To serve a possible inner-day mismatch of generation and demand, a necessary buffer capacity of 40% / 50% (min./max.) of the daily electrical energy generated by renewables was assumed.

EU 2030 targets [20, 21] for the share of renewable electricity generation as well as other forecasts were used as a benchmark for the min./max. scenarios (see Figure 18).

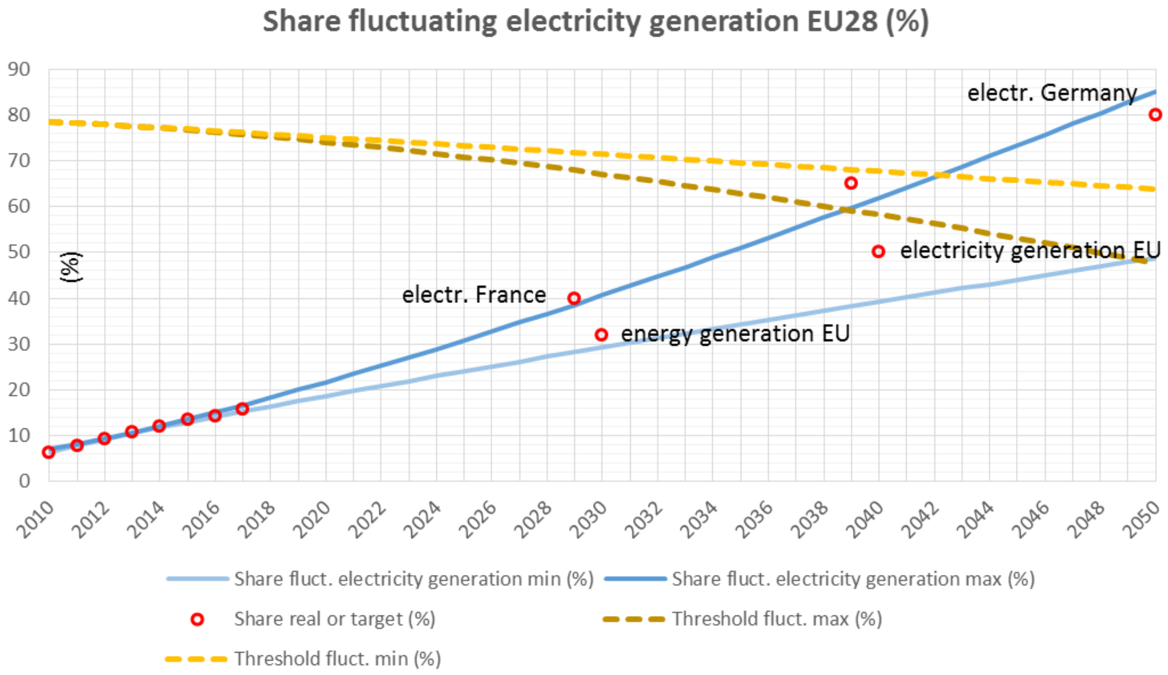


Figure 18: Share of fluctuating sources in the electricity generation mix of the EU28 and forecast model as well as targets for renewable electricity and energy set on national or European level and other studies and threshold share requiring energy storage systems [22–29].

Besides compensating for an inner-day mismatch between electricity generation and demand, battery storage systems can also offer other services for the electricity system, e.g. regulation of grid load and power line load, provision of balancing energy and others. In accordance to the data presented in section 2.3.4.3, a forward projection of the market growth of utility scale ESS was chosen to account for these other applications.

A lifetime of 20 years with a replacement rate of 5% was assumed for home ESS and a lifetime of 20 years with a battery replacement rate of 10% within this lifetime was assumed for large scale ESS (for further discussion see section 2.7.1.4 and task 6). System capacities were modelled by a power law (see section 2.7.1.3) based on present-day values. The assumptions for the market model are summarized in Table 10 and Table 11.

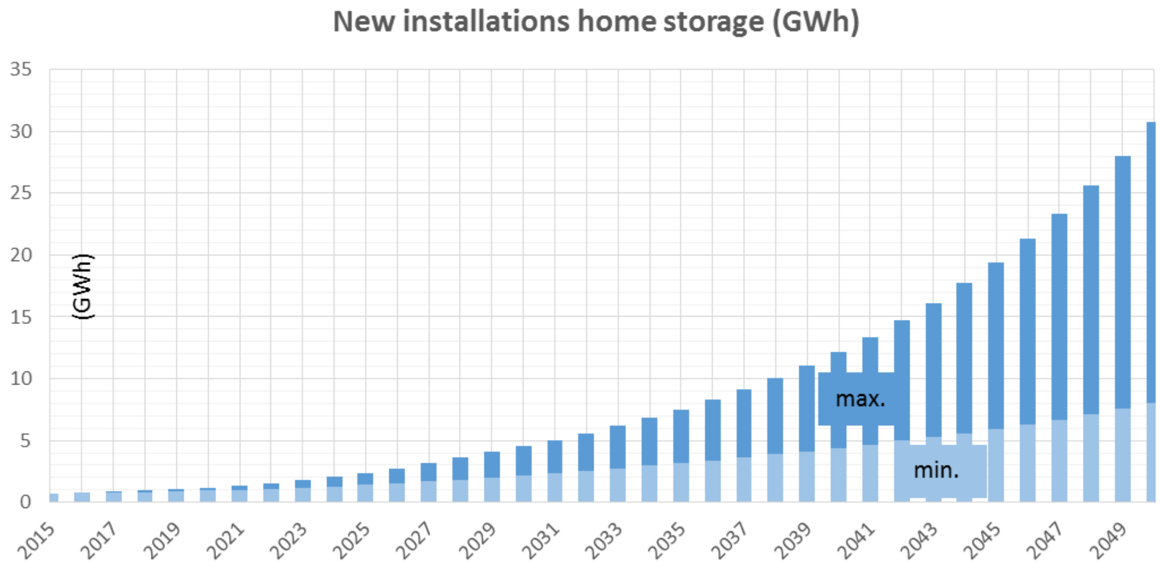
Parameter	**Min. value**	**Max. value**
Number of new rooftop PV installations EU28, 2017	190000	
Yearly growth rate of new rooftop PV installations EU28 until 2050	4%	7%
Share of new rooftop PV installations equipped with ESS 2014 / 2050	30% / 70%	30% / 90%
Utility scale ESS battery capacity installations EU28, 2017	500 MWh	
Daily energy storage requirements due to high share of fluctuating electricity generation: Share of daily fluctuating electricity to be stored in ESS.	40%	50%

Table 10: Assumptions and input parameters for the ESS market and growth model.

Parameter	**Value**
Home ESS lifetime	20 years
Large scale ESS lifetime	20 years
Home ESS battery replacement rate	5%
Large scale ESS battery replacement rate	10%

Table 11: Assumptions and input parameters for the ESS battery demand model.

The results of these calculations are shown in Figure 19 and Figure 20.



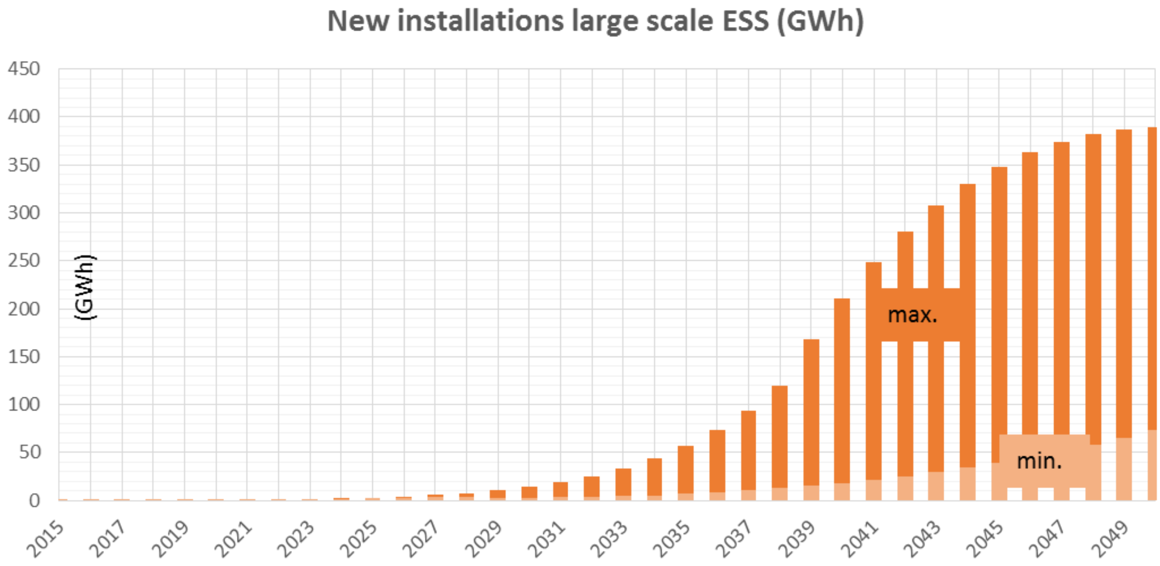


Figure 19: Forecast home storage and large scale ESS installations until 2050.

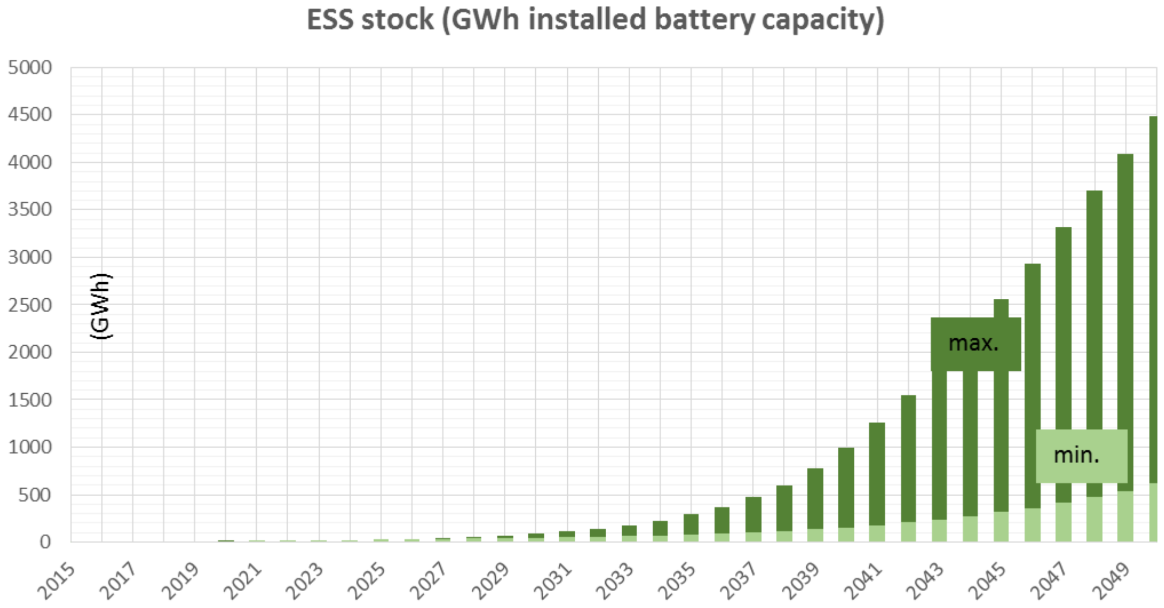


Figure 20: Forecast ESS capacity stock until 2050.

2.3.5. Summary of the market sales forecast and estimation of the future battery stock

As shown in sections 2.3.2 and 2.3.4, several drivers exist for the application of battery storage systems in stationary and motive applications. While the demand for battery capacity generated by BEV and PHEV passenger cars was on the level of several GWh for 2017, the ESS markets might still be below the 1 GWh mark in the EU.

With respect to the growth rates for the sales of xEV and ESS (see sections 2.3.3.3 and 2.3.4.2), forecasts for the total amount of new installations (including replacements) of batteries in the EU28 are shown in Figure 21.

It can be expected that the demand for battery capacity in the EU28 will amount to 30 - 35 GWh in 2020, 180 - 230 GWh in 2025 and 500 - 800 GWh in 2030. The short-term demand will mainly be driven by passenger electric vehicles. Higher shares resulting from commercial vehicles and ESS can be expected in the mid- and long-term.

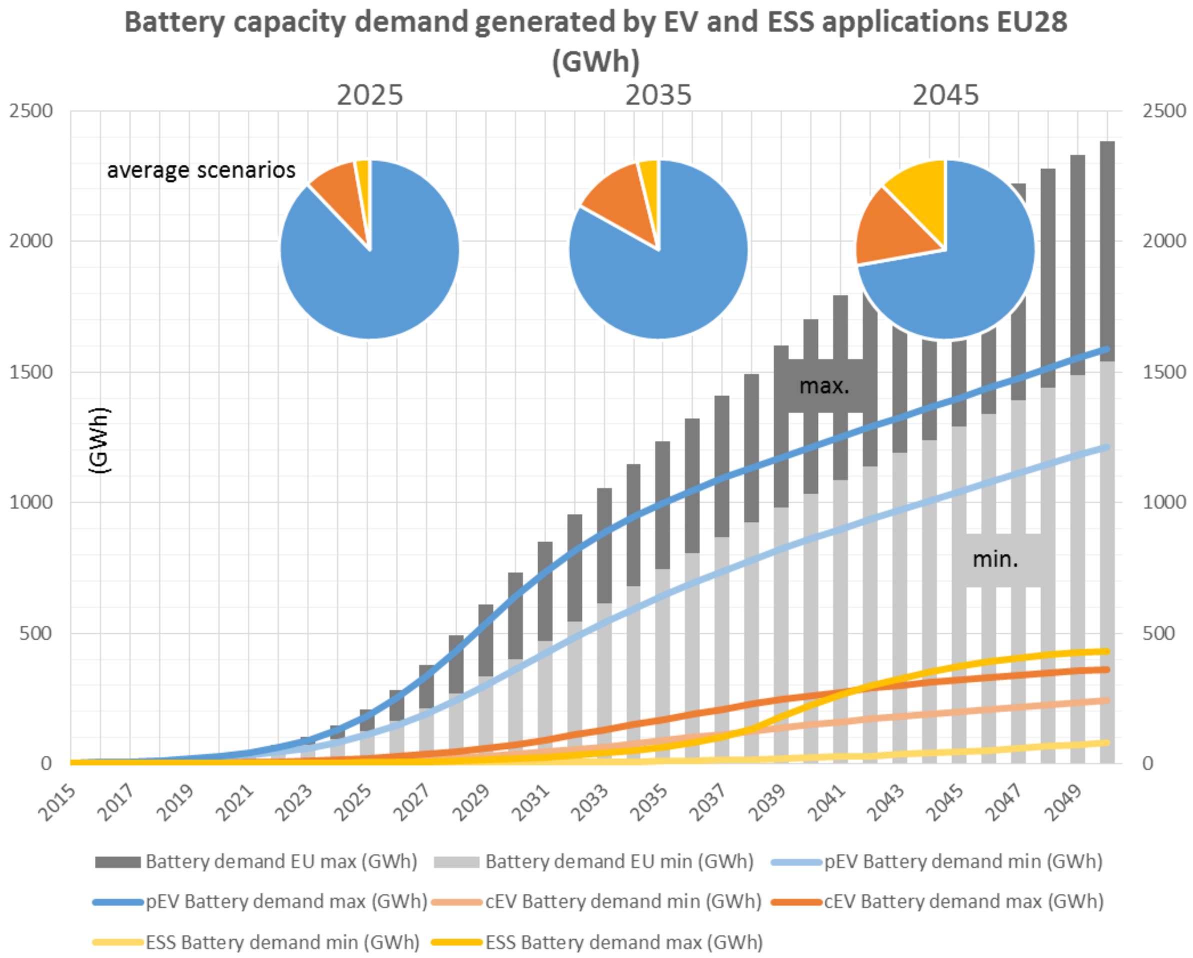


Figure 21: Battery capacity demand derived from new installations in xEV (passenger EV, commercial EV) or ESS and replacements in existing systems in the EU28.

It should be noted that the shown battery capacity demand scenarios are rather insensitive against changes in the set of input system lifetimes (1) and battery replacement rates (2). As discussed in the previous sections, rather long system lifetimes and accordingly high battery replacement rates were assumed. From the perspective of batteries designed to deliver a certain service, e.g. a fixed energy throughput over their lifetime or a certain driving range for electric vehicles, the total capacity needed is not heavily influenced by a possible mismatch of system lifetime and battery lifetime (replacement rate) in the model. In other words: the model results in units of GWh are the same for high vehicle lifetimes and high battery replacement rates or short vehicle lifetimes and low battery replacement rates.

Hence, although no sufficient information on system lifetimes (strongly depending on purchasing and reselling behaviour of end-customers) are available yet, the applied model can give estimates on battery capacity demand based on the assumptions in section 2.7.1.4.

The resulting calculated battery decommissions are given in Figure 22.

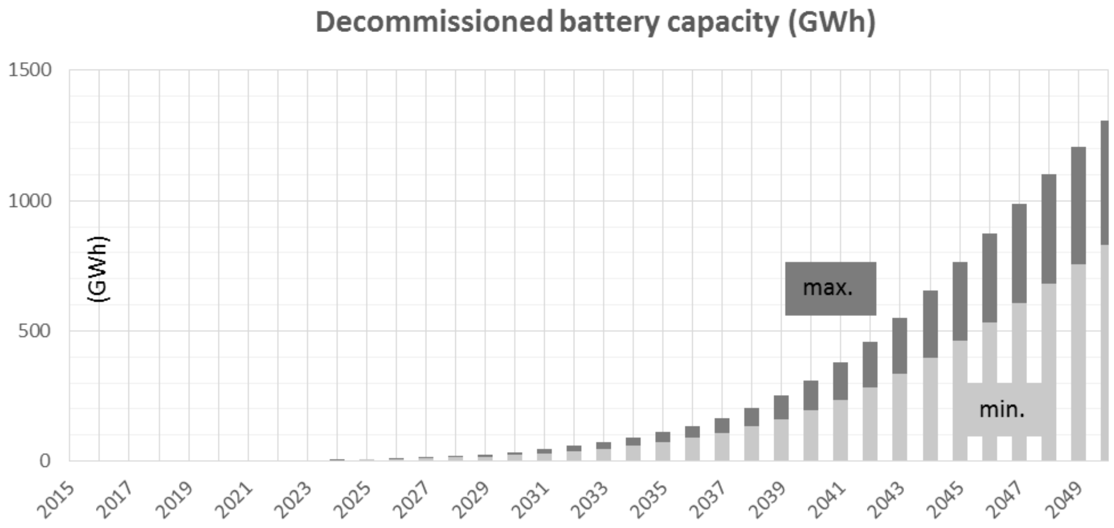


Figure 22: Decommission of batteries due to replacements or due to the end of life of applications.

2.4. Market trends

2.4.1. General objective of subtask 2.3 and approach

The following chapter provides a comprehensive market overview on global battery sales, demand, and players. As one potential technology for meeting the market demand, lithium-ion batteries are discussed in this section in detail. Starting with the market development of LIB between 2010 to 2017, scenarios until 2025 to 2030 are presented including a meta-analysis of several most recent market reports (e.g. [30–39]). Step by step, the regional markets and markets by applications will be specified.

2.4.2. Market drivers and CO2 legislation [40]

Climate and energy policies are main drivers for the energy future and are expected to lead to an increasing demand for energy storage in the mid and long term (see Figure 23): According to the European Union´s decarbonization objective, a reduction of greenhouse gas (GHG) emissions to 80 – 95 % below 1990 levels should be achieved by 2050.

In particular, for the transport sector currently no full decarbonisation is foreseen [41], even in the longer term (other sectors have to compensate with higher GHG reductions). The overall reduction achieved in the transport sector by 2050 is only around 60 % below 1990 levels. The increasing trend in emissions seen over the past 20 years is expected to reverse by the CO_2 legislation. From 2020 on, the fleet average to be achieved by all new cars is 95 grams of CO_2 per kilometer (compared to 130 g/km in 2015).

Many other governments world-wide have specified CO_2 emission targets and are striving towards a low carbon economy. Particularly in the field of passenger and commercial vehicles, fuel consumption and emission targets have been installed, which significantly drive the introduction of battery or fuel cell powered electric vehicles. Among these emission policies, the targets set by the EU are among the most ambitious (see Table 12). Meeting them will require a significant share of electric vehicles.

	Japan	China	Korea	USA	EU
Fuel consumption target 2020, (l/100 km)	4.9	5	4.2	5.8	4.1
CO_2-emission target 2020, (g/km)	115	117	97	136	95 (until 2021)
CO_2-emission target 2025, (g/km)	-	94	-	91	81

Table 12: Overview about fuel consumption and CO_2-emission targets for passenger vehicles of the EU and other countries leading battery and electric mobility markets [42].

In this context, electric mobility is gaining importance since electric vehicles, especially plug-in hybrid and full battery electric vehicles can help to achieve or fulfill these limits due to improved CO_2 footprints compared to conventional cars. However, for low CO_2 footprints over the lifetime of electric cars, a high share of “low carbon” renewable energy sources (RES) in the energy mix is needed and important (Figure 23, left side).

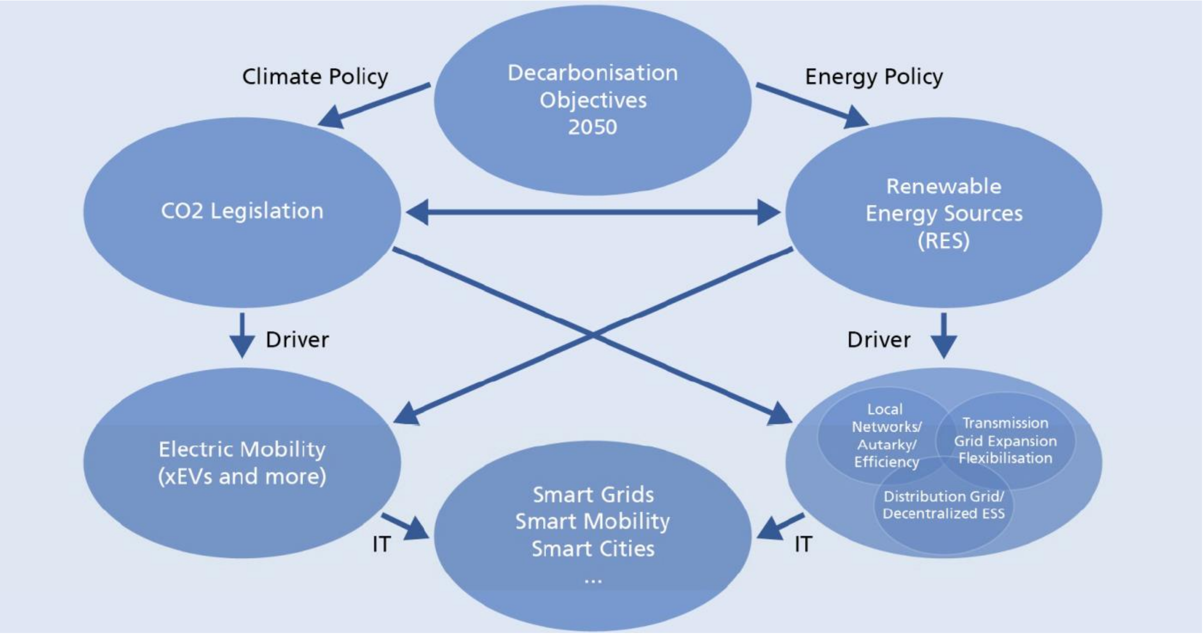


Figure 23: Climate and energy policies as drivers for future energy storage demand [40].

The EU Energy Roadmap 2050 [43, 44] has shown across six scenarios that the decarbonization goal can be achieved if the share of renewable energy sources (RES) among the power generation capacity is high (> 60 % until 2050) for all scenarios. Especially for the high RES scenario the share of fluctuating energy generation (wind, photovoltaic – PV) is the strongest which has to be balanced. Grid expansion and/or flexibilization measures (e.g. demand side management, power to gas, and vehicle to grid besides stationary battery storage) are potential solutions. Thus, the high RES scenario is the most interesting scenario with respect to a potential future demand for energy storage solutions (ESS) on local, distribution and transmission grid levels (Figure 23, right side). In order to have a significant GHG reduction with EVs it will also be important to achieve the RES targets.

2.4.3. The developing battery market

The total annual battery market is currently on the level of 45-60 billion Euro representing approximately 400-500 GWh (including Lead-acid, Lithium-Ion and other batteries) [45]. Lithium-ion batteries (LIB) have succeeded because of their high gravimetric and volumetric energy densities and have a market share of about a third in terms of value among the whole battery market. The growth is driven by the decreasing cell costs of less than 150 €/kWh for a standard cylindrical cell (lowest prices) approaching the 100 €/kWh mark in the next years. This cost degression is result of increasing capacity demand and production and thus represents economy of scale effects.

Although the LIB market is drastically growing with annual growth rates of up to 30 percent on average (in terms of battery capacity demand), the dominating battery technology in terms of capacity is still lead-acid, representing about 90 percent of the global demand in volume around 2010 and 80 percent in 2017.

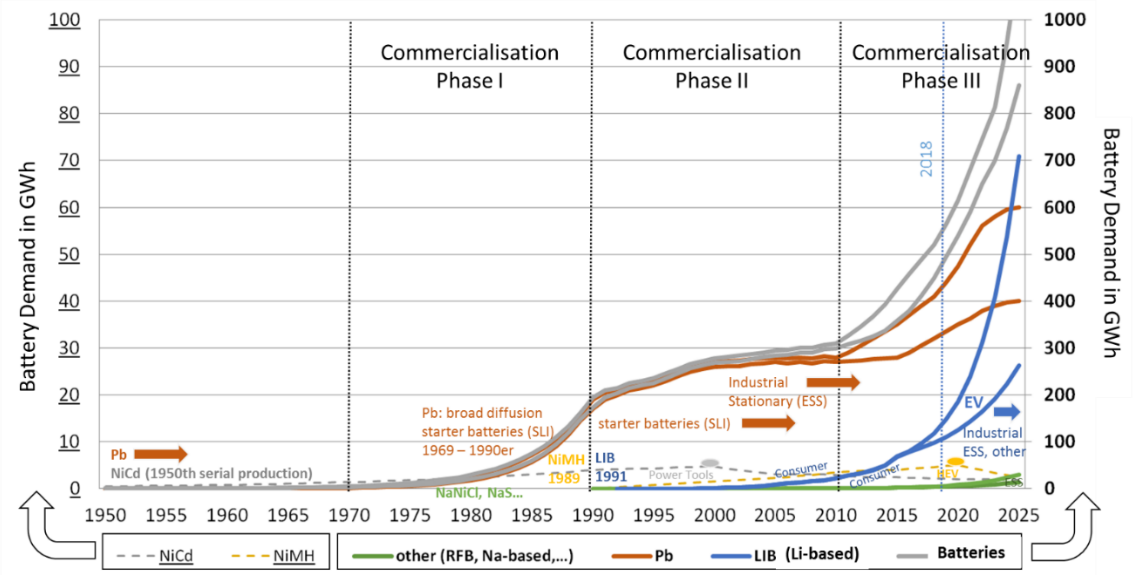


Figure 24: Historical development of the global battery demand in GWh (left axis for NiCd, NiMH, right axis for all other battery types; grey: total battery demand) [46].

Other mature battery technologies like NiCd (still partly used in power tools) and NiMH (still used in hybrid electric vehicles, HEV) are slowly declining. The diversification of future battery applications however will also broaden the range of battery technologies. Emerging technologies like Na-based, Metal-Sulfur or Redox Flow batteries are developing and may lead to attractive solutions e.g. with respect to cost and resource availability. However, due to very strict requirements on volumetric energy densities, these technologies are expected to be relevant for stationary or other special markets and less relevant for the passenger electric vehicle market. In general, each technology has its own strengths and weaknesses and none of them can satisfy all user demands. Hence, a broader application-specific technology portfolio is urgently needed in order to provide alternative technology solutions in the future.

Based on an expected high dynamic development of the global LIB demand, the TWh level will likely be reached before 2030 and grow further after 2030. It is therefore very likely that LIB will soon transform into the dominating energy storage technology.

Figure 25 shows three different scenarios for the global demand for LIB between 2010 and 2030 (green curves) along with global production capacities (orange and blue curve).[45] While at the beginning of the decade, the demand and sales numbers followed the medium growth rate scenario (trend), the market has been approaching the high growth rate scenario in the last years. This is mainly result of the strong engagement of politics and respective regulation and subsidy programs for electric mobility. As can be seen from the graph, the share of demand generated by motive applications is expected to significantly grow in the next years and might account for more than 75% of the total LIB demand by 2025.

To face this increasing demand for LIB cells accordingly, production capacities need to be build up in the near future. Based on the currently existing cell production capacities and the global announcements from established and new cell producers until 2025, the LIB cell production capacities (blue line in Figure 25) have been identified. Compared to 15 GWh added production capacity between 2013 and 2016, around 50 GWh will be added annually in the next years leading to around 700 GWh production capacities until 2025 (in the optimistic case, see blue line in Figure 25). The announcements include established players such as Panasonic (JP), LG Chem (KR), Samsung (KR), SKI (KR), BYD (CN), Lishen (CN), CATL (CN), CALB (CN), OPTIMUM (CN) and several further Chinese cell producers. Also, new players such as BMZ/TerraE (DE), Northvolt (SW), Boston Energy (US, AU), Energy Absolute (Thailand), are included, while accounting for the different stages of expansion [32, 39].

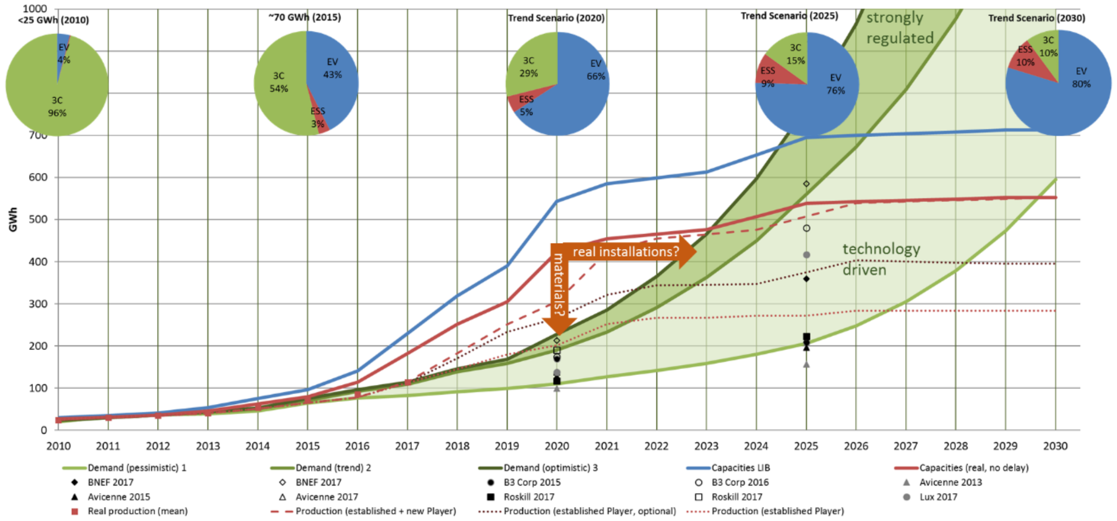


Figure 25: Global LIB cell production capacities vs. demand 2010 to 2030 [45].

2.4.4. Battery markets by application

Diversification of applications for batteries

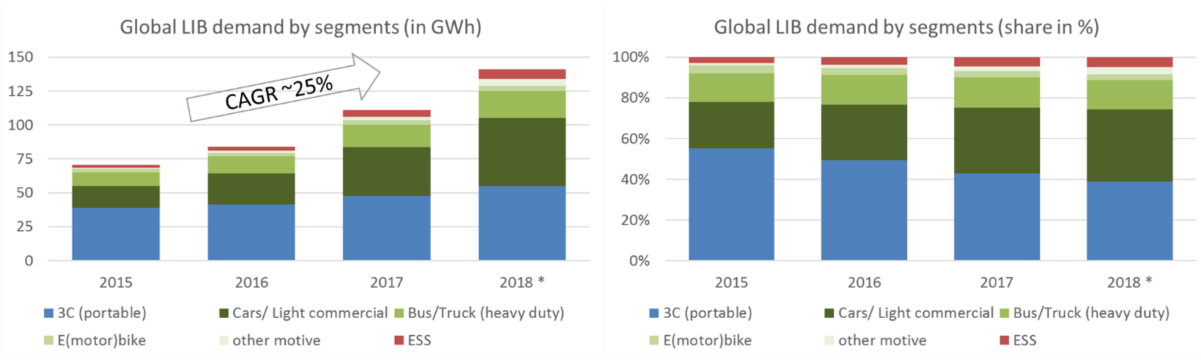
The above described global developments of battery demand and production strongly concern high-energy lithium-ion batteries with the cell chemistries NMC, NCA (Ni-rich and Co-reduced cathodes) and Si/C (high capacity Si/C anodes with 5-10% or higher Si content) and cell formats cylindrical (e.g. 21700), large pouch or prismatic cells. The target is to develop and produce cells with improved gravimetric and volumetric energy densities and reduced costs in order to meet the requirements of the automotive industry. Electric passenger cars are driving the demand and thus the development of the battery technology. The resulting optimized and cost reduced batteries define the benchmark today and in the future.

LIB demand by applications

In Figure 26, the global LIB demand is broken down to the three main sectors for battery demand, which can be characterised each having different profiles of requirement:

- electric mobility or electric vehicles (EV, including e.g. passenger cars, light commercial vehicles, buses, trucks, scooters, ebikes, etc.),
- stationary energy storage systems (ESS), and
- portable devices (3C – Computer, Communication, Consumer).

Since their market introduction in the early 1990s, the LIB cell demand developed to almost 25 GWh dominantly resulting from portable devices. In 2015 the cell demand of about 70 GWh was distributed already almost 50:50 between 3C and EV applications.



Main segmentation:
3C: computer, communication, consumer = batteries for portables
Motive: xEV cars, commercial, trucks, busses, (motor)bikes, industrial mobility = batteries for traction
ESS: stationary applications from small kWh home solar to above MWh installations = batteries for stationary applications

Figure 26: Global LIB demand (in GWh and share in %) by segment [46].

Since 2015, the global LIB demand has increased with compound annual growth rates (CAGR) of ~25% from about 70 GWh to about 110 GWh in 2017. The market for electric vehicles currently grows with 30-40% (and more depending on the application and region) and a diversification in applications (e.g. buses, trucks, other light to heavy commercial vehicles, marine applications, drones, etc.) can be observed.

With the diversification of future markets and applications, cost sensitive markets will arise for which optimized high-energy and cost reduced automotive cells of certain cell formats will be used. However, also applications with stronger requirements on long lifetime, high cycle life, fast charging capability, safety, etc. will emerge and diffuse, where cost is not the most relevant factor and other battery technologies (i.e. cell chemistries, formats) can provide a unique selling proposition and hence lead to a product differentiation.

2.4.4.1. LIB markets for 3C applications

Portable devices (3C) have been the main applications for LIB cells in the past. Power tools, medical devices and wearables are expected to be products with an emerging future market for small LIB cells but with enormous quantities. The price per kWh does not play a dominating role for these applications. As far as charging is concerned, technologies such as energy harvesting and wireless charging are expected to be introduced in the future. For many markets and products such as household devices, garden, cleaning, power tools, other mobile leisure applications, etc. today mostly cylindrical LIB cells of the format 18650 or smaller pouch type cells are used. With the introduction of 21700 cells also larger cylindrical cells become available now and are expected to be used in such applications. Although different specific cell chemistries might be suitable, it can be stated that the 3C segment is expected to lead to a comparably small battery capacity demand compared to the EV segment and will not be the limiting segment with respect to the risk of resource dependencies. From the perspective of recycling however, resource issues might be more significant for smaller devices as collection rates are smaller as compared to industrial batteries, and batteries may more easily end up in wrong waste streams, limiting the amount of resources that may be recovered.

In the next few years, growth rates of about 5 to 10 percent are expected for the 3C markets, while laptop battery demand is developing at lower growth rates and power tools, medical devices, etc. are supporting the growth rates for the battery demand.

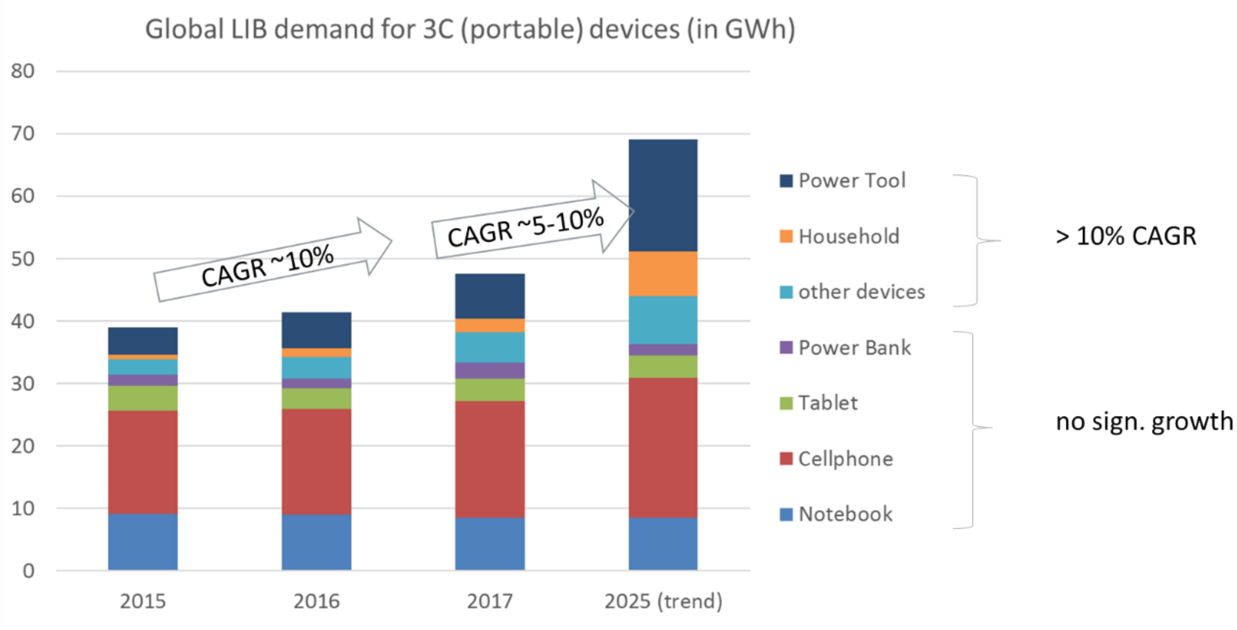


Figure 27: Demand and growth of the 3C LIB market [46].

2.4.4.2. LIB markets for stationary (ESS) applications

Stationary energy storage systems (ESS) can be divided into different size classes with regard to the capacity and charging times. Both parameters decide about the application area (e.g. small PV storage at home, peak load to long-term storage) [47]. Beyond that, the price per stored kWh over the lifetime is the economic key factor (as synthesized by the LCOE: levelized cost of energy). In contrast, gravimetric and volumetric energy densities play a subordinate role. Due to that, lead-acid batteries were often used as storage technology for off- and on-grid storage. Currently, LIB is being established for commercial use and meanwhile reach an annual demand of some few GWh. Other electrochemical storage technologies such as sodium-sulfur batteries are still used but the demand for LIB is strongly increasing for ESS. It is expected that 2nd life concepts for batteries that had their first life in electric vehicles will gain importance together with market diffusion in the EV segment, as the requirements on the batteries are less demanding in the ESS segment (e.g. maximum currents). This however will require the development of according business models, standardization, etc. The much broader available technology portfolio for ESS applications, the use of 2nd life batteries and the fact that electric vehicle batteries that are connected to the grid on a large scale with higher market diffusion can be regarded as stationary storage systems as well (vehicle to grid V2G, grid to vehicle G2V) help to reduce the risk of technological and resource dependencies in the future.

The market for stationary storage applications (ESS) is experiencing growth rates of 20 to 30 percent depending on individual market forecasts (in the last years CAGR have even been on the level of 60%, but decrease with increasing size of the market, see Figure 28).

The market is currently on the level of few GWh including applications from smaller PV storage systems of 5-10 kWh to larger industrial and grid connected installations for self-consumption, peak shaving, etc. on the MWh level. Regarding these growth rates, LIB for ESS applications rapidly gain importance as decentral storage solutions compared to the currently dominating central pumped hydro storage (PHS). Forecasts to 2025 differ, but expect an ESS LIB demand between 20-50 GWh (partially higher, e.g. in [35]) but all forecasts identify high growth rates.

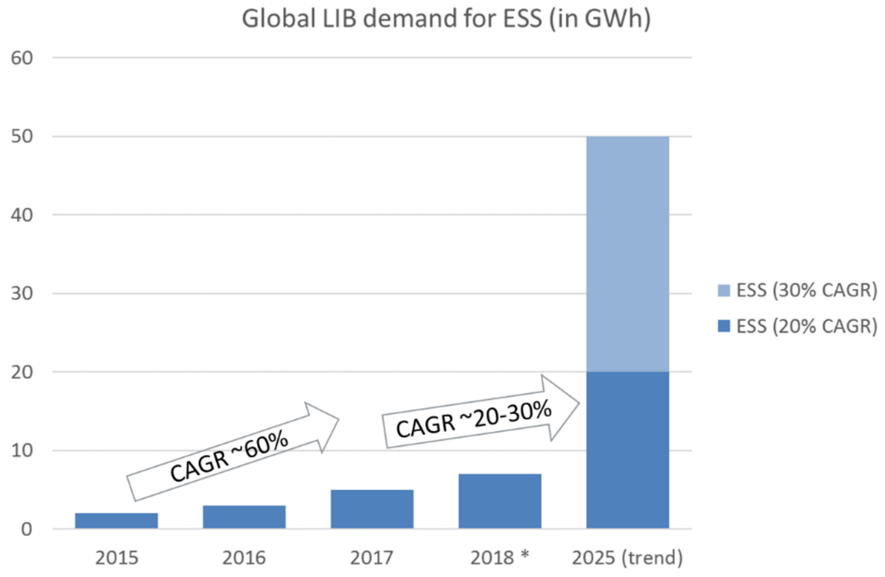


Figure 28: Demand and growth of the ESS LIB market [46].

2.4.4.3. LIB markets for electric vehicle applications

One of the biggest challenges for batteries for electric vehicles (EV, including electric cars, buses, trucks, etc.) apart from their price, is the increase of their volumetric and gravimetric energy densities. The volumetric energy density is even more important for OEM due to restricted and fixed space and location of the battery in an electric vehicle. A very relevant parameter of a battery is its charging and discharging power, in particular in continuous operation. It determines the fast-charging capability, which is an important argument in the use and the establishment of the market. At the same time, this sets limits to the high-performance operation (e.g. vehicle acceleration) since the battery might be derated to protect it from damage. This illustrates the conflicting effect of different parameters on the battery lifetime. Price, volume, weight, and thus charge density as well as charge/discharge rate in terms of usage and durability are the most urgent challenges for battery manufacturers.

The market for EV batteries is currently at the level of about 50 GWh (including electric passenger cars, busses, trucks, ebikes, scooter, forklifts, etc.). Growth rates are at 20 to 40 percent and the demand for EV batteries will lead to a LIB demand share of about 66 % in 2020, 76 % until 2025 and 80 % or higher in the long term. Electric passenger cars (BEV and

PHEV) define the by far largest market within the EV segment and are clearly driving the technology development of high energy Lithium-Ion or Lithium-based batteries in the future.

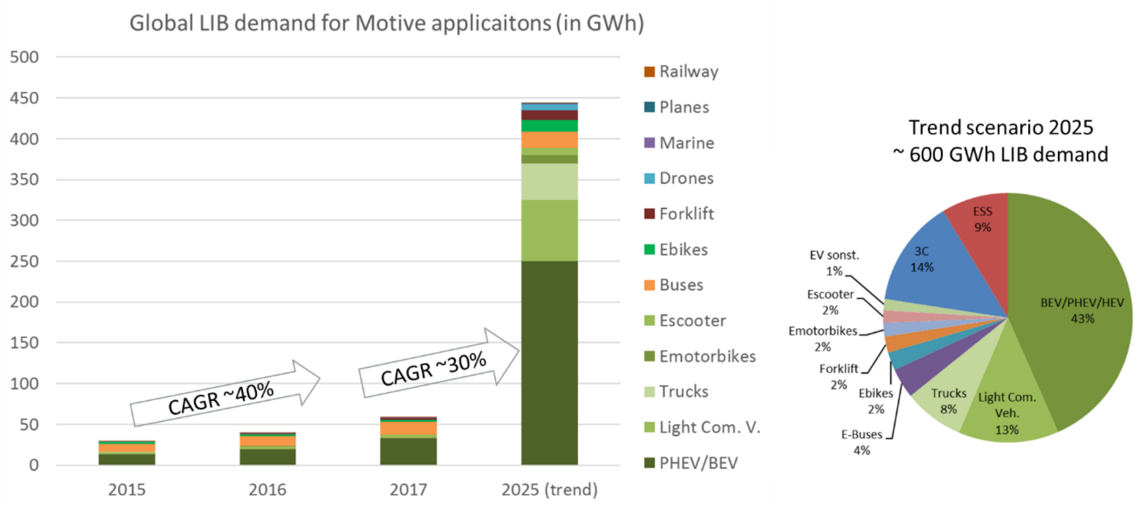


Figure 29: Demand and growth of the EV LIB market [46].

Other motive (or stationary or portable) markets / applications besides the highly competitive electric passenger cars therefore can offer interesting growth markets also for smaller cell producers beyond the large Japanese, Korean and Chinese cell producers. These markets or applications very often define concrete requirements for the battery performance, they require an in depth understanding and design from the cell chemistry, format to the module/pack and system integration and they still vary strongly by region and are connected to individual system integrators or OEM. This is because each technology has its own strengths and weaknesses and none of them can satisfy all user/application requirements. Hence, a broader application specific technology portfolio is even urgently needed in order to provide alternative, individual technology solutions for these emerging markets/applications.

2.4.5. Market channels and production structure

2.4.5.1. Global production capacities and major players

Since their commercialization in the 1990s, LIB have predominantly been produced by Japanese and Korean companies. Driven by the Chinese government, particularly cell producers but also companies covering other steps of the LIB value creation chain have been established in China. Due to a policy of simultaneous support for LIB production as well as for application markets and due to an extensive subsidy scheme, a large share of LIB production capacity is located in China today.

Figure 30, Figure 31, Figure 32 and Figure 33 show the global LIB production capacities of major cell producers in 2018 as well as forecasts for 2020, 2025 and 2030 respectively [48]. The data is based on announcements made by the cell producers (until November 2018). As discussed in section 2.4.3, the actual time-frame for the implementation of the capacity expansions is often delayed with respect to the original announcements. Hence, minimum and maximum values for the production capacities are given.

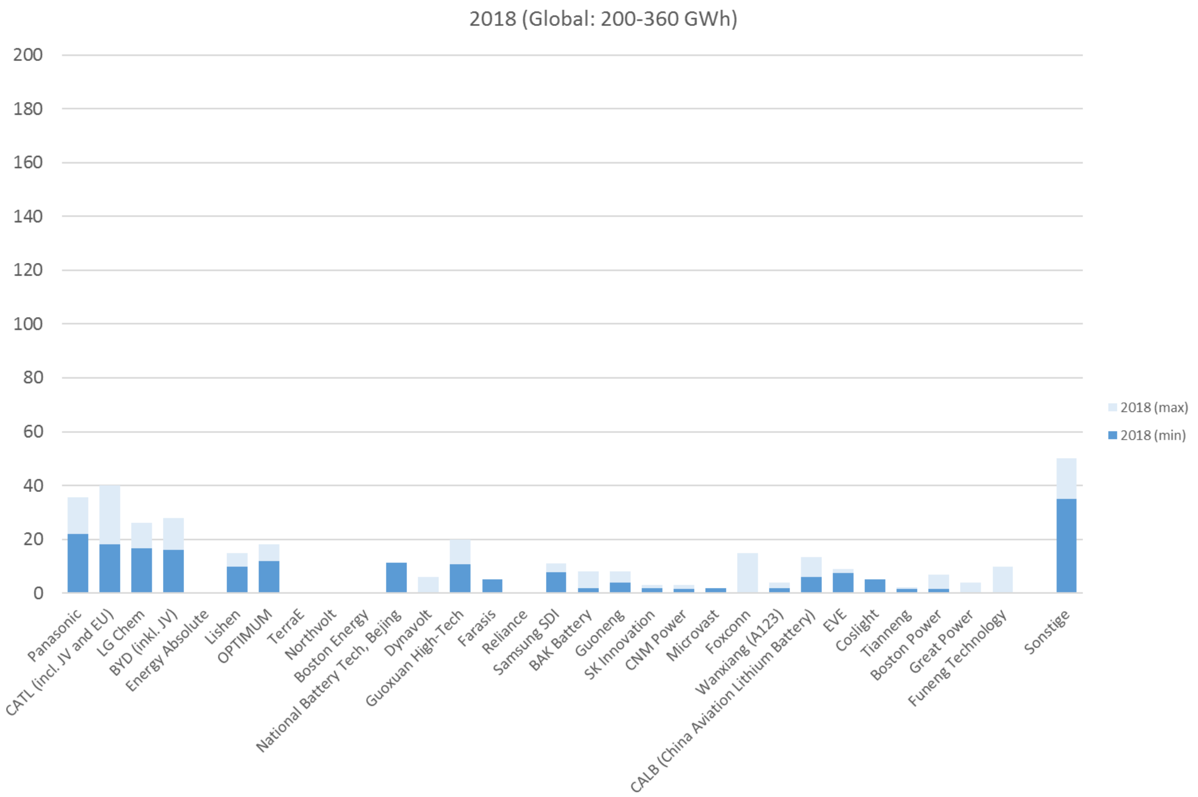


Figure 30: Global LIB production capacities of major cell producers in 2018 [48].

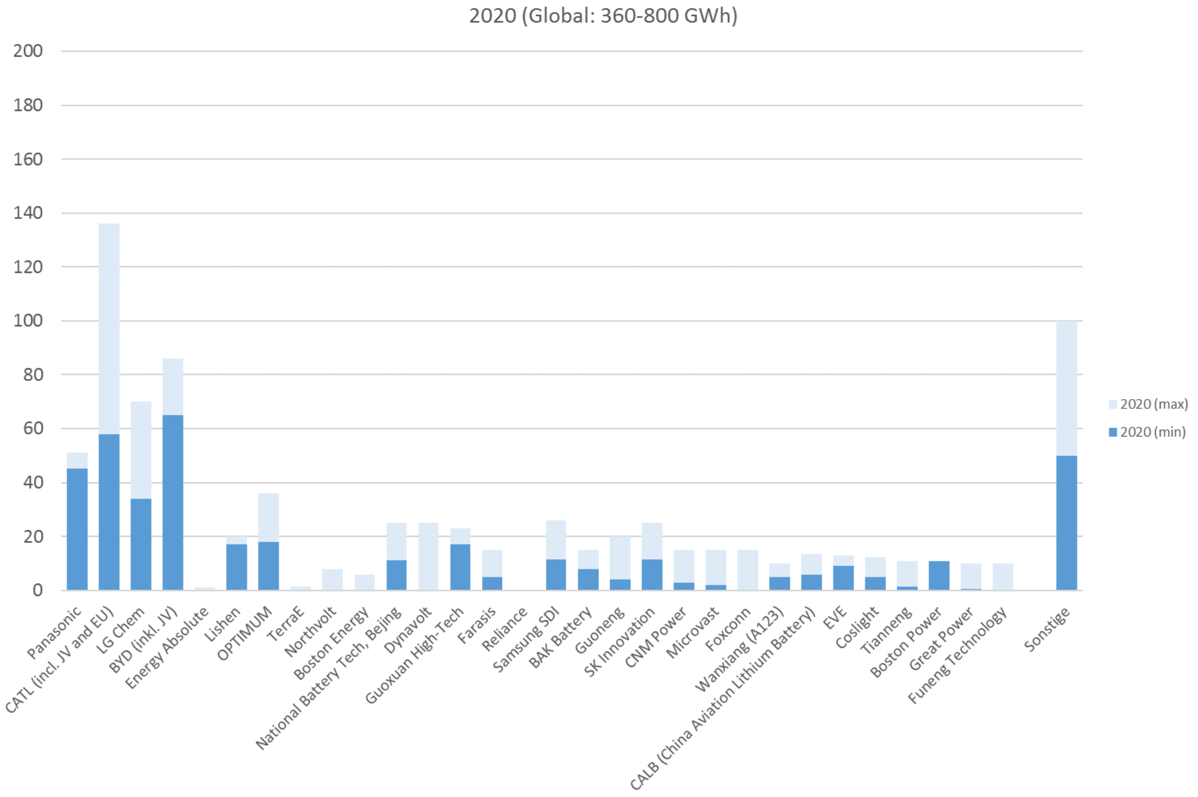


Figure 31: Global LIB production capacities of major cell producers in 2020 [48].

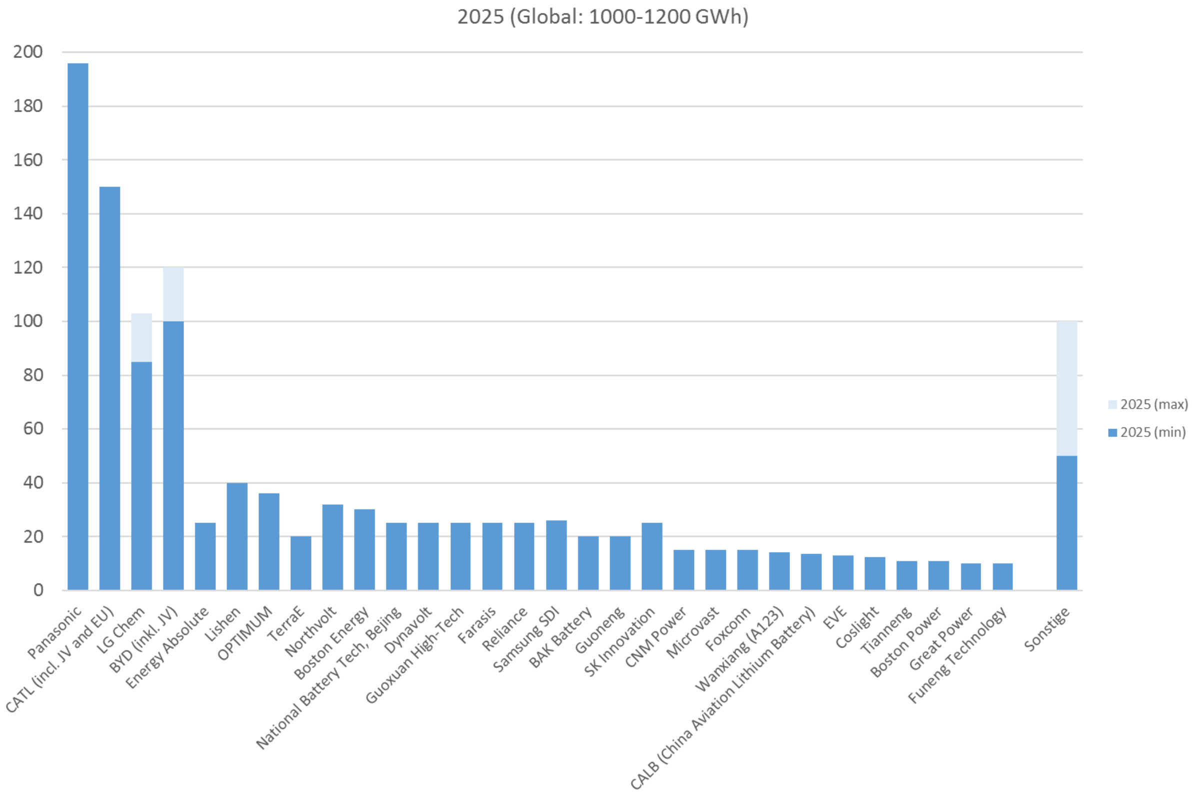


Figure 32: Global LIB production capacities of major cell producers in 2025 [48].

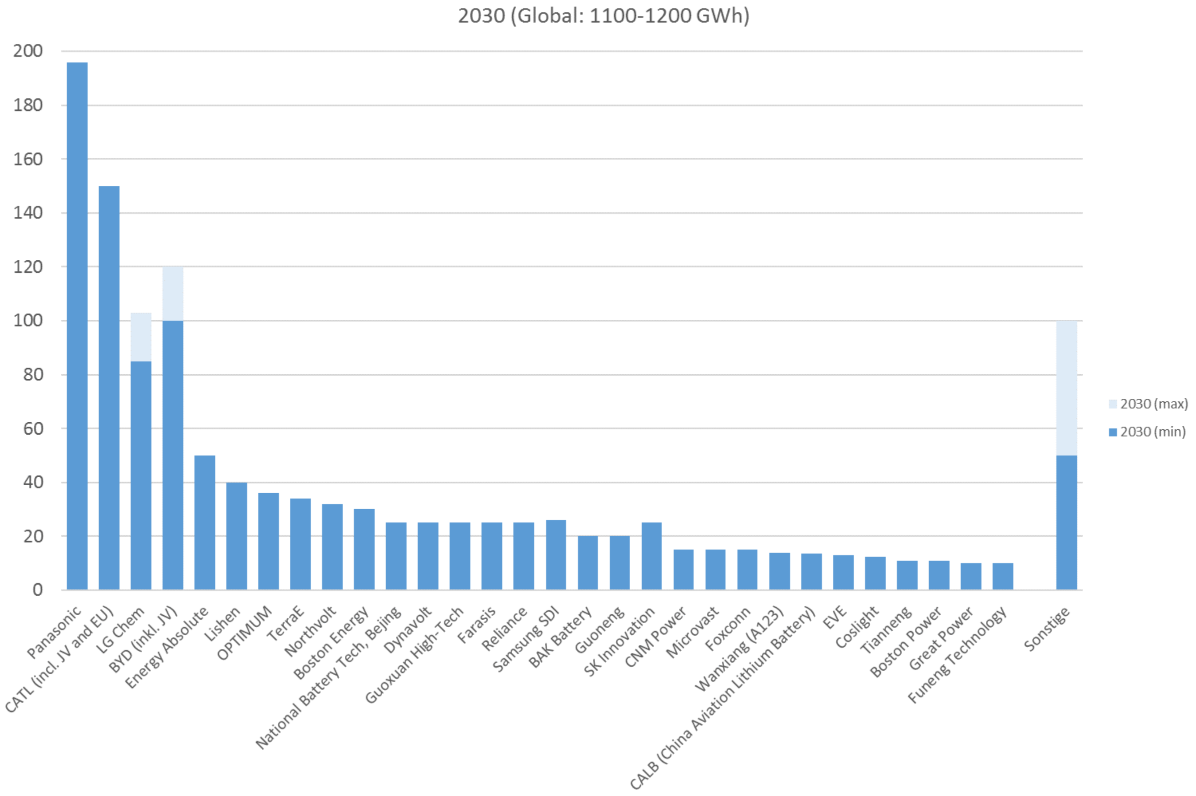


Figure 33: Global LIB production capacities of major cell producers in 2030 [48].

Until 2030, the announced production capacities add up to more than 1 TWh. In total, there are about 30 cell producers which have announced to build up production capacities of more than 10 GWh/year, which can be considered to be a threshold in order to be able to produce at competitive cost [48]. If the announced capacities are fully utilized, the “big 4” (Panasonic, CATL, LGC and BYD) will be able to fully cover the market demand (>550 GWh) until 2025.

2.4.5.2. Employment effects of battery manufacturing

Due to the high dynamics of the industry, exact estimations on the job creation potential of battery manufacturing and the upstream value chain are not known yet. Up to now findings are based on medium sized factories, while future large Giga-factories and advances in automation might yield high efficiencies and change the structure of employment found in today’s factories.

Several studies give estimations on current and future employment effects. A study published in 2016 [49] estimates a job potential of 1,050 to 1,300 full time equivalents for a 13 GWh cell factory. Additional 1,400 to 3,100 full time equivalents could be created in the associated supply chain and logistics sector. Data aggregated by the JRC suggests 90 to 180 direct jobs in cell production per GWh production capacity and a factor of 3.7 to 7.5 translating direct jobs roughly into 300 to 1000 indirect jobs per GWh [51].

A recent study from 2018 [50] considering engineering and equipment manufacturing as well as the associated supplier industry suggests a global employment of 24,000 full time equivalents until 2025 (assuming a global market of 500 GWh) or 90,000 full time equivalents until 2033 (assuming a global market of 3.3 TWh). The job-creation potential for the engineering industry of the European Union is estimated at 25,000 full time equivalents until 2033.

Based on these estimations, employment effects of 100 to 150 jobs per GWh of production capacity can be assumed for battery cell production. Indirect jobs might be in the order of 100 to 500 per GWh.

2.4.5.3. Europe's position in the global battery value chain

In the EU, several actors are positioned which cover production steps along the whole value chain of LIB, starting from raw material production to production of cells and systems and finally recycling. However with respect to global markets, only few organizations within the EU have a market share of more than 1% in their specific segment, e.g. BASF, Germany in the field of electrolyte production [42].

Due to the strong base of automotive OEM in Europe, particularly battery pack manufacturing and system integration is taking place on large scale in Europe. A particular gap in the value chain is caused by the lack of a large-scale cell production, capable of serving the volumes and prices required by the automotive industry.

An overview about the present and future position of European cell manufacturers and production plants located in Europe is provided in Figure 34 and Figure 35.

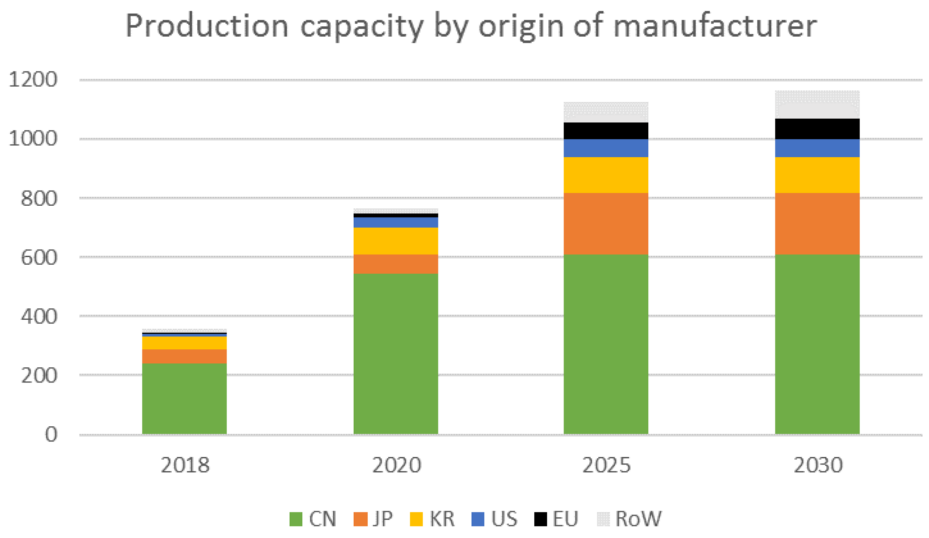


Figure 34: LIB cell production capacities in GWh/year by origin of manufacturer (company) [52].

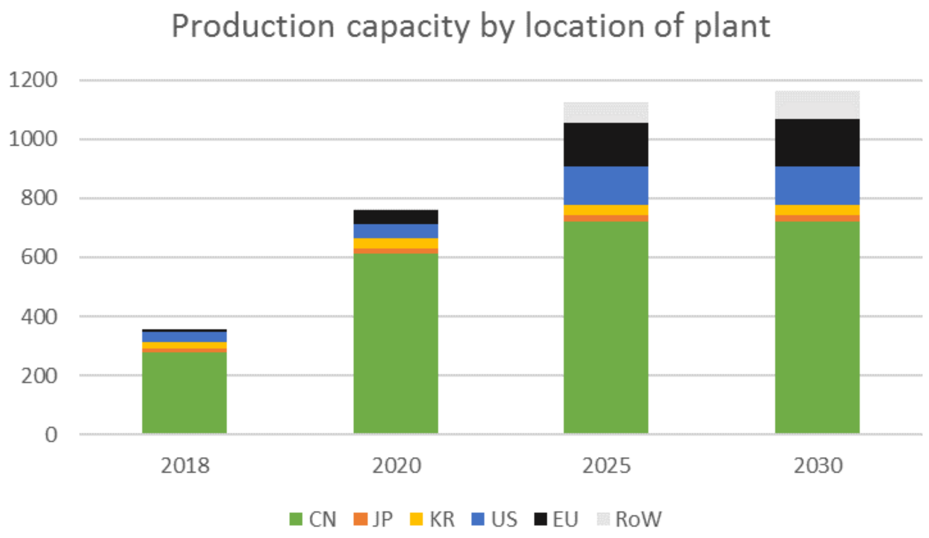


Figure 35: LIB cell production capacities in GWh/year by location of plant [52].

Several consortia are currently attempting to build up a European large scale cell manufacturing such as Northvolt (Sweden) with 32 GWh until 2023 or Saft (together with Siemens and Manz) [53]. Recently, the German government announced plans for funding of a Battery-Cell-Alliance between Germany and Poland with cell production capacities in the regions Lausitz (Germany) and Westpoland [54, 55]. At the cross section between R&D and large-scale production also a Research Production with 600 Mio EUR funding is foreseen, whereas the Fraunhofer Society should coordinate and run such a research production [56]. The announced funding from the German government sums up to 2 bn EUR. Other announcements concern the joint German-French strategy for a potential funding and build-up of a cell production [57].

Given all these announced investments and production capacities to build up in the next years, the cell production capacities of European cell manufacturers could sum up to over 40 GWh beyond 2025. In contrast, main Asian cell manufacturers have already started with cell production (e.g. LG, SDI) or plan to build up production capacities until 2020 to 2025. In concrete, there are plans from: [58–67]

- CATL (China) to build 14 GWh in Germany, Erfurt beyond 2020
- LG Chem (Japan) to build 15 to 24 GWh (for 0,3 Mio EVs) in Poland beyond 2020
- Samsung SDI (Japan) to build 10 to 15 GWh beyond 2020 in Hungary (including a recent 5 GWh announcement for 21700 cells for Land Rover
- SK Innovation (Japan) to build 7,5 GWh in Hungary beyond 2020
- Panasonic/Tesla to build a Gigafactory in Europa around 2025
- as well as from BYD (China), GS Yuasa (Japan) and Farasis (US) to build production capacities between 2020 and 2025.

The production capacities from Asian (or non-European) cell manufacturers might sum up to well above 82-96 GWh by 2025 and including BYD, GS Yuasa, Farasis, etc. capacities far above 100 GWh can be expected. Together with the new EU cell producers this could easily sum up to serve the demand in Europe. But it also clearly indicates the competition the emerging European players will have to face (besides the fact that the plans of the Asian companies are expected to be realized already several years earlier compared to the plans of the novel EU companies).

2.4.5.4. Product design trends and technology roadmap

Concerning the battery technology or type (by chemistry, format, etc.), which will most likely be produced to address this increasing demand, the global roadmaps of cell producers are basically similar: Based on state-of-the art cell design (e.g. LFP, NCA based “generation 1” and NMC:111 to NMC:532 “generation 2a/b” Li-ion batteries) [68] and state-of-the-art production equipment, incremental improvements are expected in the next few years but with the target to get to higher-energy lithium-ion batteries. Concerning the electrolytes, still liquid electrolytes will be used but will be adopted to the changing electrode materials (e.g. with additives). Current trends for layered oxide cathodes describe the development of Ni-rich (Co reduced) materials (NMC or NCA). A few cell producers are already using NMC811, NCA+ or comparable cathode materials, others are still adopting NMC622 (also referred to as “generation 3a”). On cathode side maybe even lower-cost Li-rich high energy NMCs (HE-NMC) with a high share of Mn might be produced and applied within the next ~10 years, as Mn is cheaper than Ni (also referred to as “generation 3b”). On anode side, the trend is to incorporate Si-nano particles to make use of the alloying reaction between Si and Li yielding a high capacitance. This however comes at the cost of cycle life.

All-solid-state batteries are on the roadmap of many battery producers but also of OEM (also referred to as “generation 4”). Their theoretical key performance parameters (KPI, volumetric and gravimetric energy density above 300 Wh/kg and 500 Wh/l and respective power density) are suitable for electric mobility (EV). Main R&D-challenges result from a missing larger scale manufacturing process, particularly for ceramic solid.state electrolytes which promise to yield the highest advantages over state of the art technologies. It is possible that first all-solid-state batteries might not be competitive in terms of energy density, but might feature superior safety properties. Theoretically, energy densities of 350-400 Wh/kg and higher are possible which might be realized in optimized future cell concepts.

Out of the broad range of alternative battery technologies, other cell chemistries might feature certain USP (unique selling proposition) compared to Li-ion batteries, but (according to the current level of knowledge), do not reach the necessary KPIs in terms of combined volumetric (above 400 Wh/l on cell level) and gravimetric energy density (above 200 Wh/kg on cell level), power density and cycling stability (corresponding to a range of 150,000 to 300,000 km for passenger EVs) necessary for electric mobility. USPs of these alternative technologies might however be their cost due to a high availability of resources (e.g. Na-based), their gravimetric energy density (e.g. S-based) or others. From today's perspective, it is however unclear which alternative battery technologies will reach commercial feasibility, since often fundamental challenges are not yet solved (e.g. concerning the manufacturability, stability of materials and electrochemical systems, reaction kinetics, etc).

2.5. Consumer expenditure base data

2.5.1. General objective of subtask 2.4 and approach

Subtask 2.5 gives an overview about average production costs and consumer prices, incl. VAT (for consumer prices; street price) / excl. VAT (for B2B products), as well as an estimation of repair and maintenance as well as installation and disposal costs.

Due to their recent larger scale market introduction, there is still little experience with maintenance as well as disposal expenses. Hence, only estimations can be made based on isolated sources.

2.5.2. Development of LIB cell costs

As the core of LIB based energy storage systems, the battery cell exhibits the highest cost share. During the last years, particularly standardized 18650 format LIB cells have experienced a steep cost learning curve, benefiting from production scale effects, but also from technological advancements on material level increasing the energy density per volume and weight and decreasing the amount of cost intense Cobalt-based components. Compared to this benchmark, larger format LIB cells (pouch, prismatic) utilized in xEV and ESS feature lower energy densities at higher cost per kWh. There are however no principal limitations, which would prevent a performance and cost development similar to what was observed for cylindrical cells. Figure 36 shows the cost learning curves for cylindrical as well as larger format LIB cells [45]. Today, costs for cells suitable for automotive use are around 150 €/kWh (cylindrical) and around 200 €/kWh (pouch/prismatic). In specific cases, prices around 100 €/kWh have been reported already [69]. It should however be noted, that with the current market situation, LIB prices being below costs are not unlikely to occur.

Assuming more or less constant resource prices, production costs of the different cell formats are expected to approach and fall below the mark of 100 €/kWh between 2020 and 2025. Taking further developments on material level into account, costs around 60-100 €/kWh seam feasible past 2025.

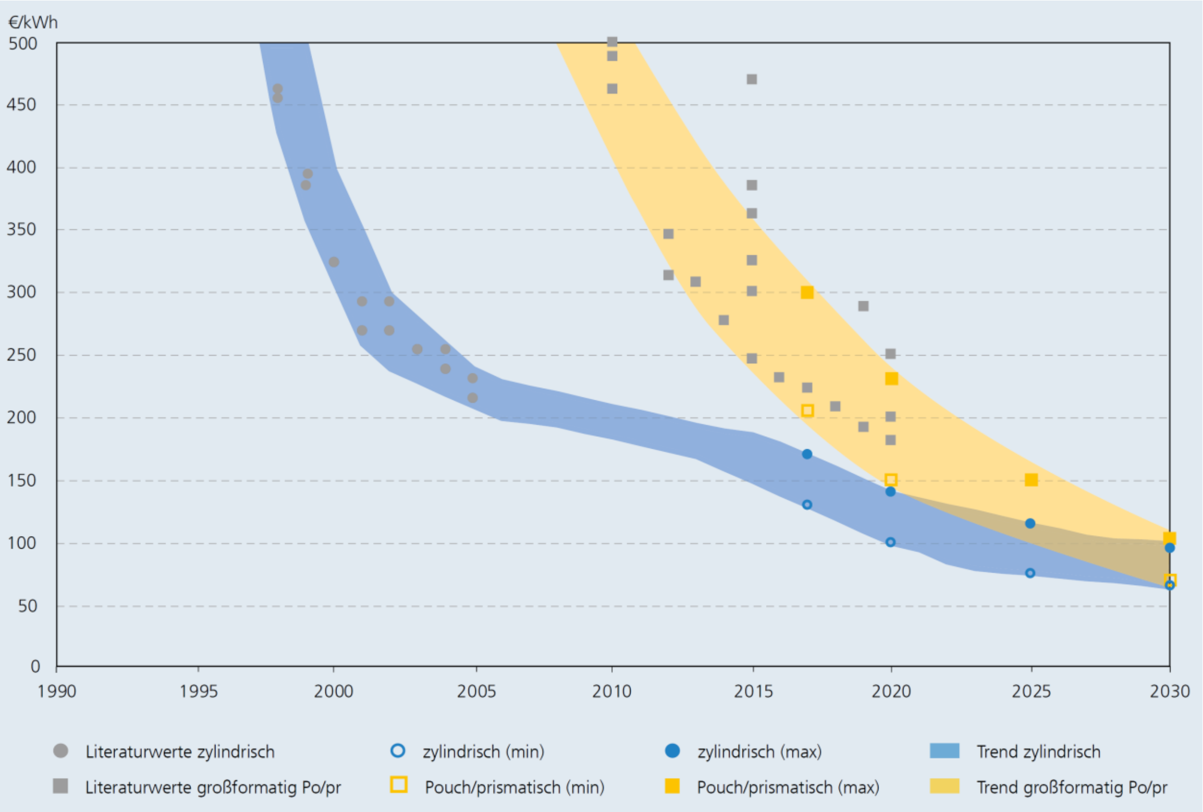


Figure 36: Cost learning curves for large LIB cells (cylindrical and pouch/prismatic) [45].

Similar cost learning curves have been observed for other battery technologies (see Figure 37). In principal, cost degression can be limited by demand (compare NiCd) or by reaching material cost limits (compare Pb). Also, the diffusion of battery technologies in new markets or applications can lead to further technological improvements and justify higher production costs (compare deviation of NiMH, Pb). Following the available data for LIB cells, approx. 100 \$/kWh (~89 €/kWh) are reached at a cumulative yearly production of 1TWh. This mark is expected to be reached between 2020 and 2030.

Beyond 2030, LIB production costs are however expected to start deviating from this curve due to limiting raw material prices.

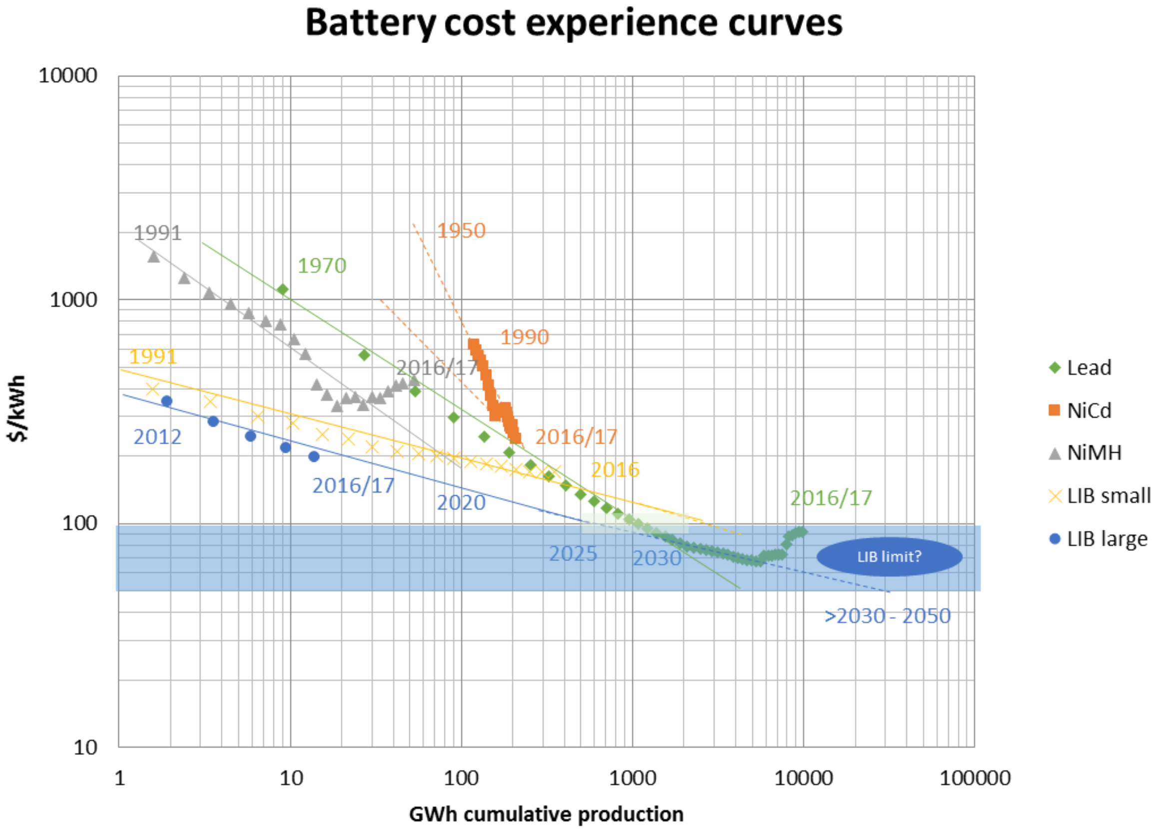


Figure 37: Cost learning curve for different battery technologies [48].

2.5.3. Development of storage cost for xEV and ESS

2.5.3.1. Consumer prices for xEV batteries

From end-customer perspective, prices for xEV batteries only appear as either replacement costs for a battery module or system (in case of failure not covered by warranty) or as price difference of several versions of the same car model, e.g. as long-range and mid-range version. At present, there is no information on replacement or spare part prices available. Figure 38 shows the price difference of base and extended range versions of five car models launched in 2018 and 2019. The data available so far is very limited. Prices for upgrades are in the range of 200 – 500 €/kWh. Note however, that the range upgrade often comes with a performance upgrade also resulting in higher cost for the whole drivetrain including motor and breaks.

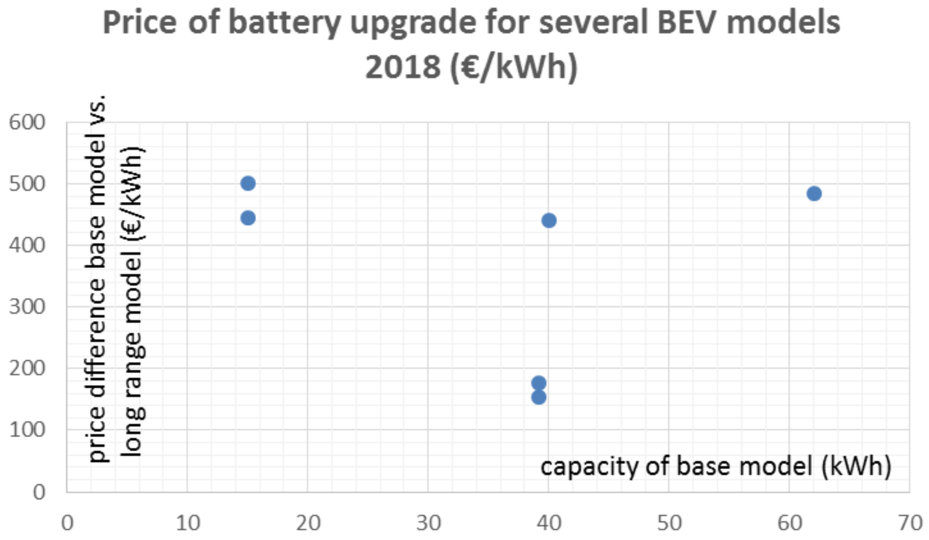


Figure 38: Difference in end customer price of base version and high range version of several BEV models launched in 2018 and 2019.

2.5.3.2. Consumer prices of home storage systems

According to recent end-customer price data provided in [70] for 2018, typical consumer prices for small scale (~10 kWh) stationary home storage systems are between 5000 and 15000 Euros, leading to a relative price of 800 to 1200 €/kWh. It is expected that these system prices will benefit from the growing battery markets (also xEV), since similar LIB cell types can be applied in both application areas. With respect to inverters and other system related costs, the smaller market volume of home ESS indicates lower economy of scale effects as compared to battery cells.

2.5.4. Installation, repair and maintenance costs

So far, no comprehensive information on repair and maintenance costs for the battery system of xEV are available. The price range for refurbishing of batteries might be of the order of 100 $/kWh [71].

Installation costs of home storage systems are estimated to be between 900 – 3500 € [72]. So far, there is no comprehensive information on repair and maintenance costs available.

2.5.5. LIB life-cycle, disposal and recycling considerations

After their end of life in a respective application, batteries can either be disposed, recycled or, if suitable, be used in a second life application. Recycling or re-use heavily depends on a working collection and return system. Today, respective systems are installed for consumer batteries on national level. With respect to EV or ESS applications, no comprehensive / EU wide collection system exists. OEM have different strategies for the collection of used batteries.

With respect to second life applications, several pilot scale activities are taking place. There is still considerable remaining effort regarding the development of reliable techniques determining the state of health of used batteries as well as regarding efficient methods to integrate used battery(-systems) in second life applications (e.g. EV → ESS).

The future volume of available batteries for a potential second life application is still not clear, since it will heavily depend on battery design and usage patterns. The strategy of automotive OEM regarding second life applications is not known. A design matching battery and vehicle lifetime would mean no available battery capacity for a second life use. The over-engineering of batteries for reasons of reliability would add to the cost of EV, however, might yield batteries with a state of health acceptable for second life use.

Second life applications might extend the overall operation time of batteries. At the final end of life, recycling of batteries might either yield regenerated cathode materials or recovered metals (particularly aluminium and steel from the case/housing and Cu, Mn, Co, Ni and potentially Li from the cells). The metals value of an NMC622 battery is around 20 Euro/kWh [48]. Hence, recycling techniques will have to be energy and cost efficient in order for battery recycling to make a self-sustainable business case. Otherwise disposal and recycling costs might become additional cost components adding to battery prices.

2.6. Recommendations

2.6.1. General objective of subtask 2.5

This task makes recommendations with regard to a refined product scope from an economical/ commercial perspective (e.g. exclude niche markets) and identify barriers and opportunities for Ecodesign from the economical/ commercial perspective.

2.6.2. Refined product scope from the economical/ commercial perspective

Secondary batteries, particularly LIB, will become a TWh market in the next years. As a main component of EV and of ESS, their production and use characteristics will have major impact on the overall greenhouse gas footprint of these applications.

Considering the typical lifetime of 10 to 20 years of batteries, significant numbers and volumes of batteries will be decommissioned starting around 2030. Hence, not only the production and use phase, but also the treatment of batteries after their end of life will have a high impact on their environmental footprint.

From market perspective, it is reasonable to consider all stages of LIB life from their production to treatment after their end of service life.

2.6.3. Barriers and opportunities for Ecodesign from the economical/ commercial perspective

The battery markets as discussed in the previous sections are strongly growing. Any Ecodesign or other battery relevant regulation implemented in the near future hence has the chance to steer the development during the crucial phase of scale-up of production capacities. If this time frame is however missed, the implementation of regulations by producers might become more difficult, since production infrastructure invests have already been placed.

The largest markets for batteries will be passenger electric vehicles. Important vehicle performance parameters, which determine their competitiveness (e.g. the vehicle range) are predominantly determined by the battery. A possible Ecodesign regulation should aim at reducing the environmental footprint of batteries (and thereby of electric vehicles) in the context of a high battery performance.

Since a high competitiveness of EV (particularly against combustion powered vehicles) will be necessary to achieve a fast transition and any associated CO_2 targets, Ecodesign regulations should not increase battery costs substantially and/or get in the way of a massive deployment of EV to decarbonise road transport.

2.7. Annex

2.7.1. Sales and stock model description

2.7.1.1. Modelling of addressable electric applications markets

Vehicle markets (in units of registrations in the EU28 per year) and ESS markets (in units of number of installed home PV systems or in units of overall renewable (PV, wind) electricity generation in the EU28 per year) were modelled by exponential functions.

$$Mt_{app.}(t) = M_0 \times Exp(t/\tau)$$

With $Mt_{app.}(t)$ being the total market volume of an application, M_0 the market size in 2015 and $\tau \times Ln(2)$ the time t necessary to double the initial market volume M_0. M_0 and *Tau* were chosen to fit existing market data.

$$M_{app.}(t) = c \times M_0 \times Exp(t/\tau)$$

With $M_{app.}(t)$ being the addressable market and c a factor equal or smaller than 1. Parameter $c < 1$ was chosen to take into account that not the whole existing market $Mt_{app.}$ might be addressable by battery electric technologies. E.g. a share of vehicles primarily used for long distance travel might not be addressable by BEV, but by PHEV/HEV only.

The market addressable for passenger PHEV/HEV (as a transition technology on the path to full electric vehicles) was modelled as the difference of total vehicle sales and BEV sales:

$$M_{PHEV}(t) = c \quad \times Mt_{passenger}(t) - S_{BEV}(t)$$

The market addressable for passenger BEV was modelled like $M_{app.}(t)$ with $c < 1$.

2.7.1.2. Modelling of sales numbers of xEV and new installations of ESS

Yearly sales numbers $S_{app.}(t)$ for the different applications were modelled by logistic growth functions. Logistic functions can model diffusion of technologies into existing markets with a given market volume M. The market volume can be a moving target $M = M(t)$. The relative change of sales numbers $S'_{app.}(t)/S_{app.}(t)$ is proportional to the market volume not yet developed by a technology $M_{app.}(t) - S_{app.}(t)$.

$$S_{app.}(t) = M_{app.}(t) \times \frac{1}{1 + Exp(-M_{app.}(t) \times (t - t_0)/\tau)(\frac{M_{app.}(t)}{S_{app.}(t_0)} - 1)}$$

With *Tau* being a time constant and $S_{app.}(t_0)$ being the yearly sales volume at year t_0 (e.g. 2015).

Short time constants *Tau* of few years were used to model ESS sales. Due to limitations of the existing electricity grid to only buffer a certain share of fluctuating PV and wind generated electricity, the further expansion of renewable electricity generation might be strongly coupled to ESS installations. Hence, ESS sales were modelled to closely follow the assumed installations of renewable power in the limit of “very fast” market diffusion ($\tau \rightarrow 0$).

The following applications / sub-markets were considered and modelled:

- Passenger electric vehicles: (1) small (mini), (2) compact and vans (comp), (3) upper / luxury class and SUVs as (a) BEV, (b) PHEV, (c) HEV
- Light commercial vehicles (1) as (a) BEV, (b) PHEV, (c) FCEV

- Heavy commercial vehicles (1) as (a) BEV, (b) PHEV, (c) FCEV
- Buses (1) as (a) BEV, (b) PHEV, (c) FCEV
- Home ESS (1) as “BEV”
- Large ESS (1) as “BEV”

2.7.1.3. Modelling of battery system capacities

At present, the average energy content of a BEV passenger electric vehicle battery is above 40 kWh. Small vehicles offering space for one or two persons often feature a capacity of less than 10 kWh, while the models with highest capacity sold in EU28 countries approach the 100 kWh mark. The amount of battery capacity installed in passenger PHEVs is about 10 kWh and has remained on a constant level over the last years (see Figure 39).

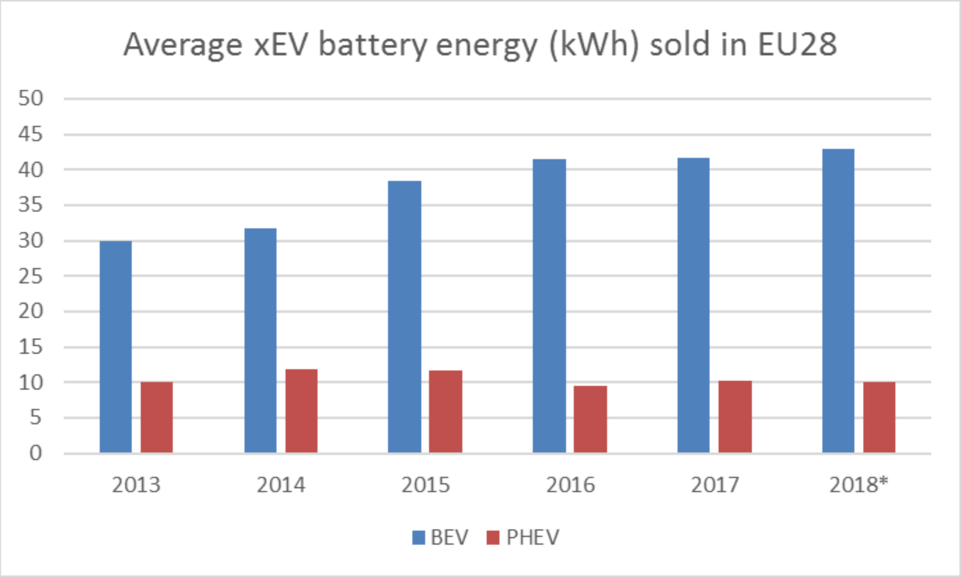


Figure 39: Averaged battery capacity of xEVs sold in EU28 member countries based on sales volumes of xEV models [3].

In particular BEV battery capacities increased in the last years from 30 kWh in 2013 to more than 40 kWh in 2018 (EU sales and production averages). With respect to announcements made by OEM and information on models launched in 2018 and 2019, we expect average capacities to approach the 60 kWh mark. In the long term, we expect BEV capacities to converge towards a value sufficient to provide average driving ranges of some 100 km. Battery capacity growth rates are hence supposed to slow down.

Some movement can also be expected for the system capacity of home storage ESS once systems are used for self-consumption optimization of EV charging.

Battery capacities $E_{Batt.}(t)$ of the different applications were modelled by power laws.

$$E_{Batt.}(t) = E_0 + k \times (t - t_0)^b$$

With E_0 being the average battery capacity in year t_0, k the growth rate, t the time in years and b an exponent < 1. The parameters were chosen to fit existing data.

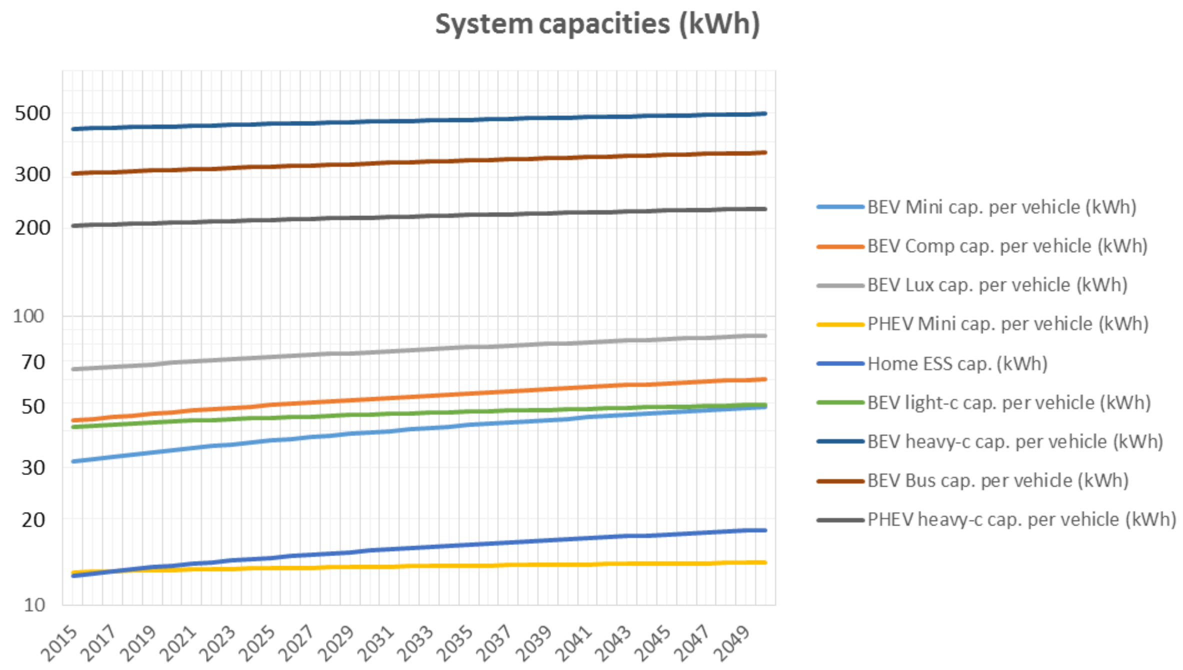


Figure 40: Average system battery capacity model forecast.

Large scale ESS capacities were not modelled in the frame of this study.

2.7.1.4. Modelling of battery replacement rates [70, 73–78]

The replacement rate defines the share of batteries installed in year *t* that has to be replaced within the lifetime of a system (xEV, ESS). This might either be interpreted as partial replacements in every system sold, e.g. one battery module in a system consisting of several modules, or, more likely, complete replacements of the battery in only some systems.

At present, there is no sufficient data available on the average lifetime of batteries in electric vehicles or stationary storage. Battery lifetime largely depends on the usage profile of applications as well as on the ambient and operational temperature.

Since passenger vehicles mostly remain parked, calendar ageing might be an important factor determining the battery lifetime. Depending on the type of cells and ageing conditions, calendar lifetime (SoH down to 80%) of LIB can be assumed to be between 10 and 30 years.

Usage and cycling is a deteriorating factor, which might be of high importance particularly for commercial or ESS applications. The cycle life of LIB (SoH down to 80%) ranges from 500 to 1000 full cycles for high energy batteries and up to several thousand full cycles for industrial grade batteries. The total energy throughput of batteries can be significantly improved, if maximum depth of discharge and maximum state of charge are limited. Besides energy throughput (cycling), temperature as well as charge and discharge power are decisive factors for deterioration. Frequent use of fast charging of electric vehicles for example is supposed to accelerate ageing of the battery.

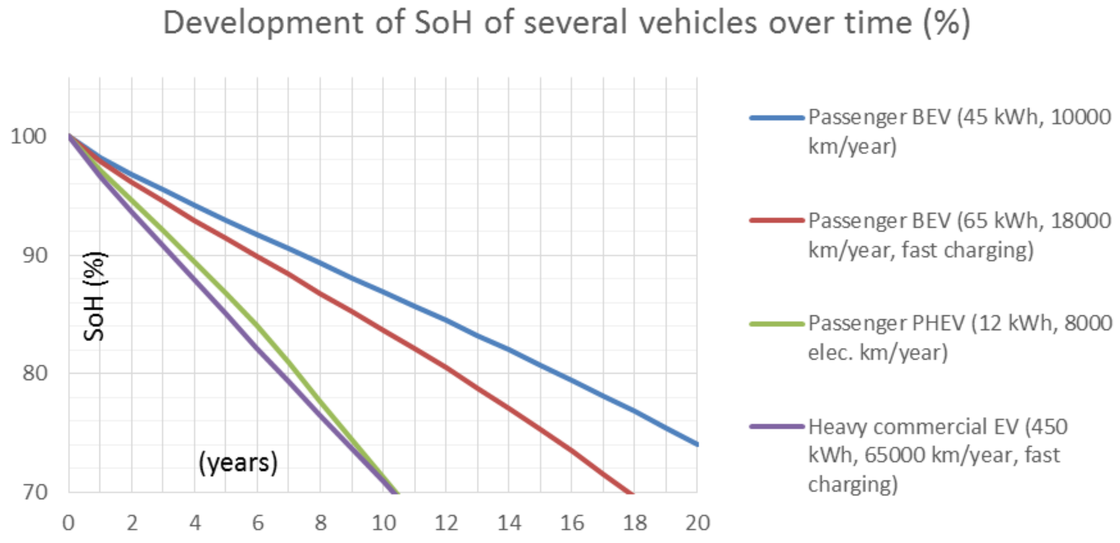


Figure 41: Calculated development of the SoH of vehicle batteries over time. A battery cycle life of 700 full cycles (100% DoD) was assumed for passenger BEV and of 2000 full cycles (100% DoD) for passenger PHEV and of 3000 full cycles (100% DoD) for heavy commercial EV. Utilization of 60% (45 kWh BEV) to 80% (450 kWh heavy EV) of the nominal installed battery capacity per charge/discharge cycle. Ageing at an average temperature of 15 °C.[8]

Figure 41 shows exemplary calculations for different EV models and usage scenarios. According to this data, the state of health of a passenger EV used with a usage profile typical for the majority of cars in the EU, is supposed to remain sufficient (larger than 80%) during the lifetime of the vehicle. Hence, battery replacement rates are expected to be rather low. Other usage forms, particularly commercial usage of heavy and light vehicles with frequent use of fast charging and long operation time (meaning longer periods at elevated battery temperature) might however deteriorate the battery much faster.

As compared to xEV batteries, batteries for ESS applications may exhibit a better cycling stability and lifetime, since they are not as strongly optimized on high energy densities, but have to stand frequent (e.g. daily) cycling. Typical usage profiles of storage systems also feature a comparably low load. Dimensioning of system power and system storage capacity often does not exceed currents of 1C.

Within the battery demand and stock forecast model, battery replacement rates $Rp_{Batt.}(t)$ were assumed to be constant over time $Rp_{Batt.}(t) = Rp_{Batt.}$.

2.7.1.5. Modelling of average system lifetimes (xEV, ESS)

Average system lifetimes $Lt_{system}(t)$ were assumed to be constant. $Lt_{system}(t) = Lt_{system}$. Parameters were estimated based on manufacturer statements and typical lifetimes for combustion powered vehicles.

According to statistics provided in [5], the average vehicle age in the EU28 in 2016 for passenger cars was 12 years, for light commercial vehicles 11 years and for heavy commercial vehicles 12 years. The vehicle average age seems to be increasing by about 0.1 to 0.2 years/year. With respect to the stock of 250 to 260 million passenger cars in the EU28, the market volume of 13 to 14 million vehicles per year would translate into a passenger car lifetime of 17 to 18 years.

2.7.1.6. Calculation of battery replacements

Battery replacements $Rp_{Batt.}(t)$ (either in units of GWh or units of number of systems) were calculated by assuming a uniform distribution of battery replacements over the lifetime $Lt_{system}(i)$ of battery systems installed in year i.

$$Rp_{Batt.}(t) = \sum_{i \geq t - Lt_{system(i)}}^{t} \frac{Rr_{Batt.}(i) \times S_{app.}(i) \times E_{Batt.}(i)}{Lt_{system}}$$

2.7.1.7. Calculation of system and battery decommissions

In addition to batteries replaced and decommissioned during the lifetime of an application (replacements), batteries installed in an application at the end of life of the application are considered as additional decommissions.

Decommissions of batteries $Dc_{Batt.}(t)$ (either in units of GWh or units of number of systems) were assumed to happen at the end of life (EoL) of the applications. Within the model, EoL was distributed in a range of +/-25% of Lt_{system} around the average lifetime Lt_{system} (see Figure 42). Any second life usage was neglected.

$$Dc_{Batt.}(t) = \sum_{i=t-1.25 \times Lt_{system}}^{t-0.75 \times Lt_{system}} \frac{S_{app.}(i) \times E_{Batt.}(i)}{0.5 \times Lt_{system}}$$

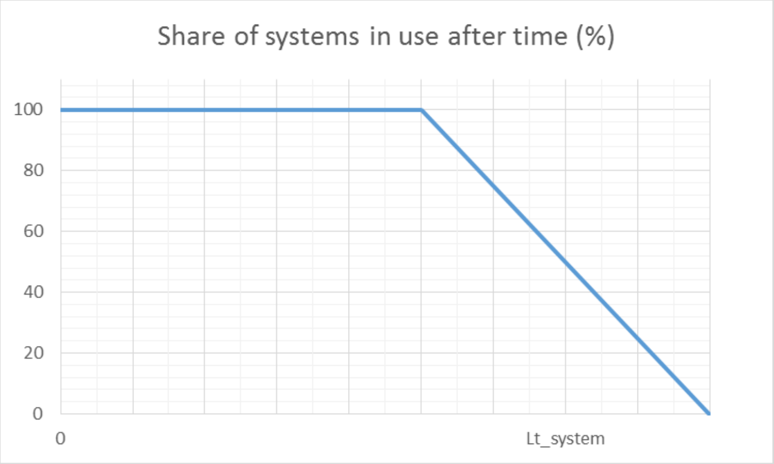


Figure 42: Share of systems in use after time.

2.7.1.8. Calculation of yearly installed battery capacity

The yearly installed battery capacity $Sb_{app.}(t)$ in the EU28 was calculated as:

$$Sb_{app.}(t) = S_{app.}(t) \times E_{app.}^{Batt.}(t) + Rp_{app.}^{Batt.}(t)$$

2.7.1.9. Calculation of battery capacity stock

The stock of battery capacity $C_{app.}$ installed in the EU28 in year t was calculated as:

$$C_{app.}(t) = \sum_{i \leq t} S_{app.}(i) \times E_{app.}^{Batt.}(i) - Dc_{app.}^{Batt.}(i)$$

2.7.2. System/BMS related PRODCOM categories

Within the NACE2 classification, there are no explicit categories for LIB system components like the battery management system, however there are categories including components, which are likely to be applied in the power electronics or BMS of battery packs and systems. A selection is listed in Table 13. Automatic circuit breakers, as a part of technology crucial for battery management systems, are aggregated under PRODCOM categories 27122250 and 27122230.

27122370	Electrical apparatus for protecting electrical circuits for a voltage ≤ 1 kV and for a current > 125 A (excluding fuses, automatic circuit breakers)
27122350	Electrical apparatus for protecting electrical circuits for a voltage ≤ 1 kV and for a current > 16 A but ≤ 125 A (excluding fuses, automatic circuit breakers)
27122330	Electrical apparatus for protecting electrical circuits for a voltage ≤ 1 kV and a current ≤ 16 A (excluding fuses, automatic circuit breakers)
27122250	**Automatic circuit breakers for a voltage ≤ 1 kV and for a current > 63 A**
27122230	**Automatic circuit breakers for a voltage ≤ 1 kV and for a current ≤ 63 A**
27904155	Inverters having a power handling capacity > 7,5 kVA
27904153	Inverters having a power handling capacity ≤ 7,5 kVA

Table 13: PRODCOM categories related to batteries [1].

2.7.3. Circuit breakers as an example for BMS electronics

LIB cells as gathered in category 27202300 are only one of the subunits of battery systems. Housing, protection, cooling, electrical and electronic components are supposedly measured in different PRODCOM categories (e.g. 27122250 Automatic circuit breakers for a voltage ≤ 1 kV and for a current > 63 A and 27122230 Automatic circuit breakers for a voltage ≤ 1 kV and for a current ≤ 63 A).

Figure 43, Figure 44, Figure 45 and Figure 46 show production, import, export and EU sales and trade data for automatic circuit breakers as potential component of BMS. EU consumption values do not show a clear upward trend comparable to the values for battery technologies. Although an increase of export and import values can be observed, no clear correlation with the production of battery systems for xEV or stationary storage in Europe can be observed.

We conclude that the analysis of individual storage system related PRODCOM categories does not allow to assess the market development for complete battery systems.

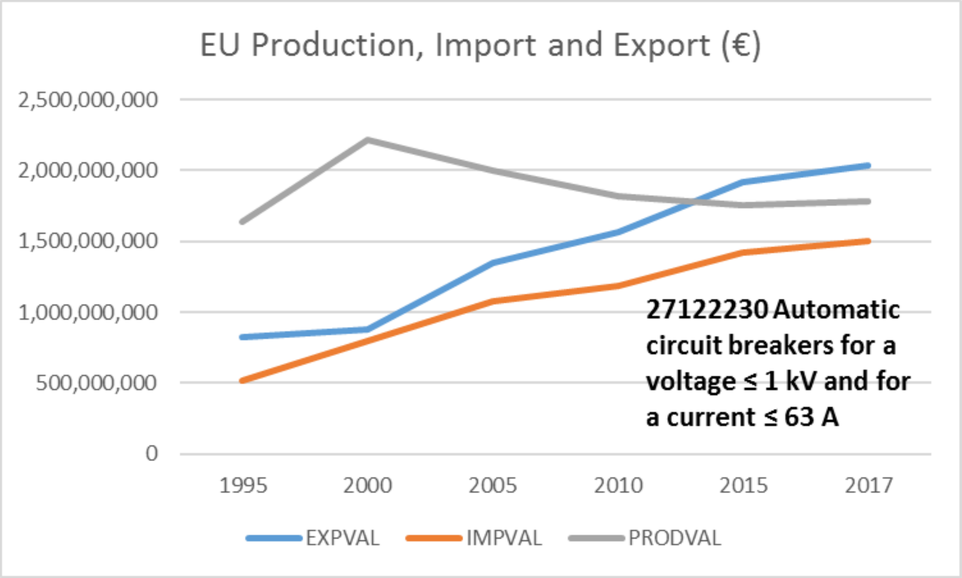


Figure 43: EU production, import and export summarized in PRODCOM category 27122230: Automatic circuit breakers for a voltage ≤ 1 kV and for a current ≤ 63 A [2].

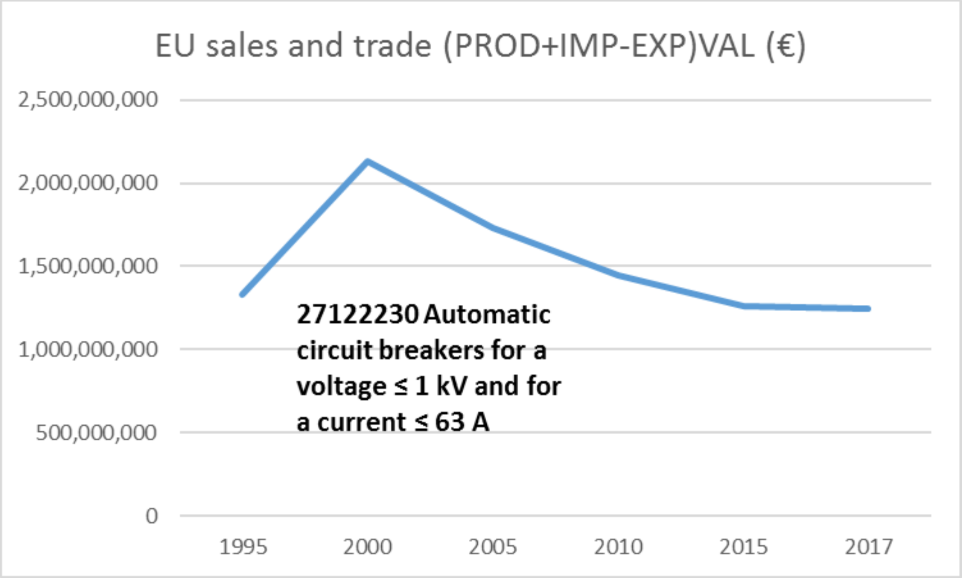


Figure 44: EU sales and trade (PROD+IMP-EXP) summarized in PRODCOM category 27122230: Automatic circuit breakers for a voltage ≤ 1 kV and for a current ≤ 63 A [2].

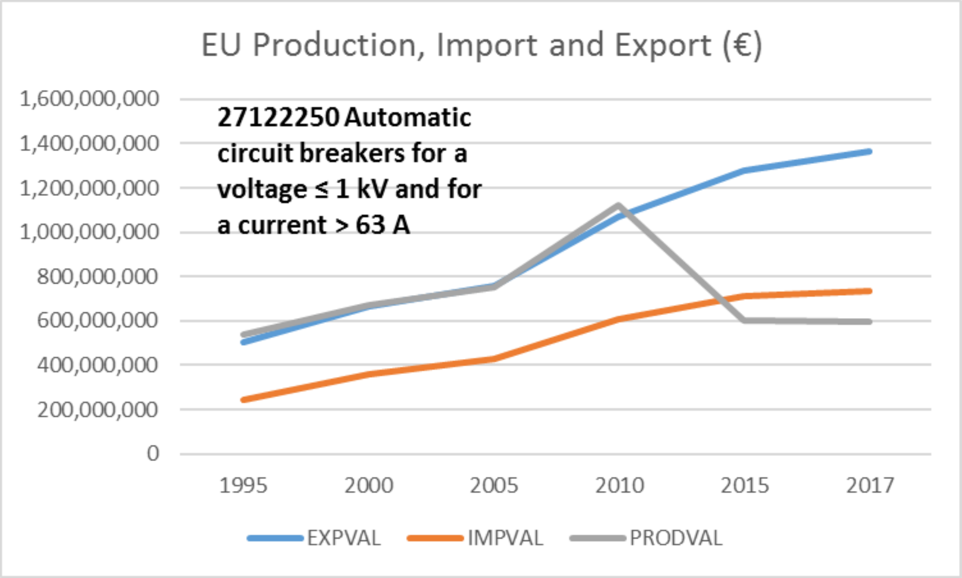


Figure 45: EU production, import and export summarized in PRODCOM category 27122250: Automatic circuit breakers for a voltage ≤ 1 kV and for a current > 63 A [2].

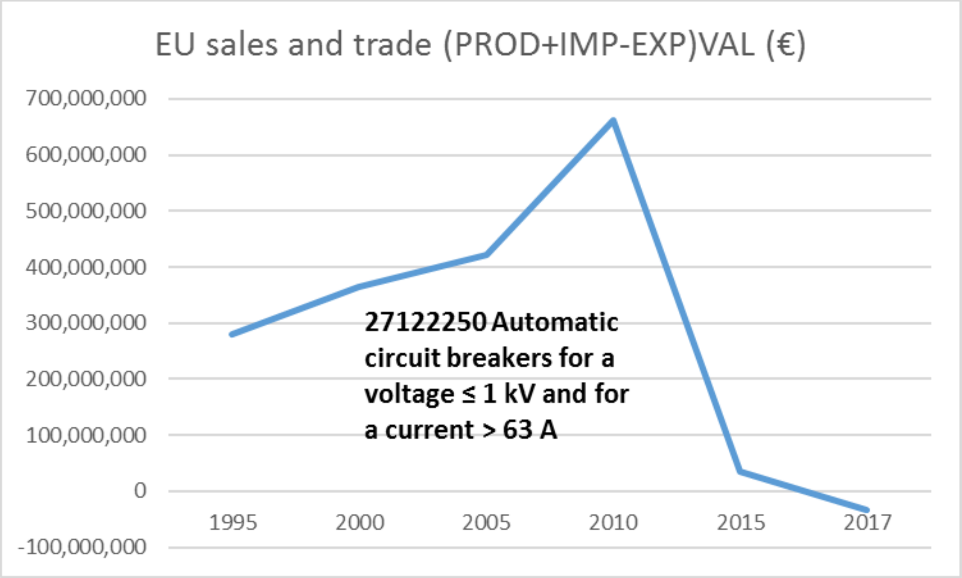


Figure 46: EU sales and trade (PROD+IMP-EXP) summarized in PRODCOM category 27122250: Automatic circuit breakers for a voltage ≤ 1 kV and for a current > 63 A [2].

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Preparatory Study on Ecodesign and Energy Labelling of Batteries under FWC ENER/C3/2015-619-Lot 1

TASK 3 Report

Users – For Ecodesign and Energy Labelling

VITO, Fraunhofer, Viegand Maagøe

August 2019

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Project website: https://ecodesignbatteries.eu/

Version history:

Version 1: Version made available in December 2018 for the Stakeholders to comment and discuss in the first stakeholder meeting.

Version 2: Version made available in April 2019 in preparation of the second stakeholder meeting

- review based on the input from the stakeholder comments (some data input and remarks on the base case selection)

- QFU formula and Application Service Energy formula improved, calculation of losses added

- substitution of base case passenger BEV and light commercial BEV with BEV medium-to large-sized and BEV small-sized

- adapted argumentation for base case selection

- some data assumptions, related to the bases cases were changed

- missing sections were added

Version 3: (this version) Version made available in August 2019

- consideration of feedback from the second stakeholder meeting and of written feedback received after the second stakeholder meeting

- argumentation for selection of base cases slightly adapted (LCV represented partially by passenger cars)

- information on potential impact of vehicle to grid services on battery added

- increase of annual cycles of residential ESS due to provision of grid services discussed

- discrepancy of battery and vehicle lifetime addressed

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List of abbreviations

Abbreviations	Descriptions
AC	Alternating current
Ah	Ampere-hour
AS	Application service energy
BEV	Battery-electric vehicles
BMS	Battery management system
C	Capacity
C_n	Rated capacity
DC	Direct current
DOD	Depth of Discharge
E	Energy
EOL	End of life
EPA	Environmental Protection Agency
E_{Rated}	Rated energy
ESS	Energy storage system
EV	Electric vehicle
FC	Full cycle
FESS	Flywheel energy storage systems
FTP	Federal Test Procedure
GHG	Greenhouse gases
GVW	Gross vehicle weight
HDT	Heavy-duty truck
HDTU	Heavy-duty tractor unit
I	Current
ICEV	Internal combustion engine vehicles
I_t	Reference test current
kWh	Kilowatt hour
L_{Cal}	Calendar life
L_{Cyc}	Cycle life
LFP	Lithium iron phosphate
LIB	Lithium-ion battery
$NaNiCl_2$	Sodium nickel chloride
NaS	Sodium-sulphur
nC	C-rate
NEDC	New European Driving Cycle
NiMH	Nickel-metal hydride batteries
NMC	Nickel manganese cobalt
Pb	Lead-acid
PEF	Product environmental footprint
PEM-FC	Proton exchange membrane fuel cell
PHEV	Plug-in-hybrid-electric vehicle
PV	Photovoltaic
Q_{FU}	Quantity of functional units
R	Internal resistance
RFB	Redox-flow battery

RT	Room temperature
SD	Self-discharge
SOC	State of charge
SOH	State of health
SOH_{cap}	Capacity degradation
T	Time
V	Voltage
VKT	Vehicle kilometres travelled
V_L	Voltage limits
V_{OC}	Open circuit voltage
V_R	Rated voltage
WLTP	Worldwide Harmonized Light Vehicle Test Procedure
η_E	Energy efficiency
η_V	Voltaic efficiency

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3. Task 3: Users

The objective of Task 3 is to present an analysis of the actual utilization of batteries in different applications and under varying boundary conditions as well as an analysis of the impact of applications and boundary conditions on batteries' environmental and resource-related performance. The aims are:

- to provide an analysis of direct environmental impacts of batteries during use phase
- to provide an analysis of indirect environmental impacts of batteries during use phase
- to provide insights on consumer behaviour regarding end-of-life-aspects
- to identify barriers and opportunities of batteries linked to the local infrastructure
- to make recommendations on a refined product scope and on barriers and opportunities for Ecodesign

3.1. Subtask 3.1 - System aspects in the use phase affecting direct energy consumption

Subtask 3.1 aims at reporting on the direct impact of batteries on the environment and on resources during the use phase. Direct impact refers to impact, which is directly related to the function of the battery: the storage and provision of energy. Different scoping levels will be covered in the analysis: first, a strict product approach will be pursued which is then broadened to an extended product approach. After that, a technical system approach will follow, leading to an analysis from a functional system perspective.

- **Strict product approach:** In the strict product approach, only the battery system is considered. It includes cells, modules, packs, a battery management system (BMS), a protection circuit module (PCM) and passive cooling and heating elements (plates, fins, ribs, pipes for coolants). The operating conditions are nominal as defined in standards. Since relevant standards (e.g. IEC 62660, ISO 12405, IEC 61427-2, and IEC 62933-2) already differentiate between specific applications, those will also be discussed within this approach and base cases will be defined.
- **Extended product approach:** In the extended product approach, the actual utilisation and energy efficiency of a battery system under real-life conditions will be reviewed. Further, the influence of real-life deviations from the testing standards will be discussed. In that context, the defined base cases will be considered.
- **Technical system approach:** Batteries, as defined in Task 1, are either part of a vehicle or of a stationary (electrical) energy storage system, which comprise additional components such as a power electronics (inverter, converter), chargers, active cooling and heating systems and other application related equipment. However, energy consumption of these components is considered indirect losses and thus, discussed in chapter 3.2.
- **Functional approach:** In the functional approach the basic function of battery systems, the storage and provision of electrical energy, is maintained, yet other ways to fulfil that function and thus other electrical energy storage technologies are reviewed, as well.

3.1.1. Strict product approach to battery systems

As mentioned in Task 1, the product in scope is the battery system, referred to as battery. It comprises one or more battery packs, which are made up of battery modules, consisting of several battery cells, a battery management system, a protection circuit module, and passive cooling or heating elements, such as plates, fins or ribs as well as coolant pipes (see Figure 1 within the red borderline). Active cooling and heating equipment, such as fans, heat exchangers for tempering of coolant, heat pumps, heater elements etc., is usually located outside of the battery system, thus cooling and heating energy is considered as indirect loss. Furthermore, power electronics (e.g. inverter, converter), chargers and other application-related equipment (see Figure 1) is located outside of the battery system as well and thus, losses related to those components are also considered as indirect losses or even entirely out of the scope of this study and thus external.

Depending on the application, the number of cells per module, of modules per pack and of packs per battery or even the number of battery systems to be interconnected can vary.

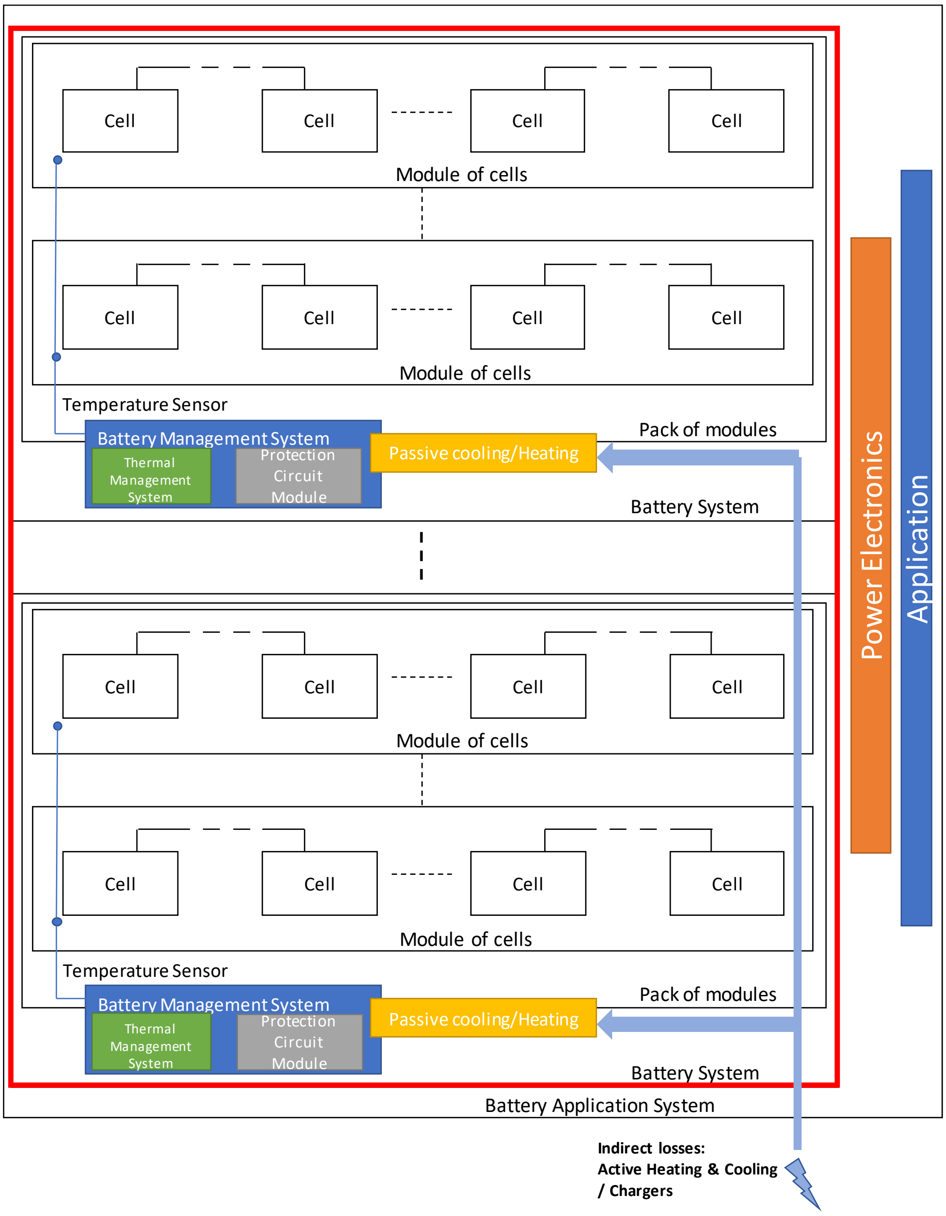


Figure 1: Representation of the battery system components and their system boundaries.

The primary function of a battery is to deliver and store electrical current at a desired voltage range and accordingly the storage and provision of electrical energy. Consequently, following the definition in Task 1, the functional unit (FU) of a battery is defined as one kWh of the total energy delivered over the service life of a battery, measured in kWh at battery system level, thus, excluding charger-, power electronics-, active cooling and heating equipment- as well as application-related losses. This is in line with the harmonized Product Environmental Footprint (PEF) for High Specific Energy Rechargeable Batteries for Mobile Applications (Recharge 2018). Accordingly, a battery is no typical energy-consuming product as for example, light bulbs or refrigerators are, but it is an energy-storing and energy-providing product. Thus, energy consumption that can directly be linked to a battery, as understood within that report, is the battery's efficiency in storing and delivering energy. Initially, the functional unit and the battery efficiency will be defined, before standard testing conditions concerning battery efficiency are reviewed and base cases are defined.

As already explained in Task 1, energy consumption during the use phase of a battery beyond its efficiency can include losses from power electronics and losses during charge, discharge and storage. Those will be modelled as 'indirect system' losses, which are part of a subsequent section 3.2. This is a similar approach to the PEF where it is called delta approach (EC 2018). It intends to model energy use impact of one product, in this case the battery, by taking into account the indirect losses caused by another product, in this case the charger. This means that the excess consumption of the charger shall be allocated to the product responsible for the additional consumption, which is the battery. A similar approach is pursued in section 3.2.

3.1.1.1. Key parameters for the calculation of the functional unit

The functional unit is a unit to measure the service that an energy related product provides for a certain application. Key parameters of a battery that are related to the functional unit and the links of those parameters to the Product Environmental Footprint pilot are the following:

- **Rated energy E_{Rated} (kWh)** is the supplier's specification of the total number of kWh that can be withdrawn from a fully charged battery pack or system for a specified set of test conditions such as discharge rate, temperature, discharge cut-off voltage, etc. (similar to ISO 12405-4 "rated capacity"). E.g.: 80 kWh/full cycle
- **Capacity (Ah or kWh)** is the total number of ampere-hours that can be withdrawn from a fully charged battery under specified conditions (ISO 12405). Strictly, the ampere-hours are used in the standards but this parameter can be also be expressed in kilowatt-hours (see Task 1).
- **Depth of Discharge DOD (%)** is the percentage of rated energy discharged from a cell, module, and pack or system battery (similar to IEC 62281) (similar to PEF "Average capacity per cycle"). Some tier 1 battery suppliers use DOD as the state of charge window for cycling: e.g. 80%
- **Full cycle FC (#)** refers to one sequence of fully charging and fully discharging a rechargeable cell, module or pack (or reverse) (UN Manual of Tests and Criteria) according to the specified DOD. It is similar to the PEF "Number of cycles". The cycle life of a battery (see section 3.1.1.2.1) is usually specified in FC. e.g. 1,500
- **Capacity degradation / State of Health SOH_{cap} (%)** refers to the decrease in capacity over the lifetime (service life) as defined by a standard or declared by the manufacturer.

A SOH_{cap} of 80% at the end of a battery's service life (EOL) indicates a capacity degradation of 20%. SOH_{cap} is often indicated by SOH only. e.g. 80% SOH_{cap} at EOL

- The **quantity of functional units of a battery Q_{FU}** is the maximum number of kWh a battery can deliver during its lifetime. It can be calculated as follows (the input figures are just exemplary and could represent a battery-electric medium- to large-sized vehicle):

$$\boldsymbol{Q_{FU}} = \underbrace{E_{Rated} * \mathrm{DOD}}_{PEF\ energy\ delivered\ per\ cycle} * \underbrace{\mathrm{FC}}_{PEF\ number\ of\ cycles} = 80\mathrm{kWh} * 80\% * 1{,}500\mathrm{FC}$$
$$= 96{,}000\ \mathrm{FU}\ (\mathrm{kWh\ per\ battery\ lifetime})$$

Consequently, it is assumed, that the DOD defines the energy delivered per cycle and that the absolute value of the energy delivered per cycle stays constant over the battery lifetime. This can be justified by the BMS, that usually limits the usable battery capacity in such a way, that the absolute DOD can be assured over the whole battery lifetime.

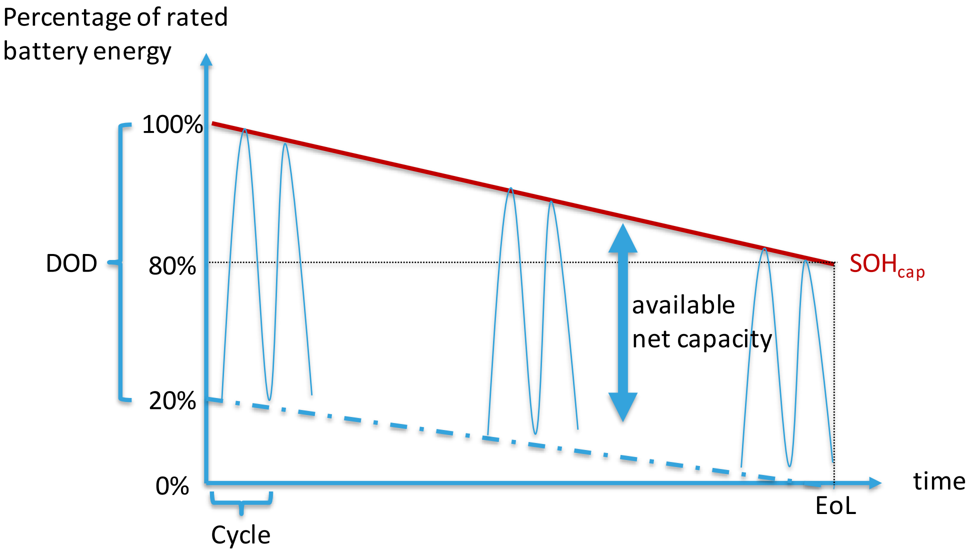


Figure 2: Visualisation of terms related to Q_{FU} calculation.

3.1.1.2. Standards for battery testing and testing conditions

Having a look at standards linked to the testing of battery cells and battery packs or systems, numerous tests and testing conditions can be found in standards on batteries for electric vehicles (EV) or for electrical energy storage systems (ESS).

General standard testing conditions for batteries can hardly be found. This is because (1) most standards already focus on specific applications of battery cells and battery systems for example in EV, such as battery-electric vehicles (BEV) or plug-in-hybrid-electric vehicles (PHEV) (such as IEC 62660-1, ISO 12405-4) or in on-grid and off-grid ESS (IEC 61427-2 or IEC 62933-2) and (2) for each test usually a big variety of testing conditions is specified. Parameters that define the testing conditions in the IEC and ISO standards are:

- **C-rate *n*C (A),** Current rate equal to n times the one-hour discharge capacity expressed in ampere (e.g. 3C is equal to three times the 1h current discharge rate, expressed in A) (ISO 12405-4).
- **Reference test current I_t (A)**: equals the *rated* capacity: C_n [Ah]/1 [h]. Currents should be expressed as fractions of multiples or fractions of I_t. if n = 5, then the discharge

current used to verify the rated capacity shall be 0.2 I_t [A] (IEC 61434). Note: the difference between C-rate and I_t-rate is important for battery chemistries for which the capacity is highly dependent on the current rate. For Li-ion batteries, it is of minor importance. See for more information the section “Freedom in reference capacity: C-rate and I_t-rate” in White paper (2018).

- **Temperature T / Room temperature RT (°C)** which is a temperature of 25+/-2°C (ISO 12405-4)
- **State of charge SOC (%)** is the available capacity in a battery pack or system expressed as a percentage of rated capacity (ISO 12405-4).

  with

- **Capacity C (Ah)** as the total number of ampere-hours that can be withdrawn from a fully charged battery under specified conditions (ISO 12405-4)
- **Rated capacity C_n (Ah)** which is the supplier's specification of the total number of ampere-hours that can be withdrawn from a fully charged battery pack or system for a specified set of test conditions such as discharge rate, temperature, discharge cut-off voltage, etc. (ISO 12405-4). The subscript n refers to the time base (hours) for which the rated capacity is declared (IEC 61434). In many standards, this is 3 or 5.

3.1.1.2.1. Key parameters for the calculation of direct energy consumption of batteries in applications (application service energy)

In the context of this study, it is not useful to go into the details of all of the above-mentioned standards, tests and test conditions, but to select the most important ones who are related to energy consumption. In order to be able to determine the direct energy consumption of a battery based on the quantity of functional units of a battery system, the following parameters, mainly referring to IEC 62660 and ISO 12405-4, are to be considered. IEC 62660 relates to the cell level, whereas ISO 12405 relates to the battery system level. For this study, according to the definition of the strict product approach, the system level has to be taken into consideration:

- **Energy efficiency η_E (energy round trip efficiency) (%)** - each FU provided over the service life of a battery is subject to the battery’s energy efficiency. It can be defined as the ratio of the net DC energy (Wh discharge) delivered by a battery during a discharge test to the total DC energy (Wh charge) required to restore the initial SOC by a standard charge (ISO 12405-4). E.g. 96% (PEF)
  - In most standards, energy efficiency of batteries is measured in steady state conditions. These conditions usually specify temperature (e.g. 0°C, RT, 40°C, 45°C), constant C-rates for charge and discharge (discharge BEV 1/3C, PHEV 1C according to IEC 62660, charge by the method recommended by the manufacturer) as well as SOCs (100%, 70%; for BEV also 80% according to IEC 62660, 65%, 50%, and 35% for PHEV according to 12405-4)
  - For batteries used in PHEV however, in ISO 12405-4 for example, energy efficiency is also measured at a specified current profile pulse sequence, which is closer to the actual utilisation, including C-rates of up to 20C.
  - For batteries used in ESS, in IEC 61427-2 for example, also load profiles for testing energy efficiency are defined (see Figure 3)

- **Self-discharge/charge retention SD (%SOC/month)** - each battery that is not under load loses part of its capacity over time (temporarily). Charge retention is the ability of a cell to retain capacity on open circuit under specified conditions of storage. It is the ratio of the capacity of the cell/battery system after storage to the capacity before storage (IEC 62620). E.g. 2%/month
    - Self-discharge of EV batteries is measured by storing them at 45°C, 50% SOC and for a period of 28 days (IEC 62660-1), or at RT to 40°C and 100% SOC for BEV, 80% SOC PHEV with a fully operational BMS (ISO 12405-4), storing the batteries for 30 days
    - The remaining capacity after the self-discharge period is measured at 1C for PHEV and 1/3C discharge for BEV, leading to the self-discharge.
- **Cycle life L_{Cyc} (FC)** is the total number of full cycles a battery cell, module or pack can perform until it reaches its End-of-Life (EOL) condition related to its capacity fade or power loss (EOL will be further explained in section 3.3). E.g. 1,500 FC
    - Cycle life of EV batteries is determined by using specified load profiles for PHEV and BEV application (see Figure 4) at temperatures between RT and 45°C
    - PHEV cycle life tests cover SOC ranges of 30-80% and C-rates of up to 20C. If the manufacturer's specified maximum current is lower than 20C, then the test profile is adapted in a predefined way.
    - BEV cycle life tests cover SOC ranges of 20-100%
- **Calendar life L_{Cal}/storage life (a)** is the time in years, that a battery cell, module or pack can be stored under specified conditions (temperature) until it reaches its EOL condition (see also SOH in section 3.1.1.2.3). It relates to storage life according to IEC 62660-1, which is intended to determine the degradation characteristics of a battery. E.g. 15 years
    - Ambient conditions for the determination of calendar life are 45°C and a measuring period of three times 42 days
    - Initial SOC for (P)HEV is at 50%, the discharge after storage takes place at 1C
    - Initial SOC for BEV is at 100%, the discharge after storage takes place at 1/3C

The actual service life of a battery cell, module, pack or system is defined by the minimum of cycle life and calendar life.

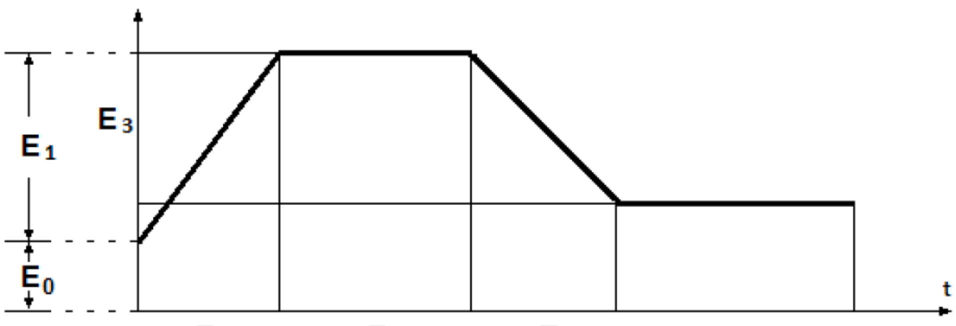


Figure 3: Typical ESS charging/discharging cycle (IEC 62933-2)

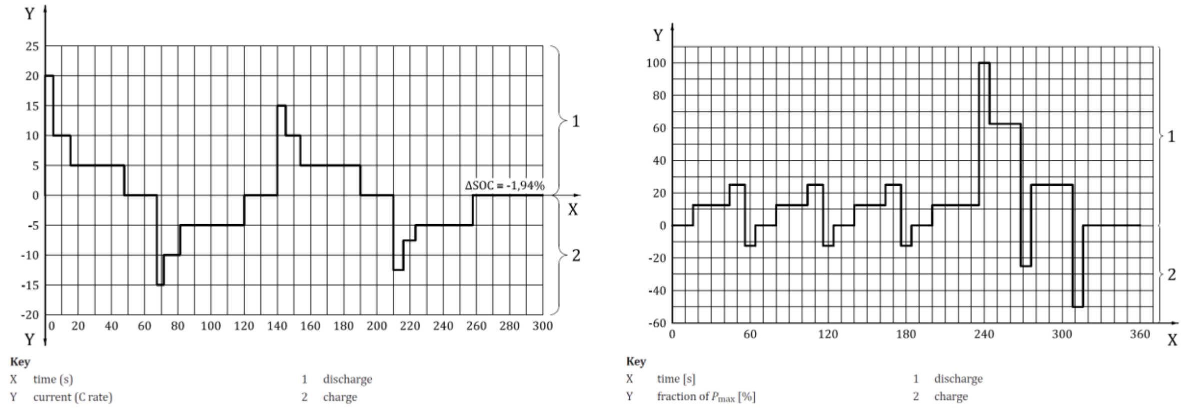


Figure 4: Cycle test profile PHEV (left) and BEV (right) (discharge-rich) (ISO 12405-4)

The **application service energy (AS)** (kWh) is the total energy required by the application over its lifetime in kWh. With the lifetime of an application (13 years), the number of annual full cycles FC_a (FC/a) (e.g. 60 FC/a), a rated energy of 80 kWh and 80% DOD it can be calculated as follows:

$$AS = Lifetime\ application * FC_a * E_{rated} * DOD$$

$$= 13 * 60 * 80 * 80\% = 49{,}920\ kWh$$

This formula can be used for all types of applications, when the number of annual full cycles is given. For EVs, given that data on annual all-electric vehicle kilometres travelled (VKT) (e.g. 14,000 km), energy consumption of the vehicle (0, 20 kWh/km) and recovery braking (20%) is available, the following formula can be used:

$$AS_{EV} = Lifetime\ application * annual\ all\text{-}electric\ VKT * energy\ consumption * (1 + recovery\ braking$$

$$= 13 * 14{,}000 * 0{,}20 * (1 + 20\%) = 43{,}680\ kWh$$

If the AS is higher than the Q_{FU} of the battery used in that specific application, more than one battery is required for that application, and thus, a battery replacement is required. The following formula is applied for the calculation of the number of batteries needed to fulfil the application service:

$$N_{bat} = \frac{AS}{Q_{FU}} = \frac{43{,}680}{96{,}000} = 0.46$$

Since that figure is lower than one, in that example, there is no need for a battery replacement.

The actual lifetime (service life) of a battery, as a simplification, is determined by the minimum of cycle life and calendar life (in reality, a superposition of both aging effects takes place). Whichever is reached first, determines the end of life. Thus, it can be calculated as follows:

$$service\ life_{bat} = \min\{\mathrm{L_{Cyc}}; \mathrm{L_{Cal}FC_a}\}$$

As explained above, when using batteries losses occur due to battery energy efficiency and self-discharge. With an average state of charge SOC_{Avg} (%) of 50%, the losses can be calculated as follows:

$$\textbf{Losses} = Q_{\mathrm{FU}} * (1 - \eta_{\mathrm{E}}) + \mathrm{SD} * \underbrace{\min\left\{\frac{\mathrm{L_{Cyc}}}{\mathrm{FC_a}}; \mathrm{L_{Cal}}\right\} * 12}_{\text{actual service life in months}} * \mathrm{SOC_{Avg}E_{Rated}}$$

$$= 86{,}400 * (1 - 0{,}96) + 0{,}02 * \min\left\{\frac{1{,}500}{60}; 15\right\} * 12 * 50\% * 80$$

$$= 3{,}840 + 192 = 4{,}032$$

For the exemplary figures chosen, the impact of a battery's energy efficiency on its direct energy consumption is a lot higher than the effect of self-discharge. Further, E_{Rated}, DOD, cycle life as well as calendar life, but also the actual annual utilisation of the battery shows high impact on the AS and thus, on the direct energy consumption of a battery.

3.1.1.2.2. Key parameters for the calculation of battery energy efficiency

As we could show in chapter 3.1.1.2.1, the energy efficiency of a battery has strong impact on its direct energy consumption. Consequently, the battery energy efficiency will be reviewed more detailed. The key parameters of a battery that are required for calculating its efficiency are the following:

- **Voltaic efficiency η_V (%)** can be defined as ratio of the average discharge voltage to the average charge voltage. The charging voltage is always a little higher than the rated voltage in order to drive the reverse chemical (charging) reaction in the battery (Cadex Electronics 2018).
- **Coulombic efficiency η_C (%)** is the efficiency of the battery, based on charge (in coulomb) for a specified charge/discharge procedure, expressed by output charge divided by input charge (ISO 11955).
- With V, I and T as average Voltage, average Current and Time for C Charge and D Discharge the **battery energy efficiency** can be calculated as follows (Recharge 2018):

$$\boldsymbol{Energy\ efficiency} = \left(\frac{V_D}{V_C}\right)\left(\frac{I_D * T_D}{I_C * T_C}\right) = (voltaic\ effiency)(coulombic\ efficiency)$$

Li-ion batteries have a coulombic efficiency close to 100% (better than 99.9% according to Gyenes et al. (2015)) (no side reaction when charged up to 100%). Consequently, the voltaic efficiency is the main lever concerning the battery energy efficiency. It is always below one because of the internal resistance of a battery, which has to be overcome during the charging process, leading constantly to higher charging voltages compared to discharging voltages. Consequently, a higher discharge voltage as well as a lower charge voltage, while all other parameters are kept unchanged, improve efficiency. Figure 5 shows charge and discharge voltages for two different cell chemistries (nickel manganese cobalt (NMC) and lithium iron phosphate (LFP)) in relation to the SOC and the resulting efficiency. It has to be mentioned however, that the scope of this study is not limited to those cell chemistries (see also Task 1 and Task 4). First it can be seen, that charge voltage is higher than discharge voltage for both cell chemistries. Second, the efficiency of NMC cells in monotonically increasing with SOC. Third, the efficiency of LFP decreases rapidly in the extremities (0 and 100% SOC) (Redondo-Iglesias et al. 2018a).

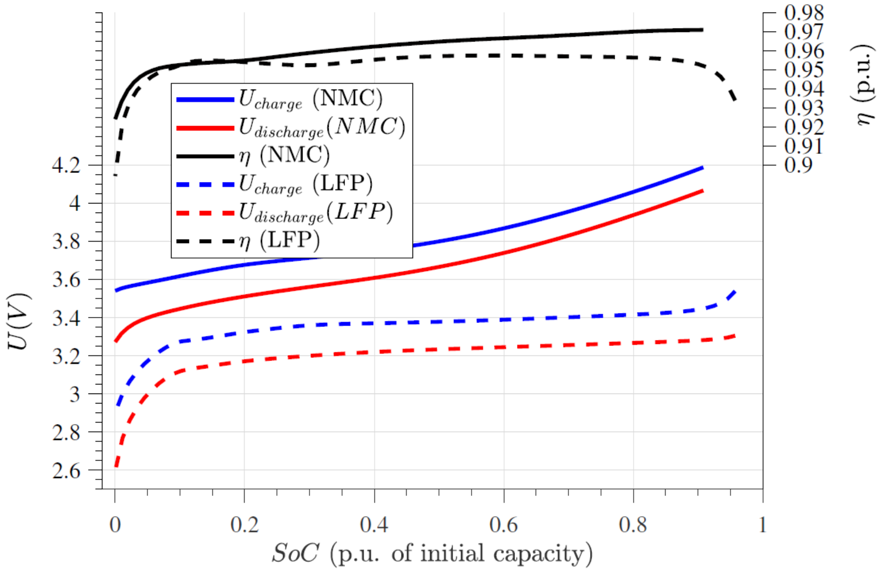


Figure 5: Charge and discharge voltages (left y-axis) and efficiency (right y-axis) of fresh cells (Source: Redondo-Iglesias et al. (2018a)).

Different cell chemistries and designs can be differentiated (see Task 4), which also differ in energy efficiency. According to Redondo-Iglesias et al. (2018a) for Lithium Iron Phosphate batteries an energy efficiency of around 95% can be assumed, while for Lithium Nickel Manganese Cobalt Oxide an energy efficiency of 96% at cell level is assumed. Recharge (2018) also assume 96% energy efficiency as an average. Including losses due to the BMS (thermal managements system, protection circuit module) leads, according to Schimpe et al. (2018) and expert interviews to a battery efficiency on system level, as defined within this study, of 92%.

Furthermore, it has to be noted that the energy efficiency strongly depends on the charge/discharge currents (C-rate, power) for given cell chemistry and design (see formula above).

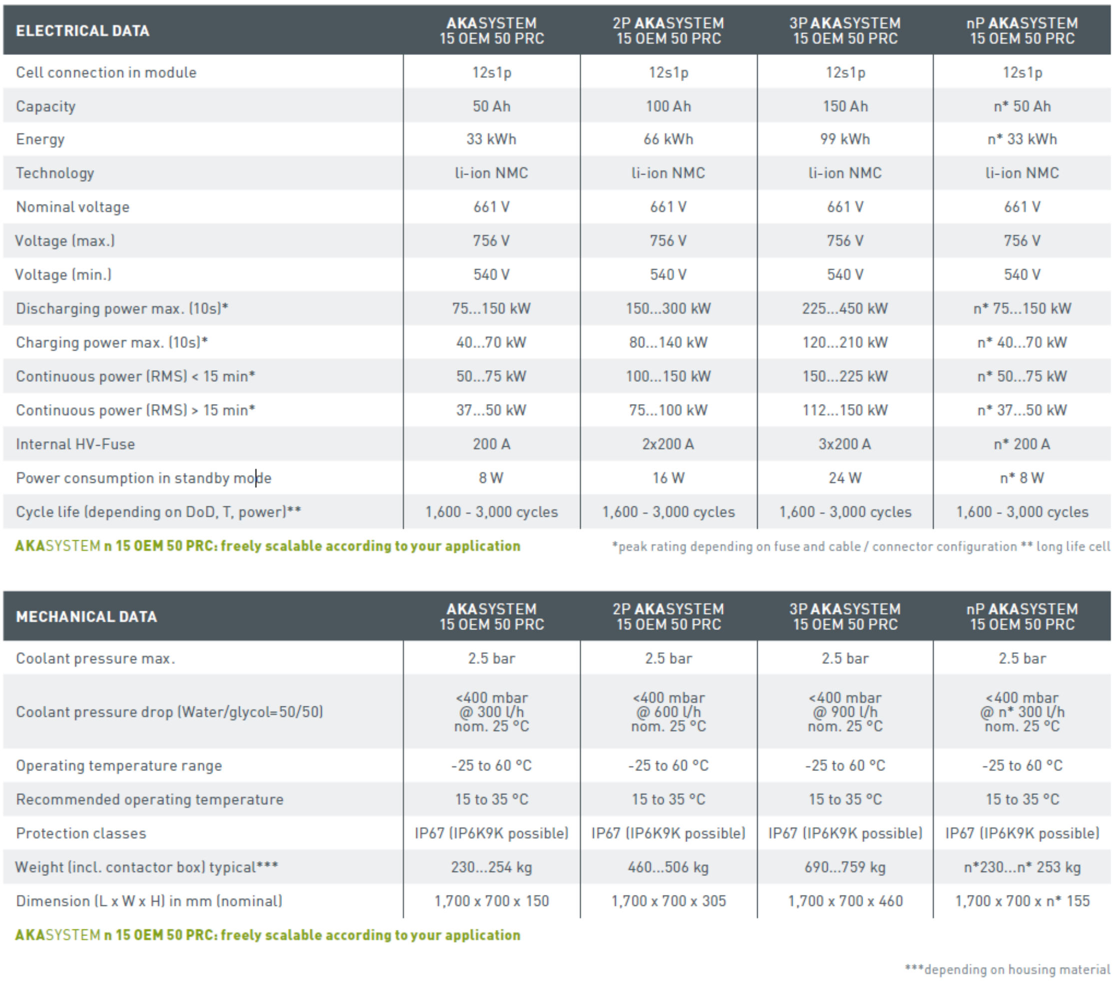
However, it has to be mentioned that these statements are not generalizable. Battery cell characteristics depend on much more than the cathode material only. Any other component (e.g. anode, electrolyte, separator), size and format (cylindrical, pouch, prismatic; see Task 4) as well as the combination of materials and the manufacturing process largely influence the cell characteristics. Consequently, generalizable statements when comparing for example NMC and LFP cells, regarding cycle life or safety, can hardly be made and have to be treated with caution.

3.1.1.2.3. Further parameters related to battery efficiency and affected energy

Besides the parameters that have already been described and discussed, further terms and definitions referring to batteries, battery efficiency and affected energy have to be introduced:

- **Energy E (kWh)** is the total number of kWh that can be withdrawn from a fully charged battery under specified conditions (similar to ISO 12405-1 “capacity”).
- **State of health SOH (%)** defines the health condition of a battery; however, no definition can be derived from standards. It can be described as a function of capacity degradation, also called capacity fade (see ISO 12405-4) and internal resistance. Depending on the application, a battery can only be operated until reaching a defined SOH, thus, it relates to the service life of a battery.
- **Internal resistance R (Ω)** is the resistance within the battery, module, pack or system. It is generally different for charging and discharging and dependent on the current, the battery state of charge and state of health. As internal resistance increases, the voltaic efficiency decreases, and thermal stability is reduced as more of the charging/discharging energy is converted into heat.
- **Rated voltage V_R (or nominal Voltage) (V)** is a suitable approximate value (mean value between 0% and 100% DOD) of the voltage during discharge at a specified current density used to designate or identify the voltage of a cell or a battery (IEC 62620).
- **Voltage limits V_L (V)** define the maximum and minimum cut-off voltage limits for safe operation of a battery cell. The maximum voltage is defined by the battery chemistry. For Lithium-ion battery (LIB) cells of LCO, NCA and NMC type 4.2 V are typical voltages. For LFP type, it is 3.65 V. However, the voltages mentioned are operational limits that should be kept in order to reach a certain battery cycle life. There are also higher voltage limits that relate to safety aspects. The battery is fully charged when the difference between battery voltage and open circuit voltage is within a certain range.
- **Open circuit voltage V_{OC} (V)** is the voltage across the terminals of a cell or battery when no external current is flowing. (UN Manual of Tests and Criteria).
- **Volumetric energy density (Wh/l)** is the amount of stored energy related to the battery pack or system volume and expressed in Wh/l (ISO 12405-4).
- **Gravimetric energy density (Wh/kg)** is the amount of stored energy related to the battery pack or system mass and expressed in Wh/kg (ISO 12405-4).
- **Volumetric power density (W/l)** is the amount of retrievable constant power over a specified time relative to the battery cell, module, and pack or system volume and expressed in W/l.
- **Gravimetric power density (W/kg)** is the amount of retrievable constant power over a specified time relative to the battery cell, module, pack or system mass and expressed in W/kg.

Figure 6 shows a typical data sheet of a battery system for use in heavy-duty vehicles. Most of the parameters and terms that have been introduced within that study can be found on that data sheet. The calendar life and the energy efficiency of the battery system, however, is not stated in the data sheet.



ELECTRICAL DATA	AKASYSTEM 15 OEM 50 PRC	2P AKASYSTEM 15 OEM 50 PRC	3P AKASYSTEM 15 OEM 50 PRC	nP AKASYSTEM 15 OEM 50 PRC
Cell connection in module	12s1p	12s1p	12s1p	12s1p
Capacity	50 Ah	100 Ah	150 Ah	n* 50 Ah
Energy	33 kWh	66 kWh	99 kWh	n* 33 kWh
Technology	li-ion NMC	li-ion NMC	li-ion NMC	li-ion NMC
Nominal voltage	661 V	661 V	661 V	661 V
Voltage (max.)	756 V	756 V	756 V	756 V
Voltage (min.)	540 V	540 V	540 V	540 V
Discharging power max. (10s)*	75...150 kW	150...300 kW	225...450 kW	n* 75...150 kW
Charging power max. (10s)*	40...70 kW	80...140 kW	120...210 kW	n* 40...70 kW
Continuous power (RMS) < 15 min*	50...75 kW	100...150 kW	150...225 kW	n* 50...75 kW
Continuous power (RMS) > 15 min*	37...50 kW	75...100 kW	112...150 kW	n* 37...50 kW
Internal HV-Fuse	200 A	2x200 A	3x200 A	n* 200 A
Power consumption in standby mode	8 W	16 W	24 W	n* 8 W
Cycle life (depending on DoD, T, power)**	1,600 - 3,000 cycles	1,600 - 3,000 cycles	1,600 - 3,000 cycles	1,600 - 3,000 cycles

AKASYSTEM n 15 OEM 50 PRC: freely scalable according to your application

*peak rating depending on fuse and cable / connector configuration ** long life cell

MECHANICAL DATA	AKASYSTEM 15 OEM 50 PRC	2P AKASYSTEM 15 OEM 50 PRC	3P AKASYSTEM 15 OEM 50 PRC	nP AKASYSTEM 15 OEM 50 PRC
Coolant pressure max.	2.5 bar	2.5 bar	2.5 bar	2.5 bar
Coolant pressure drop (Water/glycol=50/50)	<400 mbar @ 300 l/h nom. 25 °C	<400 mbar @ 600 l/h nom. 25 °C	<400 mbar @ 900 l/h nom. 25 °C	<400 mbar @ n* 300 l/h nom. 25 °C
Operating temperature range	-25 to 60 °C	-25 to 60 °C	-25 to 60 °C	-25 to 60 °C
Recommended operating temperature	15 to 35 °C	15 to 35 °C	15 to 35 °C	15 to 35 °C
Protection classes	IP67 (IP6K9K possible)	IP67 (IP6K9K possible)	IP67 (IP6K9K possible)	IP67 (IP6K9K possible)
Weight (incl. contactor box) typical***	230...254 kg	460...506 kg	690...759 kg	n*230...n* 253 kg
Dimension (L x W x H) in mm (nominal)	1,700 x 700 x 150	1,700 x 700 x 305	1,700 x 700 x 460	1,700 x 700 x n* 155

AKASYSTEM n 15 OEM 50 PRC: freely scalable according to your application

***depending on housing material

Figure 6: Typical battery system data sheet (Source: Akasol (2018)).

3.1.1.3. Definition of base cases

Looking at the global battery demand (see Task 2), **EV** and **stationary ESS** stand out, especially referring to future market and growth potential. Besides the BEV and PHEV markets, large scale ESS also show high growth rates in future. A bit lower, but still substantial are growth rates for residential ESS according to Task 2 report. In EV applications, the main purpose of batteries is supplying electrical energy to electric motors that are providing traction for a vehicle. In stationary applications they balance load (supply and demand for electricity) and consequently store electrical energy received from the grid or directly from residential power plants (such as photovoltaic (PV) systems or block-type thermal power stations) or commercial power plants (renewable or non-renewable energy sources) and feed it back to the grid or energy consumers.

Since for the two mentioned fields of application, EV and ESS, numerous specific applications can be distinguished, they have to be narrowed down further. As the purpose of this report is to identify the impact of batteries on energy consumption, those applications should be selected for further analyses that have the highest energy consumption. For the **EV** field greenhouse gases (GHG) from road transport are regarded as a useful proxy for energy consumption. Figure 7 shows, that the highest share of GHG can be attributed to **passenger cars** with more than 60%. These are followed by **heavy-duty trucks and buses**. Light duty trucks, motorcycles and other road transportation play a minor role only and are therefore not considered further.

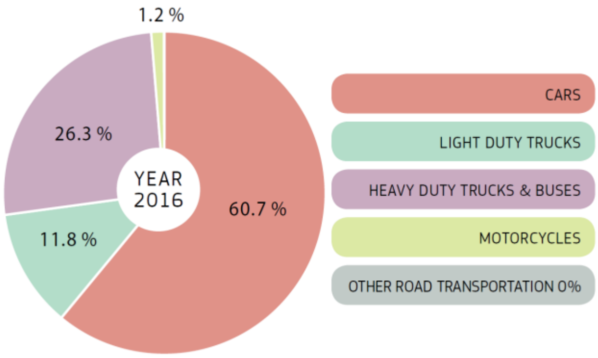


Figure 7: GHG emissions from road transport in the EU28 in 2016 by transport mean [%] (Source: European Commission (2018)).

In 2017 more than 15 mio. new passenger cars were registered in the EU28 (European Commission 2018) in contrast to less than 2 mio. light commercial vehicles/light duty trucks, which stresses the importance of passenger cars. Light commercial vehicles and light duty trucks weigh less than 3.5 tonnes and thus, are more similar to passenger cars, than to medium- or heavy-duty trucks. Due to the similarity of light commercial vehicles and passenger cars in terms of battery capacity, fuel consumption or annual mileage, light commercial vehicles are not considered as an own base case but considered to be represented by the passenger car base cases.[1] Passenger cars have, in terms of registrations but also in terms of GHG emissions, by far the highest share in road transport. For that reason and since many different passenger car segments exist, which should be represented in that study, two passenger car types are considered: small-sized cars and medium- to large-sized cars.

Furthermore, 370,000 medium-and heavy-duty trucks were registered in the EU28 in 2017, while only 42,000 buses and coaches were registered (European Commission 2018). Beyond that, the technical characteristics of buses, such as battery capacity, fuel consumption or annual mileage, do not differ significantly from the characteristics of HDT.[2] For that reason,

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[1] Battery capacities of light commercial vehicles, which are already on the market, range between 20 kWh (Iveco Daily Electric, Nissan e-NV200 Pro, Streetscooter Work Box, Citroen Berlingo Electrique) and 40 kWh (EMOVUM E-Ducato, Mercedes-Benz eSprinter and eVito (Schwartz 2018). Furthermore, for the light commercial vehicle Renault Kangoo Z.E. Boblenz (2018) states a fuel consumption of 15,2 kWh/100km according to the NEDC which is converted to 19kWh/100km according to the EPA FTP. Finally, light commercial vehicles are driven 15,500 km on average per year in the UK (Dun et al. 2015) and 19,000 km in Germany (KBA 2018), which is just slightly higher than for passenger cars.

[2] The battery capacity of urban buses ranges between 80 kWh and 550 kWh (Electrek 2017; VDL Bus & Coach 2019), while most of the buses have a battery capacity of around 200 kWh. Aber (2016) states an average energy consumption of 125 kWh per 100 km and according to Papadimitriou et al. (2013) urban buses travel on average between 40.000 and 50.000 km a year, while coaches travel up to 60.000 km on average.

considering buses as an own base case would not lead to significant new insights, regarding the Ecodesign process.

Trucks can be further differentiated according to their gross vehicle weight (GVW) in medium-duty trucks (up to 16 tonnes GVW) and heavy-duty trucks (HDT) (more than 16 tonnes GVW). Since the registrations of HDT are three times higher than those of medium-duty trucks (European Commission 2018), the former will be in the focus of this study. HDT can be heavy-duty straight trucks, semi-trailer trucks, or tractor units, referred to as heavy-duty tractor units (HDTU).

Regarding **passenger cars, BEV and PHEV** are the most promising battery-related applications (Gnann 2015). For **HDT** also **battery-electric vehicles** seem to be very promising, while for **HDTU plug-in-hybrid solutions** seem to be promising (Wietschel et al. (2017)).

There are currently four potential main applications for **stationary ESS** (see also Task 2): PV battery systems, peak shaving, direct marketing of renewable energies and the provision of operating reserve for grid stabilization in combination with multi-purpose design (Michaelis 2018). Since PV battery systems, referred to as **residential ESS** and the provision of operating reserve and multi-purpose design, referred to as **commercial ESS,** seem to have the highest market potential (see Thielmann et al. (2015b) and Task 2), they will be in the scope of this study.

The most promising battery technology (see Task 4) for both fields of application, EVs as well as ESS are large-format lithium-ion batteries. This is due to their technical (in particular energy density, lifetime) as well as economic (cost reduction) potential. It has to be noted that the product scope is still the battery system as defined in section 3.1.1. However, the utilization of the battery, represented by a load profile for example, as well as battery capacity varies.

To sum it up the following applications are in the scope of this study and define **base cases**:

EV applications:

- passenger BEV (medium to large)
- passenger BEV (small)
- passenger PHEV
- battery-electric HDT
- plug-in-hybrid HDTU

Stationary applications:

- residential ESS
- commercial ESS

The base cases defined above have certain requirements concerning technical performance parameters, such as energy densities, calendar and cycle life, C-rates (fast loading capabilities) and tolerated temperatures, which will be defined in the following sections.

Parameters for the definition of base cases

Looking at the formula for the calculation of the direct energy consumption of batteries (see chapter 3.1.1.2.1), the following parameters have to be defined for all base cases:

- Rated battery capacity
- Depth of discharge
- Annual full/operating cycles base case
- Calendar life base case
- Energy efficiency battery

3.1.1.3.1. Base cases for EV applications

Rated battery capacity on application level

The required and suitable rated battery capacity highly depends on the actual vehicle type. The bigger and heavier a car is, the larger the battery capacity should be. Currently for BEV 20 to 100 kWh (Tesla Model S and X) are common battery capacities, although larger battery capacities might be available for special sport cars. PHEV usually have a battery capacity of 4 to 20 kWh. Medium- to large-sized cars currently have a battery capacity between 60 and 100 kWh. Therefore, we take **80 kWh** for the **base case BEV (medium to large).** The current sales-weighted average of rated battery capacity for passenger **BEV** in Europe is 39 kWh, thus we assume **40 kWh** to be the battery capacity of **small-sized passenger BEV**. For passenger **PHEV** the average is at 12 kWh and stayed almost constant (see Figure 8). Therefore, we assume **12 kWh for PHEV**.

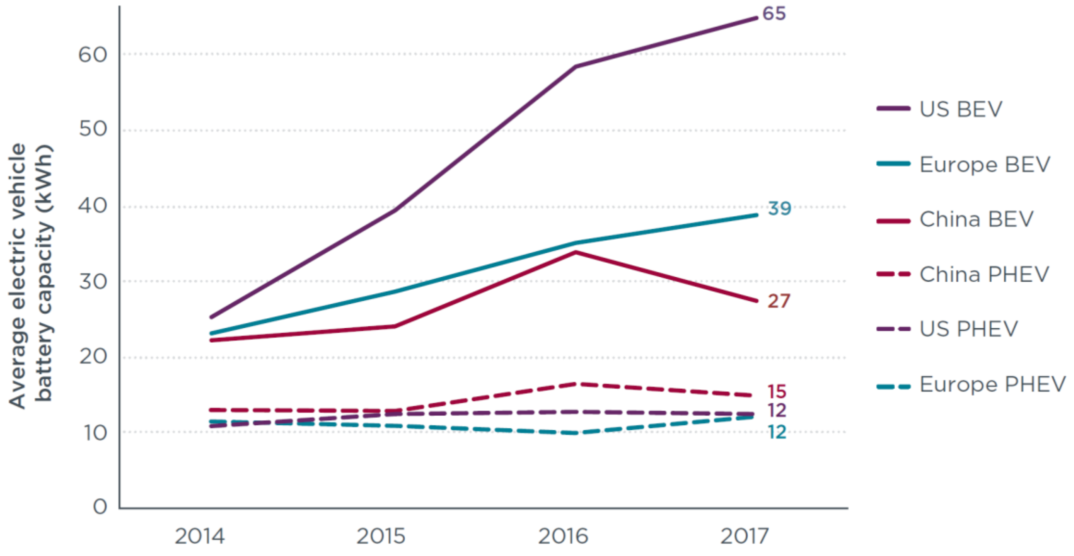

Figure 8: Sales-weighted average of xEV battery capacities for passenger cars [kWh] (Source: ICCT (2018))

In contrast to passenger cars, no battery-electric **HDT** (between 12 and 26 to gross vehicle weight (GVW)) is available on the market. So far, only some pre-series trucks are tested by selected customers (Daimler 2018; MAN Truck & Bus AG 2018). Nevertheless, truck OEM specified technical details for their announcements, ranging from 170 kWh battery energy of a DAF CF Battery Electric up to a Tesla Semi (HDTU) with 1,000 kWh battery capacity (Honsel

2018). Most of the battery capacities currently stated range between 200 and 300 kWh, however, a further increase can be expected for the future and thus, 360 kWh is assumed for the base case. According to Hülsmann et al. (2014) and Wietschel et al. (2017) for long range **HDTU** purely battery-electric trucks seem not to be a proper solution. They argue that range and costs of battery-electric HDTU are not competitive. As mentioned, some truck manufacturers however, such as Tesla (Tesla Semi) and Daimler (Freightliner eCascadia) announced HDTUs with ranges of 400 to 800 km being provided by a huge battery. Nevertheless, two drawbacks are linked with high battery capacities: First, because of their high weight, they significantly reduce payload, which is hardly acceptable for truck operators. Second, big batteries, besides their negative ecological impact, which is increasingly discussed in public and the limited availability of resources, are very expensive. Since in a business context (e.g. logistics service providers), economic aspects and as such especially the total cost of ownership of operating a truck are decisive, from the current point of view battery-electric trucks don't have a high market potential, thus plug-in hybrid HDTU are considered. Following Hülsmann et al. (2014) and Wietschel et al. (2017), a battery energy of **160 kWh** is assumed for PHEV **HDTU**.

Depth of Discharge Referring to Hülsmann et al. (2014) for BEV applications a DOD of 80% is assumed. For PHEV applications, 75% DOD seems to be reasonable, according to expert interviews.

Annual full/operating cycles and calendar life base case

The number of operating cycles[3] per year can be retrieved by dividing the all-electric annual vehicle mileage by the all-electric range of the vehicles. Thus, first the all-electric annual mileage of vehicles has to be determined, before the all-electric range and the calendar life of the base cases are defined.

Annual mileage

Although it is argued, that driving profiles of ICEV (internal combustion engine vehicles) and BEV or PHEV might differ (Plötz et al. 2017a) (on the one hand the range of EV is limited but on the other hand their variable costs are comparably low in contrast to their high fixed costs, resulting in high annual mileages being beneficial for EV) for this study it is assumed, that the same annual mileage and driving patterns apply to all powertrains. Further, for simplification reasons we do not thoroughly review distinct (daily) driving patterns and profiles but average annual and daily driving distances. However, taking Figure 9 into consideration it becomes clear that average values are just a rough approximation of the actual daily driving distances, which can vary greatly in size.

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[3] For EV operating cycles are calculated, since data can be retrieved more easily than for the calculation of full cycles.

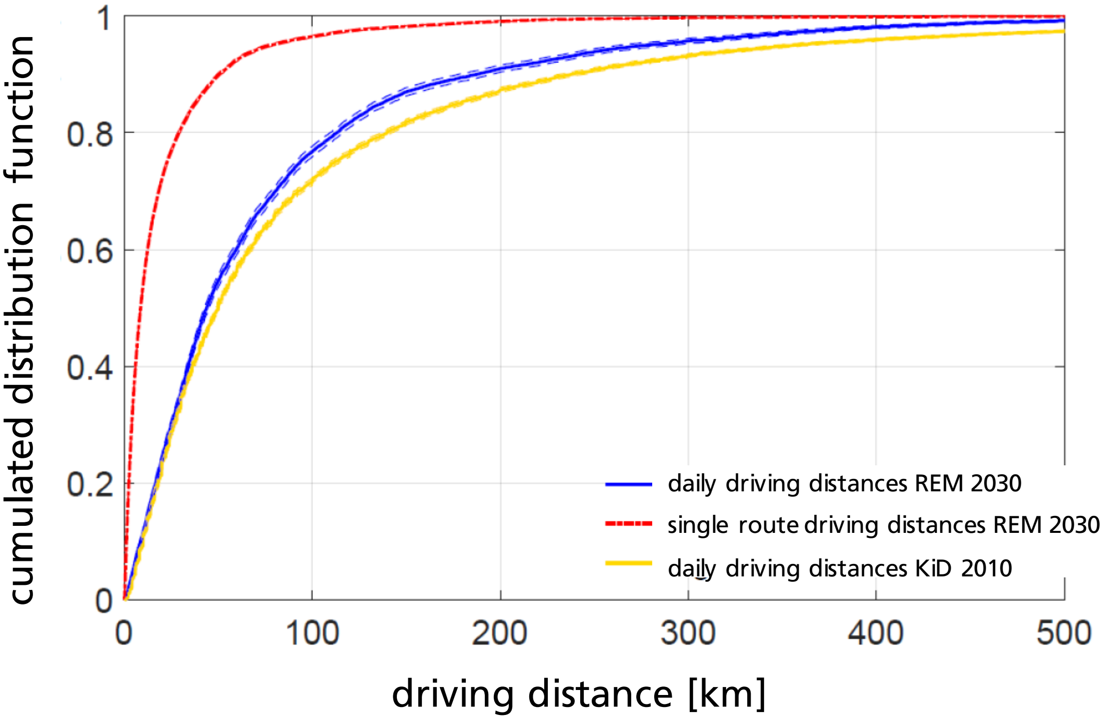


Figure 9: Daily and single route driving distances of passenger cars in Germany (Source: Funke (2018)).

The average vehicle kilometres travelled (VKT) per **passenger car** and year in the EU28 is approximately 14,000 km for medium-large passenger cars and 11,000 km for small passenger cars according to Papadimitriou et al. (2013). Further, the average retirement age of medium-large cars is around 13 years, while for small cars it is 14 years. However, the service life of EVs could be longer than that of ICEV because of less mechanical parts subjected to failure risk.

HDT drive on average **50,000 km** per year in the EU28 (Papadimitriou et al. 2013). Further, the average for **HDTU** is **100,000 km** per year. The typical operating life is **14 years** for **HDT** and **12 years** for **HDTU** in the EU(Papadimitriou et al. 2013).

All-electric range and mileage

For **BEV**, naturally the entire annual mileage is driven all electric. Plötz et al. (2017b) find, that in Germany each passenger car is used on **336 of 365 days** of the year, thus 40 km is the assumed daily all-electric mileage of a BEV passenger car. Further, the all-electric driven share of passenger **PHEV** is calculated by Plötz et al. (2017a) and it is about 40-50% with 40 km all-electric range. Since the base case PHEV's all electric range is 50 km (battery capacity multiplied with DOD, divided by energy consumption; required values to be discussed in the next paragraphs) 50% all electric mileage is assumed, leading on an annual basis to **7,000 km**. **HDT** drive on **260 days** per year (daily ~190 km all-electric for HDT and 380 km for HDTU) (Wietschel et al. 2017). Since the all-electric range of HDT is **240 km** (same calculation as for passenger PHEV) no intermediate charging is required. **HDTU** have an all-electric range of only **86 km**, thus intermediate charging is required for achieving high all-electric VKT. The HDTU however is continuously on the road, only making stops in order to account for mandatory periods of rest. A break of 45 to 60 minutes for fast charging should be sufficient, in order to fully recharge the battery, leading to a daily range all-electric range of 140 km, which might be increased further by mandatory breaks. Thus, we conclude, that 50,000 of the 100,000 kilometres per year might be driven all-electric by the HDTU.

The all-electric ranges of EVs can either be derived from measurements based on official test cycles or calculated by multiplying the rated energy by the DOD and dividing the result by the energy consumption of the vehicle (the latter approach is less accurate and it is therefore neglected). The energy consumption in that case also has to be derived from measurements according to official driving cycles.

EV energy consumption

The application service energy of a vehicle can roughly be differentiated in energy required for traction and energy required by ancillary consumers, such as entertainment systems, air conditioning or light machine, servo steering and ABS. Figure 10 shows the energy consumption [kWh] and distribution of a Nissan Leaf (2012) on a specific drive cycle (~12km). Around 30% of the energy provided to the electric motor can be fed back into the battery due to regenerative braking (explained below). However, for the base cases we assume 20% as a conservative assumption. The accessories load sums up to approximately 3%. However, it is important to note, that referring to these figures no cooling or heating of the driver cabin is included. This can increase energy consumption by around 25%.

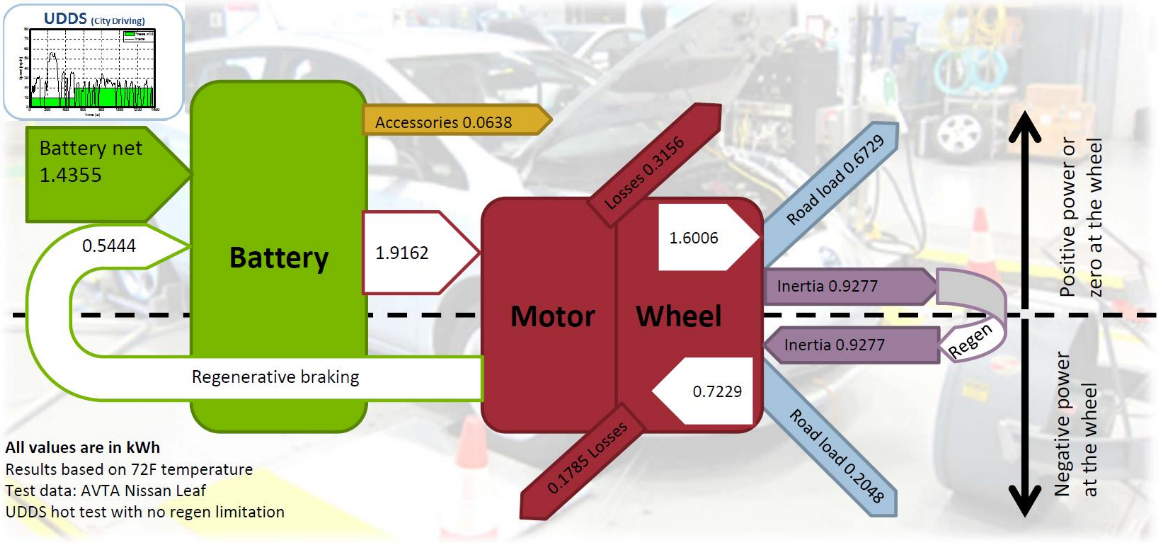


Figure 10: Battery energy efficiency losses of Nissan Leaf (2012) (Source: Lohse-Busch et al. (2012))

All of the energy consumed within a BEV (leaving out auxiliary lead-acid batteries), the total energy consumption of the vehicle has to be delivered by the battery, which is also true for the electric mode of PHEV.

The energy required by a vehicle for its traction can be calculated as follows (Funke 2018):

$$\int \frac{1}{\eta_{PT}} \left(\underbrace{\frac{1}{2} c_d \rho A v^2}_{aerodynamic\ drag\ resistance} + \underbrace{c_r m g}_{rolling\ resistance\ force} + \underbrace{ma}_{mass\ acceleration} \right) * v\ \ dt$$

With ηPT being the efficiency of the vehicle's powertrain (electric motor, gearbox, power electronics), cd as drag coefficient, ρ as density of fluid [kg/m3] (1.2 kg/m3 for air), A as characteristic frontal area of the body [m2], v as flow velocity [m/s] (driving speed), cr as rolling resistance coefficient, m as mass of body [kg], g as acceleration of gravity [m/s^2] and a as lengthways acceleration of the vehicle. When considering the traction energy requirements of a vehicle, one can see that it substantially depends on the vehicle's speed (to the power of three) but also on the vehicle's mass. This is where the **impact of the battery weight** on energy consumption becomes clear. Furthermore, **payload** plays an important role, especially for commercial vehicles. Since for example the battery weight of a Tesla Model S can be as high as 500 kg, an impact of battery weight on the traction energy consumption and consequently on the total fuel consumption can be expected. Detailed calculations cannot be part of that study, but as a rough estimation for each additional 25 kWh battery energy an increase in fuel consumption of 1 to 2 kWh/100km can be expected, while in future due to improvements of gravimetric energy density 0.5 to 1 kWh/100 km might be possible (Funke 2018).

What can also be seen from the formula presented is that vehicle speed and acceleration and consequently **individual driving behaviour** have a strong impact on fuel consumption.

Energy consumption measured with standard tests

For the assessment of passenger cars' emissions and fuel economy the **Worldwide Harmonized Light Vehicle Test Procedure** (WLTP) just recently replaced the **New European Driving Cycle** (NEDC) as reference drive cycle. It was established in order to better account for real-life emissions and fuel economy and it uses a new driving/speed profile (see Figure 11). The WLTP comprises 30 instead of 20 minutes of driving; it includes more than twice the distance and less downtime compared to the NEDC. Further, the average speed is 46.5 km/h instead of 34 km/h; also, a cold engine start is carried out, while air conditioning use is still not considered. Plötz et al. (2017a) argue, that fuel consumption of cars measured with the WLTP is closer to real-life fuel consumption, but it is still not accurate.

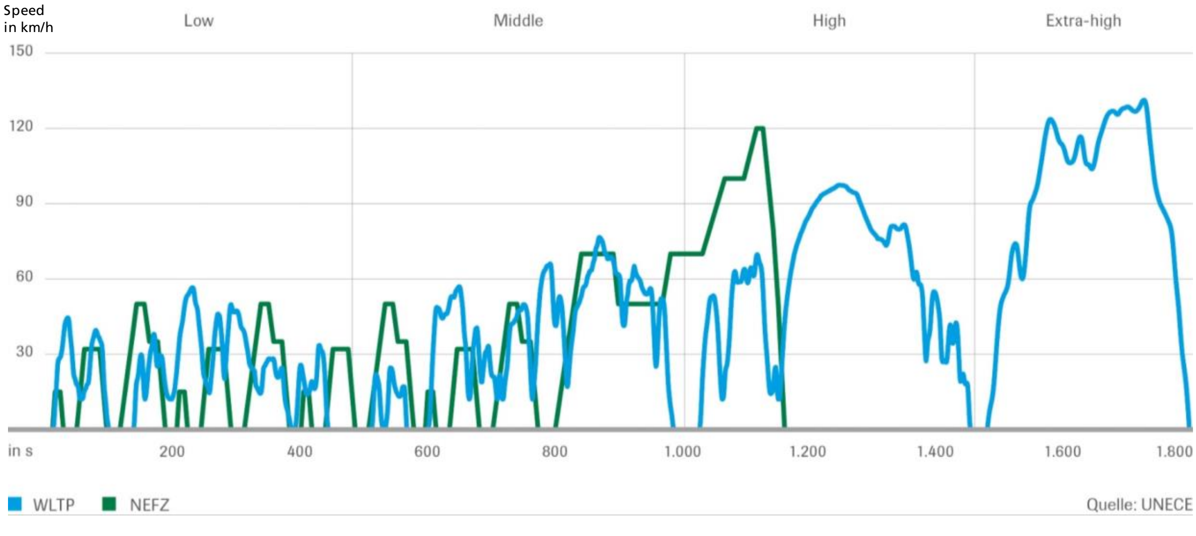


Figure 11: Comparison of speed profiles for WLTP and NEDC (Source: VDA (2018))

They consider the use of the **Federal Test Procedure** (FTP) of the U.S.-American Environmental Protection Agency (EPA) more accurate and very close to real-life behaviour (see speed profile in Figure 12). This is mainly because the FTP includes AC use and hot and cold ambient temperatures, both having big impact on the fuel consumption. That is why for the fuel consumption of the reference applications, if available, values measured with the FTP are used. According to Plötz et al. (2017a) the all-electric driving range, and thus also fuel consumption of vehicles measured with the NEDC can be assumed to be 25% lower than when measured with the FTP.

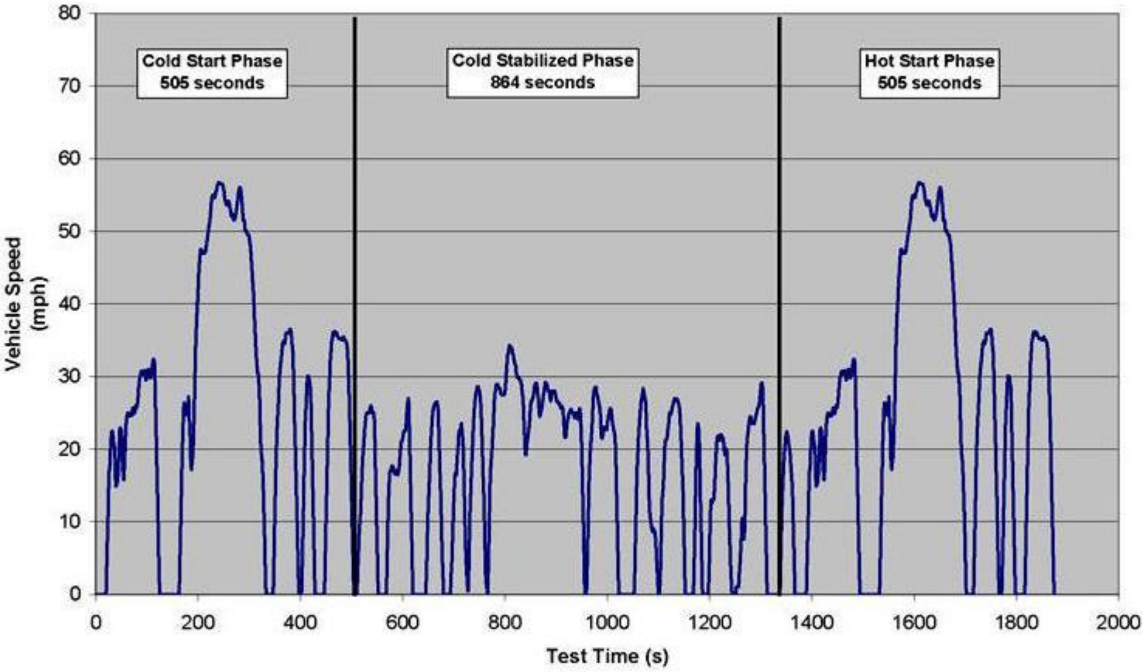


Figure 12: Speed profile of EPA Federal Test Procedure (Source: EPA (2018)).

Fueleconomy.gov (2018) provides a database of energy consumption of passenger BEV and PHEV. Analyzing the fuel consumption of medium-large and small BEV as well as PHEV and including efficiency gains in the near future, we assume that the base case BEV (medium and large) will consume 20 kWh/100km, while BEV (small) will consume 16 kWh/100km and PHEV around 18 kWh/100 km. No fuel consumption is specified for **HDT**, but from range specifications of the Daimler eActros a fuel consumption of **120 kWh/100km** can be derived. Comparing that figure to Hülsmann et al. (2014), Hacker et al. (2014) and Wietschel et al. (2017) it can be confirmed **.** For a **HDTU** a fuel consumption of **140 kWh/100km** can be derived from Wietschel et al. (2017) .

A big advantage of BEV and PHEV, that helps increasing the range, is the potential **brake energy recovery** (regenerative braking, or braking energy recuperation). During braking, a certain share of the kinetic energy can be recovered when using the electric motor as a generator, feeding back energy to the battery.

Gao et al. (2018) state that about 15% of battery energy consumption could be recovered with a 16t **battery-electric delivery truck**, while Xu et al. (2017) find, that 11.5% of the battery energy consumption could be recovered - **12%** is used as a conservative assumption. Furthermore Gao et al. (2015) find, that a plug-in electric **HDTU** (parallel-hybrid with diesel engine) is able to reduce total fuel consumption by 6 to 8% although there is not much kinetic energy recovery. The reason is associated with the more optimal utilization of the engine map. It is assumed, that the fuel consumption is reduced by **6%** on average through energy recovery, no matter if it is a plug-in-hybrid truck with a diesel engine, fuel cell or catenary system.

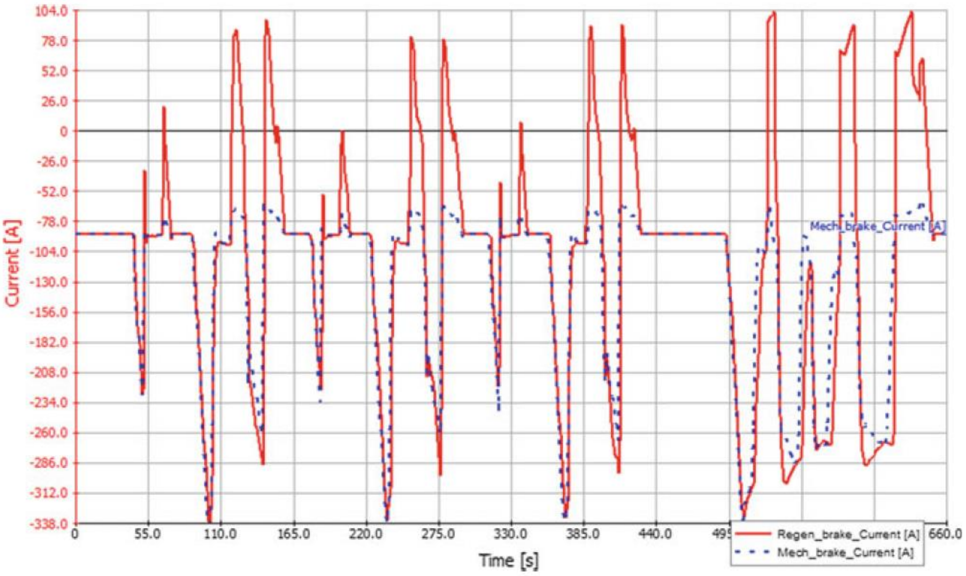


Figure 13: Current change curves (Source: Xu et al. (2017))

Calendar and cycle life of battery

It is desirable that the battery’s cycle and calendar life coincides with the vehicle lifetime. Nevertheless, especially for high annual vehicle mileage, this might not be feasible, since for batteries that are used in BEV a cycle life of **1,500 full cycles** and for batteries used in PHEV a cycle life **2,000 full cycles** are assumed (according to experts), before the batteries reach EOL condition (assuming no calendar aging). Batteries for HDT and HDTU have to be designed for higher annual mileage, thus, **2,000 full cycles** are assumed for **BEV HDT** and **3,000 full cycles** for **PHEV HDTU** (based on expert interviews). Further, a maximum calendar life of the installed battery (assuming no cycling) of **20 years** seems reasonable for all EV applications according to experts (high power or high energy required). Those lifetime figures might require full or partial battery changes concerning the applications (see chapter 3.3.2).

An important aspect that would have impact on the battery's lifetime is the potential provision of demand side flexibility by BEVs and PHEVs. One option is controlled or smart charging of EVs regarding flexible timing and charging power, which is tested and partially already implemented (controlled/delayed/smart grid-to-vehicle G2V). Smart charging can be operated by smart charging devices or by the distribution grid operator. Smart charging devices can optimize the charging of EVs economically from a user perspective by profiting from flexible electricity tariffs. A positive side-effect can be a reduced capacity degradation of the EV due to on average reduced SOCs (González-Garrido et al. 2019). Grid operator controlled smart charging reveals load-shifting potential to the distribution grid operator. Having load-shifting potential at hand reduces required grid expansion, which is due to the additional load caused by EVs, but it might also lead to "un-optimal" charging, which could decrease battery lifetime. Another option is, that EVs, which are idle and connected to the grid could be used as flexible energy storage, feeding energy back into the grid (vehicle-to-grid V2G) for which EV owners would get a compensation. This would cause additional cycling and thus reduce the battery lifetime. EVTC (2017) was able to show that delayed G2V charging does not have negative impact on the battery, while González-Garrido et al. (2019) even showed a positive effect on the battery. Both studies agree, however, that V2G charging accelerates capacity degradation significantly. González-Garrido et al. (2019) state an increased degradation of 15 to 30% depending on V2G power, while Jafari et al. (2018) state an additional battery degradation of

14 to 37% depending on the type of service provided (frequency regulation, peak shaving or solar energy integration).

Energy efficiency

As already explained above, the energy efficiency of a battery depends on the operating conditions. Assuming optimum temperatures, provided by a TMS, C-Rate is the deciding factor. For BEV at an average C-rate for charging and discharging of 0.5C the energy efficiency of the battery is about 96%. This figure relates to DOE (2012) where it is stated, that at the most demanding drive cycle an average battery efficiency of 95% can be measured. Since the most demanding drive cycle is not the most representative drive cycle we assume a slightly higher efficiency of 96%. For PHEV the same energy efficiency is assumed.

As explained in section 3.1.1.2.1, the application service energy for EVs can be calculated by either using detailed data on actual vehicle and driving characteristics or by using an assumed number of full cycles. Taking all data and assumptions into account, an annual number of full cycles and thus charging of 120 can be estimated for all passenger cars it seems reasonable that they are charged on every third day. Because of the much more frequent use, for the HDT base case 300 full cycles and for the HDTU 600 full cycles can be assumed. Beyond that, many figures that have been discussed, such as battery energy efficiency, self-discharge, battery calendar or cycle life, energy consumption of the vehicle etc. were assumed to be static as they are defined in several battery, vehicle and ESS testing standards. It has to be mentioned, however, that those figures highly depend on the actual utilization of batteries, which change according to temperature and actual driving/load profiles of the applications, for example. In this section, those deviations are not taken into consideration.

The data discussed in the previous paragraphs is summed up in Table 1. We included application specific parameters such as lifetime, VKT, energy consumption, range, DOD and typical range of the battery capacity in that application. Further, we calculated the quantity of functional units according to section 3.1.1.1 and the application service energy as well as energy consumption due to battery energy efficiency and due to self-discharge according to section 3.1.1.2.1 for each application. Those figures are related to the strict product approach.

Table 1: Summary of data required for the calculation of EV base cases

	Passenger BEV (medium to large)	**Passenger BEV (small)**	**Passenger PHEV**	**HDT BEV**	**HDTU PHEV**
Economic lifetime of the application [a]	13	14	13	14	12
Annual vehicle kilometres [km/a]	14,000	11,000	14,000	50,000	100,000
All-electric annual vehicle kilometres [km/a]	14,000	11,000	7,000	50,000	50,000
Energy consumption [kWh/100km]	20	16	18	120	140
Braking energy recovery in AS [% fuel consumption]	20%	20%	20%	12%	6%
All-electric range [km]	320	200	50	240	86
Annual number of full cycles [cycle]	120	120	120	300	600
Maximum DOD (stroke) [%]	80%	80%	75%	80%	75%
Typical capacity of the application [kWh]	80	40	12	360	160
Min capacity of the application [kWh]	60	20	4	170	n/a
Max capacity of the application [kWh]	100	60	20	1,000	n/a
Battery calendar life (no cycling) [a]	20	20	20	20	20
Battery cycle life (no calendar aging) [FC]	1,500	1,500	2,000	2,000	3,000
Application Service Energy (AS) [kWh]	**96,000**	**48,000**	**18,000**	**576,000**	**360,000**
Maximum quantity of functional units (QFU) over application service life [kWh]	**43,680**	**29,568**	**19,656**	**940,800**	**890,400**
Battery energy efficiency	92%	92%	92%	92%	92%
Energy consumption due to battery energy efficiency [kWh]	**7,680**	**3,840**	**1,440**	**46,080**	**28,800**
Self-discharge rate [%/month]	2%	2%	2%	2%	2%
Average SOC [%]	50%	50%	50%	50%	50%
Energy consumption due to self-discharge [kWh]	**192**	**96**	**29**	**864**	**384**

3.1.1.3.2. Base cases for stationary ESS

Rated energy

Referring to Graulich et al. (2018) and Figgener et al. (2018) residential ESS have an average battery energy of approximately 10 kWh, although a range of 1 to 20 kWh is possible.

The battery energy and power of currently installed commercial ESS varies widely between 0.25 and 129 MWh (see Hornsdale Power Reserve (2018) and Task 2). For commercial ESS a trend towards bigger rated energies can be seen, thus a total application rated energy of 30,000 kWh is assumed.

Depth of Discharge

According to Stahl (2017) the DOD of residential and commercial ESS is at 90%. However, that DOD is only relevant for some limited applications and thus, 80% are assumed.

Annual full cycles and calendar life base case

Batteries that are coupled with PV (residential ESS) are expected to be subject to 200 to 250 full cycles per year. The upper boundary is chosen for the base case, following expert interviews. These figures are average values that might represent central Europe. Of course, in Scandinavian countries these figures would be much lower, while in southern European countries, such as Spain or Italy these figures would be higher.

It also has to be noted, that the number of cycles might increase in future, when these residential ESS are allowed to provide grid services, such as primary frequency control on top of self-consumption. In some EU member states the regulation is about to change, in order to allow residential ESS to provide grid services. There is a lack of empirical data on how many cycles would be added. According to experts 50 to 80 additional cycles per year are realistic, which could be increased to up to one daily grid service cycle (365 annual cycles in total) for revenue-optimising residential actors.

Thielmann et al. (2015b) state, that calendar life of a battery and the PV system should coincide, which is 15 to 25 years for the latter. Thus, 25 years are assumed. Consequently, less than 5,000 full cycles would be required. For German residential ESS Holsten (2018) confirm on average around 400 full-load hours of use per year and thus 200 full cycles. Figure 14 shows a typical daily load profile of a residential PV system coupled with an ESS. The battery is charged during daytime and the stored energy is consumed during the night. Further, Holsten (2018) determine a figure of around 450 full-load hours per year for commercial ESS which corresponds to 225 full cycles. However, we assume 250 cycles, since demand for flexible ESS might increase in future due to the increasing share of renewable energy generation. Figure 15 shows the load profile of a commercial ESS, depicting the high fluctuations of feed-in and feed-out.

Cycle life and calendar life battery

For residential ESS a cycle life of the battery of 8,000 cycles and for commercial ESS of 10,000 cycles seems to be feasible (Holsten 2018), in combination with a calendar life of 25 years for residential and commercial ESS (expert interviews).

Energy efficiency

As in EV applications, an energy efficiency of 96% is assumed.

Since residential ESS are usually operated within private houses, ambient conditions are no critical issue and the operating temperature can be expected to be little under room temperature. The same applies to commercial ESS. Gravimetric and volumetric energy density are also only of minor relevance, because space and weight in private houses or commercial sites are not as limited as in EV for example (Thielmann et al. 2015b).

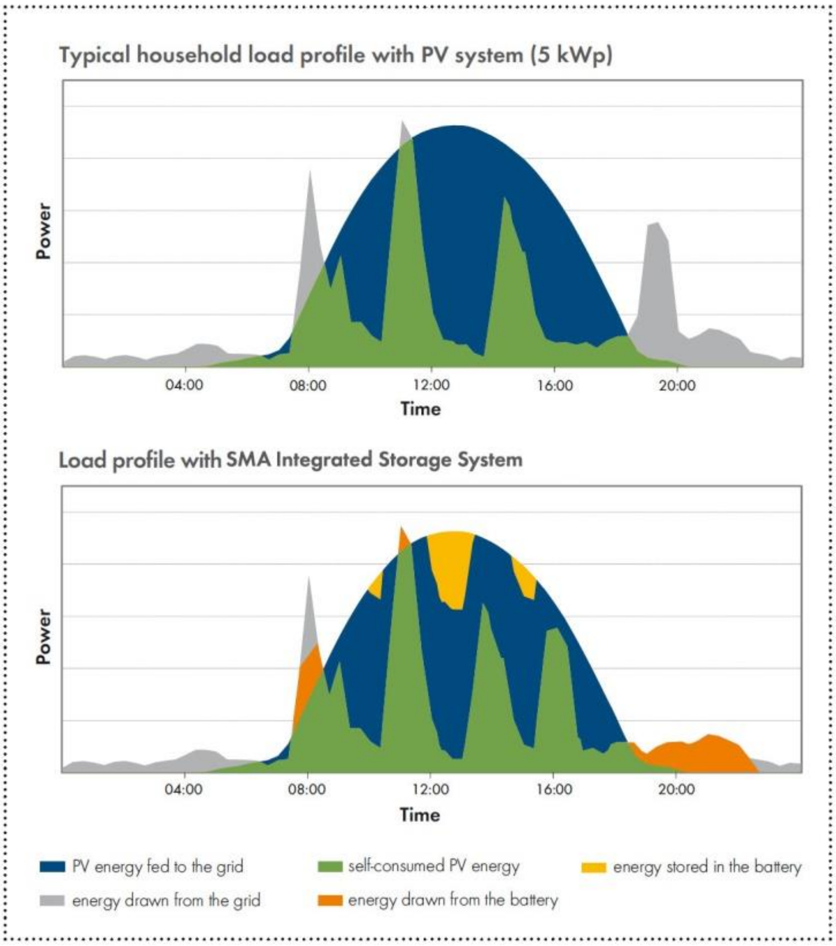


Figure 14: Household load profile of PV with and without battery (Source:(SMA 2014) SMA (2014))

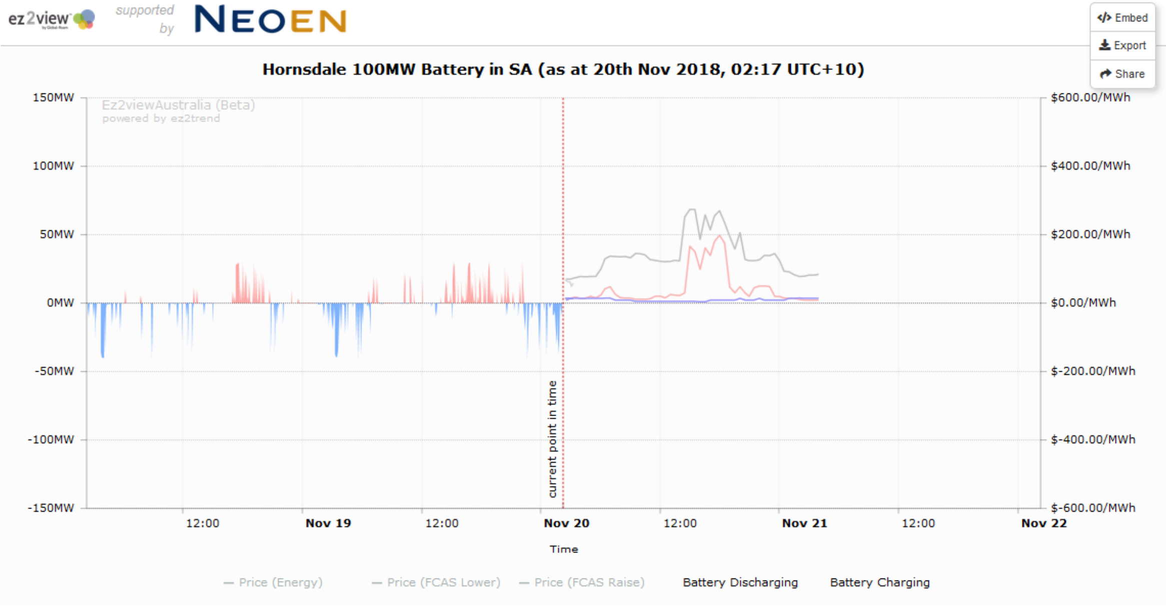


Figure 15: Load profile of commercial ESS (source: Hornsdale Power Reserve (2018))

The data discussed in the previous paragraphs is summed up in Table 2. We included application specific parameters such as lifetime, annual full cycles, DOD and typical range of the battery capacity in that application. Further, we calculated the quantity of functional units according to section 3.1.1.1 and the application service energy as well as energy consumption due to battery energy efficiency and due to self-discharge according to section 3.1.1.2.1 for each application. Those figures are related to the strict product approach.

Table 2: Summary of data required for the calculation of ESS base cases

	Residential ESS	**Commercial ESS**
Economic lifetime of the application [a]	20	20
Annual full cycles [FC/a]	250	250
Maximum DOD (stroke) [%]	80%	80%
Typical system capacity [kWh]	10	30,000
Minimum system capacity	2.5	250
Maximum system capacity	20	130,000
Battery calendar life (no cycling) [a]	25	25
Battery cycle life (no calendar aging) [FC]	8,000	10,000
Application service energy	**40,000**	**120,000,000**
Maximum quantity of functional units (Q_{FU}) over battery service life	**64,000**	**240,000,000**
Battery system energy efficiency	92%	92%
Energy consumption due to battery energy efficiency [kWh]	**5,120**	**19,200,000**
Self-discharge rate [%/month]	2%	2%
Average SOC [%]	50%	50%
Energy consumption due to self-discharge [kWh]	**30**	**90,000**

3.1.1.3.3. Summary of standard test conditions for EV and ESS battery packs and systems

Two standards that are widely used for the testing of EV batteries are IEC 62660 and ISO 12405. While IEC 62660 refers to cells testing, ISO 12405 refers to systems testing (see MAT4BAT 2016, EnergyVille 2019 and Annex to Task 1 “Analysis of available relevant performance standards & methods in relation to Ecodesign Regulation for batteries and identification of gaps” for further details). The standards related to EVs are depicted in Table 3, whereas the standard related to ESS is depicted in Table 4.

Table 3: Standard test conditions for EV (Source: based on MAT4BAT Advanced materials for batteries (2016), EnergyVille (2019) and Annex to Task 1)

Test	**Application**	**Test conditions IEC 62660-1:2010**	**Test conditions ISO 12405-4:2018**
Energy efficiency	BEV/PHEV	@100%, 70% SOC @-20°C, 0°C, 25°C, 45°C Charge according to the manufacturer and rest 4 hours discharge BEV @C/3, HEV @1C	@ 65%, 50%, 35% SOC @ 0°C, 25°C, 40°C 12s charge pulse @Imax (or 20C) and rest 40s then 16s discharge pulse @0.75 Imax (or 15C)
	BEV	Fast charging @25°C	Fast charging @0°C, 25°C

		Charge @2C to 80% SOC and rest 4 hours Charge @2C to 70% SOC and rest 4 hours	Charge @1C and rest 4 hours Charge @2C and rest 4 hours Charge @Imax and rest 4 hours
Self-discharge	BEV/PHEV	Stored @45°C, conditioned @25°C @50% SOC Determination with 1C Duration 28 days, checkup 28 days	
	BEV		@25°C, 40°C @100% SOC No load for 48h, 168h, 720h
	PHEV		@25°C, 40°C @80% SOC No load for 24h, 168h, 720h
Cycle life	BEV/PHEV	Stored @45°C, conditioned @25°C @SOC window 100%-20% and 80%-25%, Different BEV and HEV profiles Check-up every 28 days at 25°C End of test if C(current)<0.8C (initial) or 6 months	
			@25°C - 40°C according to TMS @SOC window 100%-20% different BEV profiles Check-up every 28 days @25°C Limits during check-up to be defined before
			@25°C - 40°C according to TMS SOC window 80%-30% different PHEV profiles Check-up every 28 days at 25°C Limits during check-up to be defined before
Storage life	BEV/PHEV	Tested @20°C, checkup@25°C @100% SOC for BEV, @50% SOC for HEV Discharge @C/3 for BEV, 1C for HEV Check-up every 42 days, end after 3 repetitions	

Table 4: Standard test conditions for ESS (Source: Annex to Task 1 and IEC 2015)

Test	Application	IEC 61427-2: 2015
Energy efficiency	residential and commercial ESS	Calculate average of: @ RT, max and min ambient temperature during enduring test with defined profile
Waste heat		@ Max ambient temperature during endurance test with defined profile
Energy requirements during idle state		@ RT during periods of idle state
Self-discharge		@ RT @ 100% SOC for UPS, 50% SOC for other applications 1C Check-up every 42 days, end after 3 repetitions
Service life		@ RT - 40°C according to TMS @SOC window 100%-20% with endurance test profile Check-up every 28 days at 25°C

3.1.2. Extended product approach

In chapter 3.1.1 we showed the importance of rated battery energy, depth of discharge or state of charge respectively, battery energy efficiency, self-discharge, cycle life and calendar life but also actual utilisation of batteries, stated as annual full cycles, on the direct energy consumption of batteries.

By now, the impact of these parameters was discussed from a global perspective and mainly in relation to technical standards. Thus, following the extended product approach, within this chapter the actual utilisation of batteries under real-life conditions will be discussed. Further, deviations of real-life utilisation from test standards are discussed.

Table 5 provides an overview of real-life deviations of EVs and ESS from standard test conditions and how they are considered.

Table 5: Real-life deviations from standard test conditions

Potential deviation from standards	Explanation	How it is considered
Driving profiles or load profiles	Different load profiles of batteries in urban, freeway and highway traffic but also in different regions, for example, when used in grid stabilization	Only considered via average energy consumption measured with a specific test cycle Only average cycles considered
Driving patterns	Different driving distances and duration on weekdays/ at weekend; load profiles for ESS vary over the years and within a year	Average daily driving distances and durations assumed per base case
Charging strategy	Charging C-rates, frequency and duration vary	Standard charge strategy defined for each base case
Temperature	Ambient temperatures vary (winter, summer, region, etc., even daily)	TMS is expected to be standard, thus not considered

In general, the energy efficiency of a battery is influenced by load profiles (charging/discharging and SOC ranges while being under load), which are directly linked to driving profiles of electric vehicles or load profiles of stationary applications. Driving patterns and load profiles influence no-load losses and the required annual full cycles. Furthermore, they have impact on the charging strategy, which influences energy efficiency respectively. Temperature also has strong impact on a battery energy efficiency and lifetime.

Figure 16 shows how the speed profile of a car translates into other parameters profiles, such as cumulative energy consumption, cell current, cell power, cell voltage and SOC.

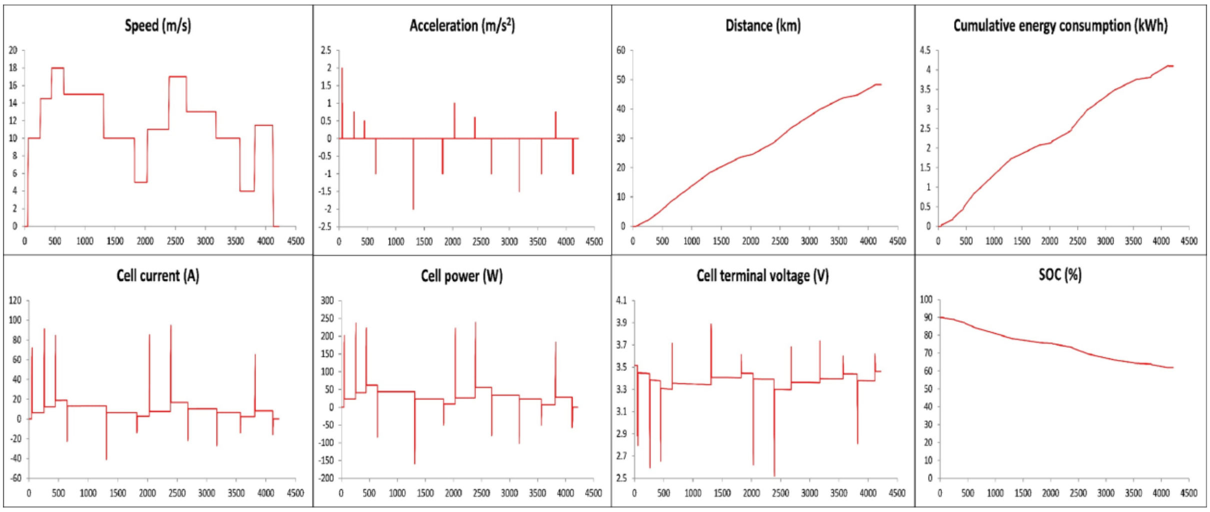


Figure 16: Example of voltage, current and SOC profiles according to speed profile over time (in seconds) (Source: Pelletier et al. (2017))

A speed profile that is supposed to be close to real-life utilisation of a passenger vehicle is the test cycle (speed profile) of the Worldwide Harmonized Light Vehicle Test Procedure (WLTP). Figure 17 shows the quite jagged WLTP test cycle, which clearly differs from the load profile of the efficiency test standards in Figure 4.

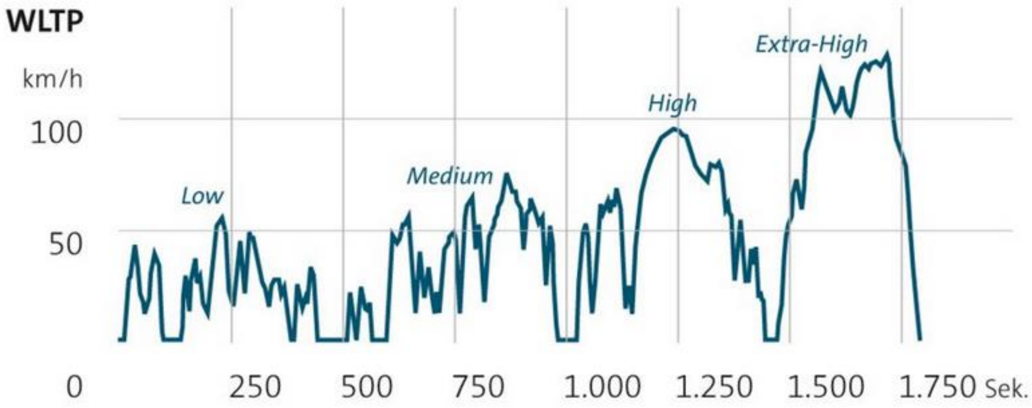


Figure 17: Speed profile of WLTP test cycle (Source: SEAT UK (2019))

Fast increasing and decreasing speed profiles induce high C-rates, which have negative impact on the batteries efficiency. Figure 18 shows the **influence of C-rate** on voltage during discharge. The higher the C-rate the faster the discharge voltage drops, leading to a lower average V_D and voltaic efficiency and thus, low battery energy efficiency. Furthermore, the total battery capacity cannot be withdrawn at high C-rates.

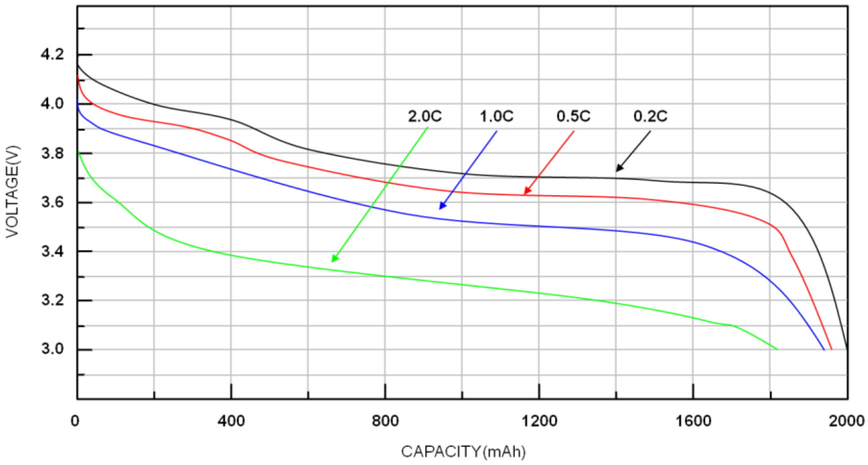


Figure 18: Voltage change at different C-rate discharge (Source: Ho (2014))

In Figure 19 a typical charging process can be seen. At the beginning, charge current is at 100%, while cell voltage increases slowly during the charging process. Battery capacity increases almost linearly at first. When reaching about 60% of the battery capacity the cell voltage reaches its maximum and stays on that level. While charge current starts decreasing down to zero the battery capacity increases until it reaches the rated capacity. Thereafter, a float charging voltage stabilizes the battery capacity and the SOC respectively.

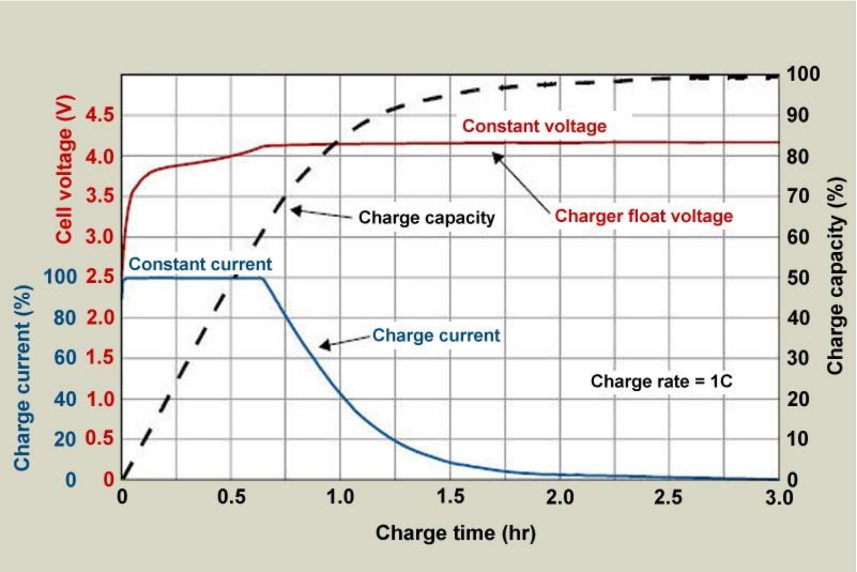


Figure 19: Charging curve of a typical lithium battery (Source: Cadex Electronics (2018)).

As stated above, a lower average charge voltage V_C is beneficial for voltaic efficiency, thus, charging between a **SOC of around 20 to 70%** is beneficial for battery energy efficiency. Advised C-rates of LIB cells lie between 0.5C and 1C. Consequently, **fast charging**, at 2C or above are unfavourable.

In Figure 20 the **impact of different temperatures** during the discharging process on voltage and SOC can be seen. With increasing temperatures, the voltage drops slower, leading to higher V_D, and higher battery capacities can be withdrawn. However, high temperatures have a negative effect on the lifetime of a battery, which will be discussed later.

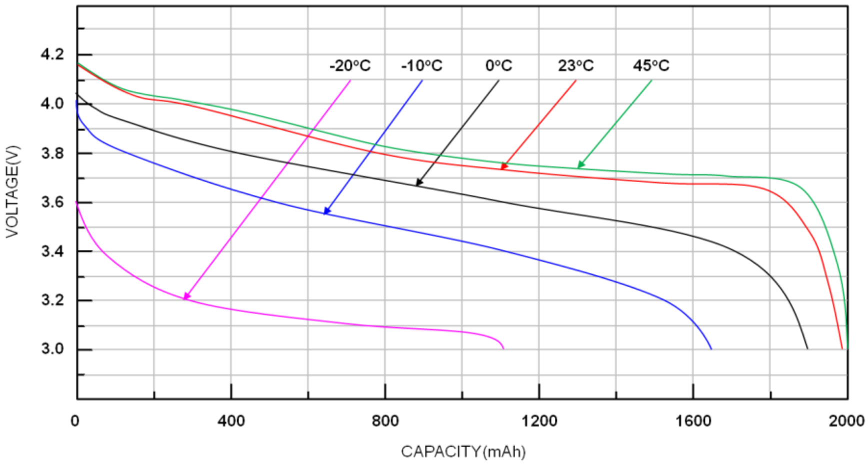


Figure 20: Voltage change for discharge at different temperatures (Source: Ho (2014))

Capacity losses of batteries can be reversible and irreversible. While irreversible losses are known as capacity fade, capacity degradation or aging respectively (which will be discussed in the next section), reversible capacity losses are known as **self-discharge**. Batteries that are stored at a specified SOC will lose capacity over time, but it is very difficult to differentiate between capacity losses due to self-discharge and capacity losses due to capacity fade (Redondo-Iglesias et al. 2018b). Nevertheless, it can be said, that self-discharge of all battery chemistries increases at higher temperatures (see Figure 21). With every 10°C temperature increase, the self-discharge effect typically doubles (Ho 2014).

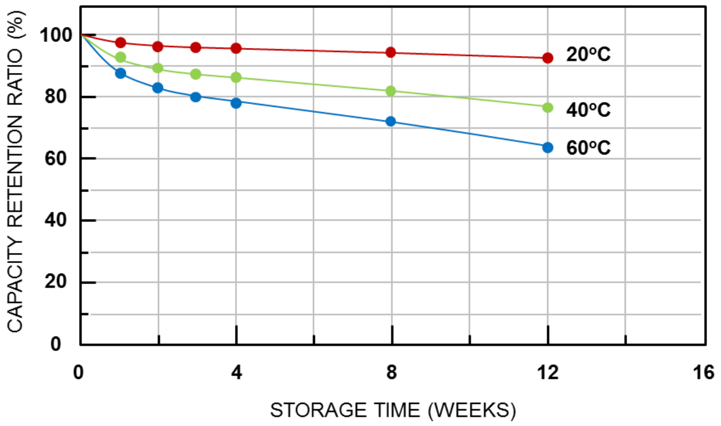


Figure 21: Capacity retention at different temperatures (Source: Ho (2014)).

Further, self-discharge depends on the battery's SOC. The higher the SOC the higher the self-discharge. A Lithium-ion battery has a self-discharge of 0 to 6.5% per month at an SOC between 30 and 65% depending on temperature (30-60°C) and of 2 to 20% at 100% SOC depending on temperature (30-60°C). As an average for lithium-ion batteries a self-discharge of maximum 2% at room temperature can be assumed even at 100% SOC (Redondo-Iglesias et al. 2018b).

3.1.3. Technical systems approach

As already mentioned, batteries are either part of vehicle or of a stationary (electrical) energy system, which comprise additional components such as a charger, power electronics (inverter, converter) and active cooling and heating systems. However, energy consumption of these components is considered as indirect losses and thus discussed in chapter 3.2.

3.1.4. Functional systems approach

In the functional approach the basic function of battery systems, the storage and provision of electrical energy, is maintained, yet other ways to fulfil that function and thus other electrical energy storage technologies are reviewed.

Alternative technologies to LIB used in EVs are fuel cells with hydrogen storage, nickel-metal hydride batteries (NiMH) or lead-acid (Pb) batteries.

Proton exchange membrane fuel cells (PEM-FC) are actually energy converters, which is why they can only be used in combination with (hydrogen) storage tank. The energy density of the PEM-FC is clearly above the energy density of today's and future LIB systems. The operating life however is still limited to approximately 6000 operating hours. In automotive applications, it is usually used in combination with pressurised storage of hydrogen. However, there are only few car models manufactured in series production.

NiMH-batteries are batteries, in which electrodes are made of nickel oxide hydroxide and a hydrogen storage alloy of nickel and so-called mixed metal with rare earth elements. The electrolyte is a potassium hydroxide solution. They are especially designed for hybrid-eletric vehicles. As traction battery, however, their potential is very low. Nickel and its supply chain are the big challenge. Since Nickel is very expensive, NiMH batteries are more expensive than LIB and beyond that, their environmental record is worse.

Pb-batteries are batteries with electrodes of lead and lead dioxide and an electrolyte of diluted sulphuric acid. They play an important role in emerging markets such as India to build low-cost vehicles and thus, to ensure cheap mobility for society. For the German and European market, they will not be used for traction purposes, but they are still state-of-the art for starter batteries. This is partly because they have already reached the end of their development potential, and in terms of their performance, for example, they are clearly behind lithium-ion batteries.

For stationary applications, mainly Pb-batteries, flywheel energy storage systems (FESS), sodium-sulphur (NaS) batteries and sodium nickel chloride ($NaNiCl_2$) batteries and redox-flow batteries (RFB) can be seen as alternatives to LIB (see also Figure *22* and Thielmann et al. (2015a)):

Pb-batteries are the benchmark technology for stationary applications in the range of up to 1 GWh and 20 MW. They are able store electricity for several minutes but also for several days. Because of their low investment costs in many stationary applications, they are state-of-the art. Their energy density however is quite low and their cycle life is limited. On the other hand, calendar life is between 10 to 20 years.

FESS store electrical energy in the form of kinetic energy by means of an electric machine, which accelerates a flywheel. They represent an economically interesting option for the storage of electrical energy, especially for those applications, where several charge and discharge cycles occur per day and thus accumulators, due to their limited number of charge/discharge cycles and super capacitors due to their high costs in relation to the storable energy, from an economic point of view are not advantageous. Their efficiency however is currently still low, which is why they are rarely used (Schulz et al. 2015).

NaS/$NaNiCl_2$: NaS batteries, in which electrodes are made from the elements mentioned above use as a solid-state electrolyte a sodium ion conductive ceramic. $NaNiCl_2$ batteries, usually also called a ZEBRA battery, use a solid-state electrolyte, which is supplemented by a combination of liquid and solid electrodes. The anode, which is separated by a separator from the exterior of the battery is made from liquid sodium, the cathode from sodium chloride or from sintered nickel, which is impregnated by a liquid saline solution of nickel chloride and sodium chloride. It requires high operating temperatures, which is why a heater in addition to a thermal insulation is used, since the otherwise; the cell would be constantly discharged. It can be used from 100kWh to 1 GWh and stores energy for 1h up to one week. The technology is available but not that present on the market, also because of its high costs for example in relation to Pb batteries.

RFB is a battery concept, which is based on the reduction and oxidation of electrolyte solutions that are pumped from storage tanks to a fuel cell like stack. They have a lower energy density than LIB and their systems are more complex. In stationary applications, they are especially relevant for large-scale installations, where their maintenance effort is adequate. One the one hand their cycle life is very high (> 10,000 cycles), on the other hand, little data on their long-term stability is available. Their requirements regarding operating conditions are quite demanding and costs are a little bit above Pb. RFB are mostly relevant for storing 100kWh up to some MWh for up to several days and solutions are already available.

To sum it up, for stationary applications currently Pb-batteries are state-of-the-art and are superior to LIB especially in terms of costs and calendar life. With improving performance and cost parameters however LIB, RFB and NaS-batteries can be an alternative, depending on power, energy and storage duration requirements.

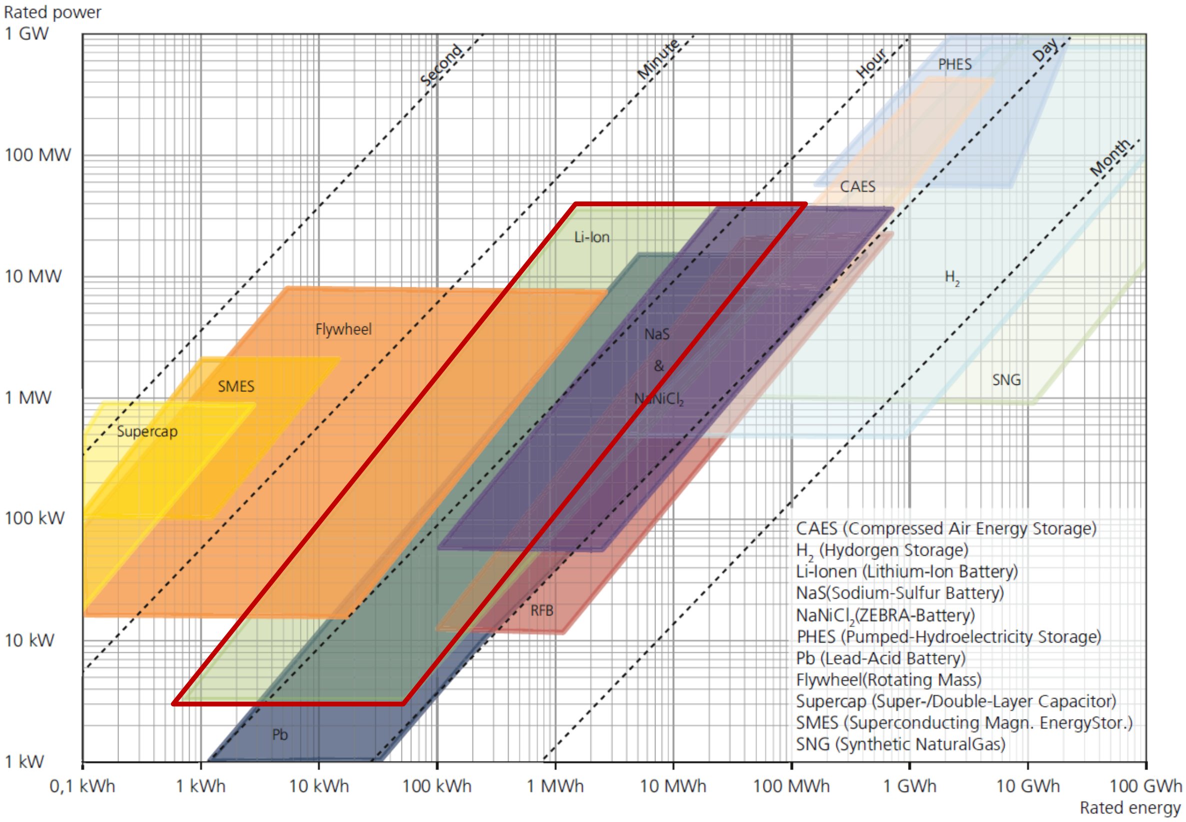


Figure *22*: Alternative stationary electrical energy storage technologies (Source: *Thielmann et al. (2015a)*)

3.2. Subtask 3.2 - System aspects in the use phase affecting indirect energy consumption

As mentioned before, batteries are part of vehicles or stationary energy systems. Consequently, further components that have impact on the energy consumption have to be considered. Power electronics (according to the system boundaries defined in Task 1), such as converters, inverters, electric engines and so on will not be included. One reason for that is that in EV as well as in stationary applications many different design options, which components to be used and how to combine them, are existent (BVES and BSW Solar 2017; Erriquez et al. 2018). Accordingly, indirect energy consumption of chargers as well as of active cooling and heating systems will be discussed in this section.

For EVs, a differentiation between regular (AC) charging and fast (DC) charging has to be made, since efficiencies of both charging types differ. While for AC chargers with 3.8 kW, which are suitable for passenger cars, a charger efficiency of 85% can be assumed (Lohse-Busch et al. 2012; Kieldsen et al. 2016), for AC chargers with 22 kW, that are suitable for trucks, an efficiency of 92% can be assumed (Genovese et al. 2015; Kieldsen et al. 2016). The efficiency of DC fast charging at 50 kW for passenger cars and 150 kW for trucks is assumed to be 93% (Genovese et al. 2015; Trentadue et al. 2018). Further, we assume, that passenger vehicles are charged with AC power for 80% of the time, since most of the day, they just stand idle and thus, there is enough time for slow charging, which is good for the battery lifetime. Trucks however spend more time on the road and thus, we assume 50% AC charging. ESS are charged DC only and based on expert interviews, a charger efficiency of

98% can be assumed. The parameters related to the calculation of direct and indirect energy consumption and all results are summed up in Table 6 for EVs and in Table 7 for ESS.

$$\left(1-\left(Share\ AC\ charge * \eta_{AC\ charger} + (1 - Share\ AC\ charge) * \eta_{DC\ charger}\right)\right) * \frac{Q_{FU}}{\eta_E}$$
$$= \left(1-(80\% * 85\% + (1-80\%) * 93\%)\right) * \frac{96{,}000}{0{,}96} = 13{,}400$$

Table 6: Summary of data required for the calculation of EV base cases (indirect energy consumption)

	Passenger BEV (medium to large)	**Passenger BEV (small)**	**Passenger PHEV**	**HDT BEV**	**HDTU PHEV**
Maximum quantity of functional units (QFU) over application service life [kWh]	**96,000**	**48,000**	**18,000**	**576,000**	**360,000**
Battery energy efficiency	92%	92%	92%	92%	92%
Energy consumption due to battery energy efficiency [kWh]	**7,680**	**3,840**	**1,440**	**46,080**	**28,800**
Self-discharge rate [%/month]	2%	2%	2%	2%	2%
Average SOC [%]	50%	50%	50%	50%	50%
Energy consumption due to self-discharge [kWh]	**192**	**96**	**29**	**864**	**384**
Charger efficiency AC [%]	85%	85%	85%	92%	92%
Charge power AC [kW]	3.8	3.8	3.8	22	22
Charger efficiency DC [%]	93%	93%	93%	93%	93%
Charge power DC [kW]	50	50	50	150	150
Share AC charge [%]	80%	80%	80%	50%	50%
Energy consumption due to charger energy efficiency [kW]	**13,983**	**6,991**	**2,622**	**46,957**	**29,348**
Heating/cooling energy requirements [%]	5%	5%	5%	5%	5%
Energy consumption due to cooling and heating requirements [kWh]	**4,800**	**2,400**	**900**	**28,800**	**18,000**

According to Schimpe et al. (2018) the battery losses in stationary applications due to heating or cooling requirements amount to 5%. The same figure is assumed for EVs.

Table 7: Summary of data required for the calculation of ESS base cases (indirect energy consumption)

	Residential ESS	**Commercial ESS**
Maximum quantity of functional units (QFU) over application service life [kWh]	**64,000**	**240,000,000**
Battery energy efficiency	92%	92%
Energy consumption due to battery energy efficiency [kWh]	**5,120**	**19,200,000**
Self-discharge rate [%/month]	2%	2%
Average SOC [%]	50%	50%
Energy consumption due to self-discharge [kWh]	**30**	**90,000**
Charger efficiency DC [%]	98%	98%
Energy consumption due to charger energy efficiency [kW]	**1,391**	**5,217,391**
Heating/cooling energy requirements [%]	5%	5%
Energy consumption due to cooling and heating requirements [kWh]	**3,200**	**12,000,000**

3.3. Subtask 3.3 - End-of-Life behaviour

The aim of this subtask is to identify, retrieve and analyse data and to report on consumer behaviour regarding end-of-life aspects of batteries from an average European perspective.

As already explained in this study, batteries have a limited cycle and calendar life. The actual utilisation of batteries in terms of cycling and the conditions under which they are operated (specific C-rates, within certain SOC or DOD ranges, at specific temperatures) decrease a batteries capacity and thus energy permanently. Further, internal resistance of a battery increases over time, and consequently energy efficiency decreases. In summary, the SOH diminishes.

The lifetime of a LIB cell is subject to its actual utilisation, thus referring to the definition of the functional unit, the **cycle life** of battery cell can be specified by full cycles at a certain DOD. 1,000 to 2,000 full cycles are feasible for BEV at a DOD of 80%, while PHEV reach between 4,000 and 5,000 full cycles at 80% DOD (Thielmann et al. 2017). With increasing fast charging capabilities that result in high charging power the load and stress for the battery grows leading to increasing requirements concerning cyclical operating life. This is a very important aspect, especially in the light of the continuously increasing charging power that already reaches up to 500 kW (ChargePoint 2019). In general, with increasing charging power, the temperature of the battery while charging increases, which in turn accelerates battery aging or requires strong thermal management in order to prevent battery aging (Collin et al. 2019). It also has to be mentioned, that the cycle life requirements for heavy-duty trucks are a lot higher, since their annual mileage is higher and also their load profile is a lot more challenging compared to passenger cars.

Service life and aging of batteries

The service life of a LIB is defined as the time between the delivery date (beginning of Life, BOL) and the point of time (end-of-life, EOL) at which properties previously defined in standards or product specifications fall below a defined value due to aging. The end of life occurs, for example according to Part 4 of DIN 43539 "Accumulators; Testing; Stationary cells and batteries", if the maximum battery energy falls below 80% of the rated battery energy, which corresponds to a SOH of 80%. 80% are also stated in condition B in the cycle life tests in IEC-62660-1. Generally that value strongly depends on the application (Podias et al. 2018). The EOL condition for passenger EV is usually between 70 and 80%, while for trucks 80% are assumed, since a certain range is essential for economic operation. Residential and commercial ESS are used until 70% are reached.

Two metrics for the definition of service life can be distinguished (as described above): Calendar life and cycle life.

In practice, the combination of both influences the total service life of a battery. **Calendar life** is another important parameter (also for End of Life (EOL) analyses). No general statements can be made because it mainly depends on the actual utilisation of the battery and largely on the ambient conditions (temperature) under which batteries are stored. Around 15 to 20 years are current expected lifetimes, which are necessary in order to be able to reach the operating life of current ICEVs. The calendar life refers to a battery, which is not cyclized, i.e. the battery is not used in the respective application or if the battery is in bearing condition. Calendar life of a battery relates to the number of expected years of use. If not being used, within the battery interactions between electrolyte and active materials in the cell and corrosion processes can take place that affect the service life. Extreme temperatures and the cell chemistry as well as the manufacturing quality are further factors that can accelerate aging. **Cycle life** is defined by the number of full cycles that a battery can perform, before reaching EOL. Full cycles are to be distinguished from partial cycles. For the latter, a battery is not entirely discharged and charged, but only within a certain range referring to the SOC. Batteries like nickel metal hydride batteries show a so-called memory or lazy effect, when a lot of partial cycle are performed, leading to accelerated aging. Most lithium-ion cells however, do not show that effect (Sasaki et al. 2013).

Aging refers to the deterioration of the electrochemical properties (e.g. lower capacity, energy density etc.). Mostly, it is determined by the **energy throughput or cyclisation.** The more cycles a battery has performed, the lower the available capacity (see Figure 23). Further, **high performance requirements** during charge and discharge of the battery and high currents (high C-rates) result in high internal heat production, which might irreversibly damage the electrode materials, directly influence, and accelerate aging (see also Figure 23).

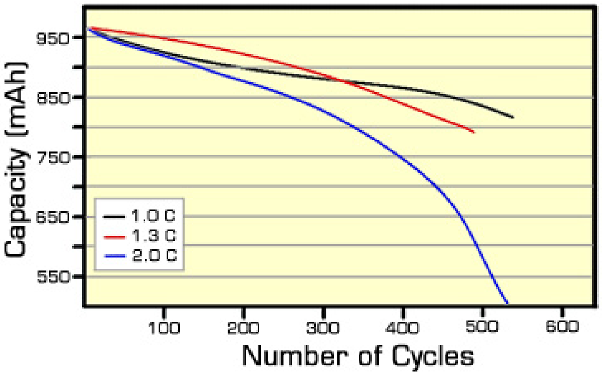


Figure 23: Aging (decrease of capacity) over number of cycles at different C-rates (Source: Choi and Lim (2002)).

Capacity decreases with time and internal resistance increases, which consequently leads to a power decrease. This is mostly due to side reactions, which take place during the charge and discharge processes in the electrolyte, such as stretching of active materials. Due to the utilisation of different materials, which are in contact to each other, a multitude of reactions might be possible. Additionally, ambient **temperature conditions** influence the increase of internal resistance and thus, potential service life as well. The higher the temperature, the faster the mentioned processes will proceed and in turn, lower service life (see Figure 24). Depending on the application and condition, active cooling might therefore be necessary.

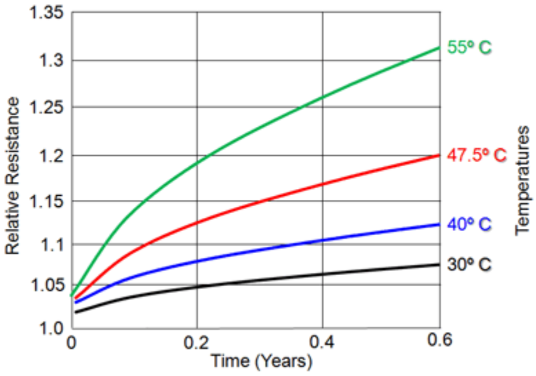
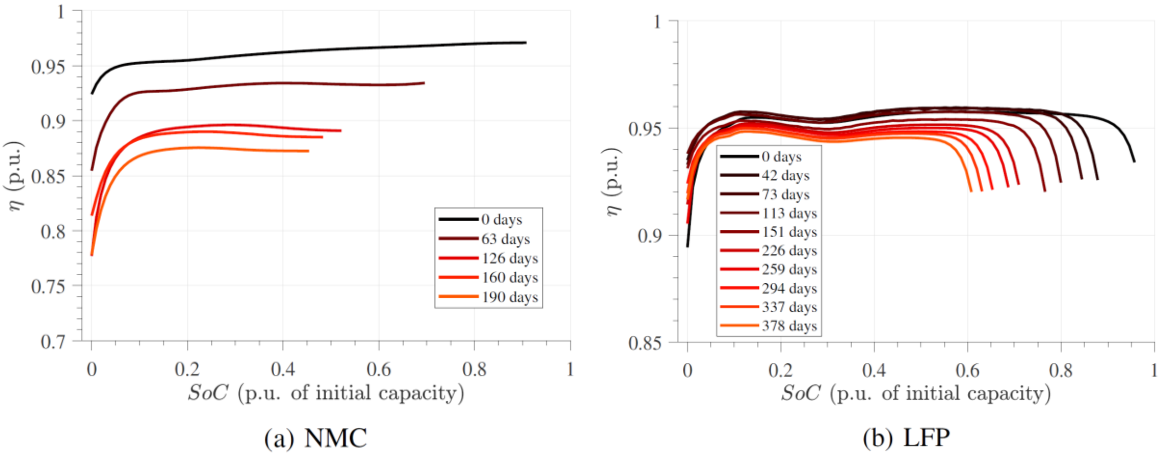


Figure 24: Internal resistance over time at different temperatures (Source: Woodbank Communications (2005)).

Figure 25 shows, how the **efficiency** and **capacity** of cells develops **under calendar aging** conditions (60°C, 100% SOC). For NMC cells efficiency decreases very quickly from 96% down to 87% within 190 days and within the same period capacity decreases by 37%. The LFP cell's efficiency, however, just decreases from 95% to 94% over a period of 378 days, while a capacity fade of 30% can be seen. Especially for NMC cells these analyses show the unfavourable impact of high temperatures and high SOC on calendar aging and energy efficiency (Redondo-Iglesias et al. 2018a).



(a) NMC (b) LFP

Figure 25: Efficiency degradation of cells under calendar ageing conditions (60°C, 100% SOC) (Source: Redondo-Iglesias et al. (2018a)).

As already discussed for the charging processes, the **SOC ranges** a battery is operated within largely influences the operating life. One the one hand narrow SOC ranges around 60% or 70% SOC significantly improve cycle life of batteries and on the other hand, they decrease capacity fade as Figure 26 shows.

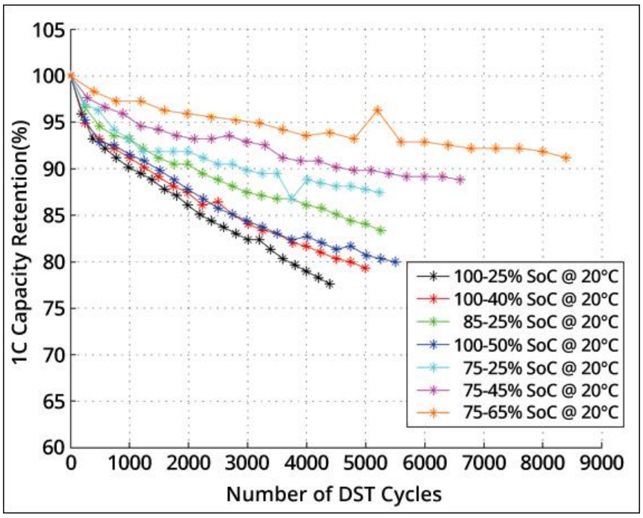


Figure 26: Capacity loss as a function of charge and discharge bandwidth (Source: Xu et al. (2018)).

Consequently, charging and discharging Li-ion only partially and at low C-rates prolongs battery cycle life and decreases capacity fade, which is also supported by Figure 27.

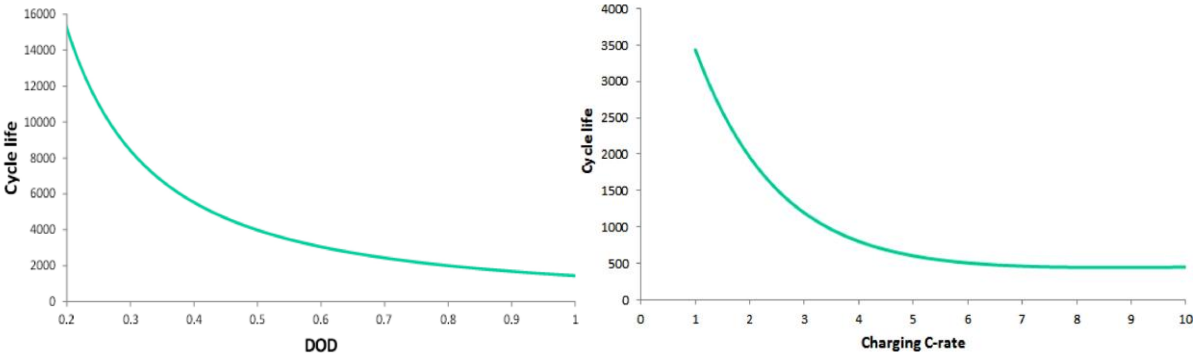


Figure 27: Cycle life versus DOD and charging C-rate (Source: Pelletier et al. (2017))

A battery is usually operated in an application until its EOL condition is reached. EOL was defined in Task 1 according to IEC 61960 and IEC 62660 as condition that determines the moment a battery cell, does not anymore reach a specified performance in its first designated application based on the degradation of its capacity or internal resistance increase. This condition has been set to 80% for electric vehicle application of the rated capacity.

Figure 28 shows how the capacity of a LIB-cell decreases over cycle life. In that case, the cell reaches EOL after approximately 500 cycles.

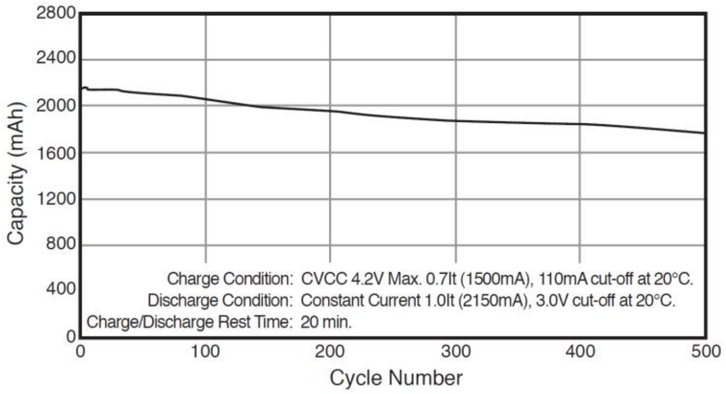


Figure 28: Lifecycle characteristics of Panasonic CGR18650CG cylindrical cell (Source: Panasonic (2008))

The impact of temperature and of DOD on the cycle life is depicted in Figure 29. With increasing DOD, cycle life shortens. The same applies for increasing temperatures, which accelerate the aging process (capacity loss/capacity fade) and lead to a lower number of full cycles.

Although having reached EOL condition for a certain application with a remaining capacity of 80% this does not necessarily mean, that a battery is not usable any more (Podias et al. 2018). The reduced capacity and energy efficiency restrict the further use, and also safety aspects have to be taken into consideration, since with enduring service life the risk of failure (electrical short, chemical chain reaction) increases.

Within this study, we discussed batteries that are utilised in either EV or stationary ESS applications, thus which are part of a bigger system or product respectively. For the discussion of EOL behaviour in this Task, a focus is set on the EOL behaviour of the applications/base cases in distinction from the EOL analyses in Task 4, which are focussed on the battery's EOL and on battery and material recycling.

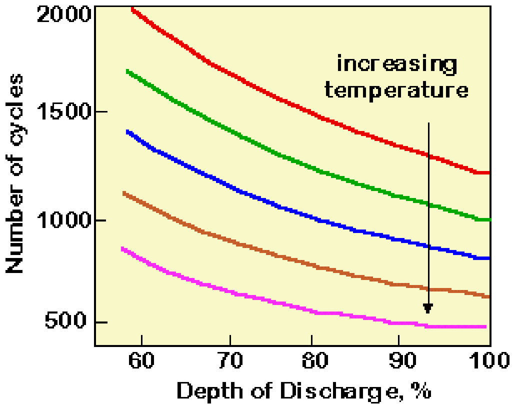


Figure 29: Number of full cycles before EOL is reached over DOD and depending on temperature (Source: TractorByNet (2012)).

In general, a LIB can pursue five ways after its first-use:

- remanufacturing
- reuse - battery is used again in the same application
- repurposing/second-use - battery is is used in another, different application, mainly stationary ESS applications. After their first use, the batteries are tested and prepared for use for energy storage in a second-use application.
- recycling - battery is “destroyed” in order to recover materials
- waste - batteries decompose on landfills

In the following sections, we focus on reuse and repurposing, since the other aspects will be covered in Task 4.

3.3.1. Product use & stock life

Table 8 shows a comparison of the service life of the base case EV applications and the batteries used within these applications. The stated service life of the batteries in full cycles and years has to be long enough, so that after the first use, the service life is not exhausted and there is remaining potential for second-use. That potential mainly refers to a second use in stationary ESS, since the EOL conditions are usually lower. Consequently, batteries used in ESS that reach their EOL are not considered to have second-use potential.

Regarding the service life in full cycles, passenger BEV batteries are not only able to provide the required number of full cycles for the application, but they exceed the requirements, which reveals **second-use potential**. PHEV, BEV HDT and PHEV HDTU batteries however are not able to provide the number of full cycles required for the application. An entirely different picture can be drawn regarding the service life in years. For all EV applications, the service life of the battery in years is longer than the application’s life, thus second-use potential is given.

Table 8: Comparison of service life of applications/base cases vs. maximum battery performance (data was drawn from the preceding sections)

	Service life (in full cycles)			**Service life (in years)**		
	Application	**Maximum battery performance**		**Application**	**Maximum battery performance**	
Passenger BEV (medium to large)	683	1,500	🟩	13	20	🟩
Passenger BEV (small)	924	1,500	🟩	14	20	🟩
passenger PHEV	2,730	2,000	🟥	13	20	🟩
HDT BEV	3,267	2,000	🟥	14	20	🟩
HDTU PHEV	9,275	3,000	🟥	12	20	🟩

🟩	suitable for second-use
🟨	to a certain extent suitable for second-use
🟥	not suitable for second-use

Four conclusions can be drawn from these figures:

- First, regarding passenger BEV, their batteries might be suitable for second-use in ESS, since battery service life in cycles as well as in years exceeds the application's service life.
- Second, for batteries used in passenger PHEV, their service life in cycle is exceed, whereas service life in years is not yet reached. Consequently, second-use potential might be given under certain circumstances, e.g. when the PHEV is not driven that much and thus, does not reach that number of cycles.
- Third, the battery service life in cycles of HDT BEV and HDTU PHEV is heavily exceeded, while service life in years is not yet reached. There might be few HDT and HDTU with low annual mileage and thus low application cycles, which might offer second-use potential. For the majority of batteries used in HDT and HDTU however, low potential for second-use is seen.
- Fourth, batteries in stationary ESS are used, until they reach the end of their life, whether in cycles or years. EOL condition is expected to be lower for ESS than for EVs, but at the time the shoulder point is reached (EOL), after which the capacity drops very fast, those batteries are not expected to be used in second-use applications. On the other hand, the lower EOL conditions of ESS allow the utilisation of second-use EV battery.

A promising way to increase calendar life of a battery, which seems to be critical for passenger cars, is to lower the SOC, when the application/vehicle is at rest (MAT4BAT Advanced materials for batteries 2016). Beyond that, it has to be noted that passenger car and truck manufacturers are expected to design the batteries in a way that they are able to last the vehicle's entire cycle and calendar life, which might increase second-use potential. However also the opposite might be the case, such that batteries last exactly as long as the vehicles, leading to almost none second-use potential.

3.3.2. Repair and maintenance practice

In general, a LIB can be considered maintenance free. If however, parts of the battery system have to be replaced due to failure, gaining access to a battery is differentially difficult, depending on the application.

Batteries used in EV are usually built in the vehicle's underbody and protected by a stable metal casing, thus requiring high effort for accessing and repairing batteries (see Figure 30). Due to the location of the battery pack within a vehicle, but also due to the high battery voltages, specialized experts are required for repair and maintenance. While the latter is also true for ESS, whether they are residential or commercial, the accessibility of ESS batteries a lot easier. In residential applications batteries are mounted to the wall (see Figure 31), whereas in commercial applications they are installed in factory like halls, thus being easily accessible.

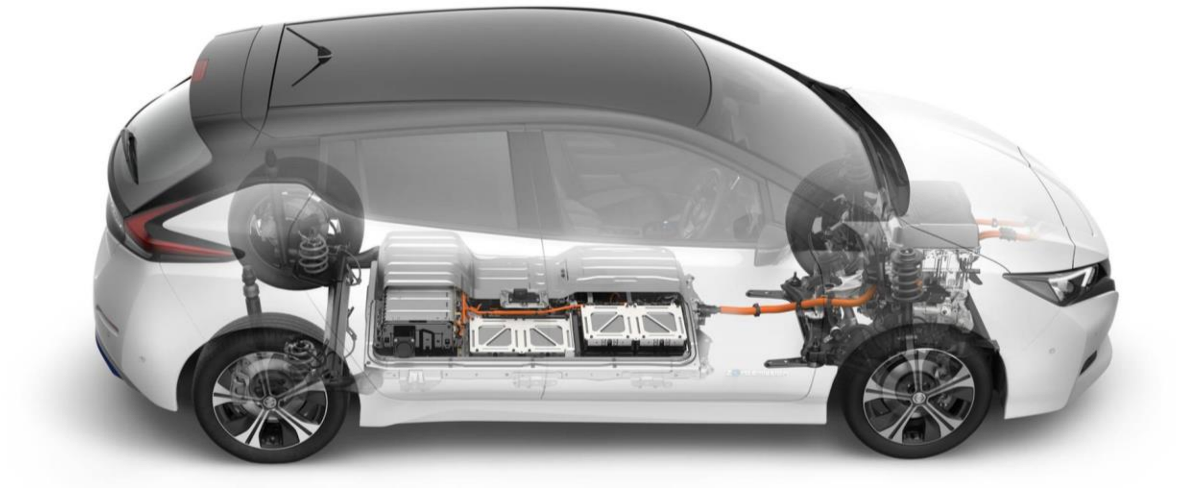


Figure 30: Position of Nissan LEAF 40kWh battery (Source: Kane (2018))

It can be expected, that in case of failure batteries in mobile applications and in commercial ESS will repaired, since otherwise the whole application's EOL would be reached, which from an economic point of view would be very unfavourable. For residential ESS, it seems possible, that they are replaced entirely. An advantage of the usual modular setup of batteries refers on the one hand to easy assembly of the components and on the other hand to simplified maintenance and interchangeability of individual modules. Lithium-ion cells are practically maintenance-free and a sophisticated BMS, balancing load and temperature evenly among all cells/modules, contributes significantly to this (Rahimzei et al. 2015). According to Fischhaber et al. (2016) replacing specific modules might also be a suitable measure to postpone a battery's EOL.

Figure 31: Kreisel Mavero home battery (Source: Kreisel Electric (2018))

In general, battery removability is stipulated in the Battery Directive. Nevertheless, the share of non-removable batteries and of batteries removable only by professionals is increasing, which often results in early EOL in the application (Stahl et al. 2018).

3.3.3. Collection rates, by fraction (consumer perspective)

The EU EOL Vehicles Directive 2000/53/EC and Battery Directive 2006/66/EC state, that vehicles and batteries have to be collected and recycled. Since disposal of waste industrial and automotive batteries in landfills or by incineration is prohibited, implicitly a collection and recycling rate of 100% is demanded.

However, the amount of batteries that are actually recycled varies according to the type of application and battery (see Figure 32). Currently, regarding the battery mass flow of batteries, LIBs are mainly found in the field of portable batteries. LIBs are included in the category “other batteries” and they sum up to approximately 37,000 t, thus representing around 18% of the mass flow. This will change significantly with the EV diffusion. Only 30% of “other” portable batteries are collected and recycled.

Regarding automotive batteries, which in that mass flow only comprise lead-acid batteries, the collection and recycling rate is over 92%, whereas for lead-acid batteries in industrial applications around 90% collection and recycling rate are achieved. Consequently, one could conclude, that a similar collection and recycling (or re-use) rate might be achievable for LIB in industrial and automotive applications. However, that would neglect that LIBs are not as easily removed from their applications as lead-acid batteries, which can be handled and transported comparably easy and whose recycling is profitable from an economic point of view. Consequently, comparable recycling rates will only be achievable by strong regulatory intervention.

For LIBs, there are currently several large-scale recycling facilities in Europe that do recycle cobalt, nickel, copper and aluminium. Since Cobalt is a critical raw material for the EU, its recovery is essential and also, its recovery is economically valuable. However, because of technological but also economic challenges, recovery of lithium is currently scarce: only some smaller facilities that have been built up in research projects are available. It should be pointed out that Umicore recently started the recovery of lithium from the slag fraction of its large-scale pyro metallurgical process (Stahl et al. 2018).

This could be subject to change, when the market of EVs and ESS and accordingly of LIB batteries to be recycled increases and/or further regulations on European level are enforced. According to Recharge (2018), it can be expected that 95% of EOL batteries are collected for second-use or recycling while 5% come to an unidentified stream.

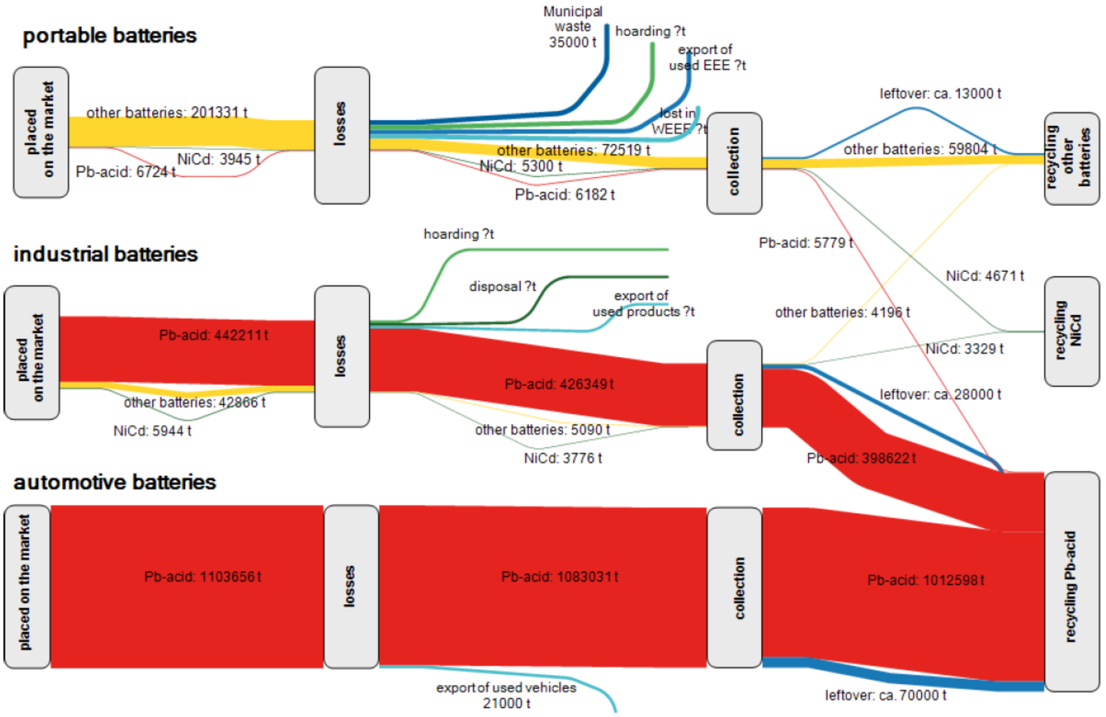


Figure 32: Mass flow diagram of batteries for EU28 in 2015 [tonnes] (Source: Stahl et al. (2018))

Table 9: Assumptions referring to collections rates of EOL batteries (Source: Recharge (2018)).

Collection rate for second-use or recycling	Unidentified stream
95%	5%

3.3.4. Estimated second hand use, fraction of total and estimated second product life (in practice)

The figures from Table 8 concerning the calendar life of applications already include second hand (second-use) utilisation time, thus only second-use applications are to be reviewed.

Currently within the EU Battery Directive, collection and recycling rates are stated. That does not address second-use applications, which are very promising. Due to missing definitions and regulations in the Directive concerning the re-use, preparation for re-use or second use, there is an unclear legal situation, primarily for battery producers (Stahl et al. 2018).

Fischhaber et al. (2016) assume that battery cells or modules with EOL capacity of 80% can be used down to an energy of 40% within a second-use application. A further utilisation might provoke a battery failure. Many experts however state, that already below 70% SOH the risk of a thermal runway increases significantly. Since the actual SOH of individual cells within a module after first-use is not known, time-consuming and thus expensive measurements and SOH-determination is required. According to Figure 33 starting in 2023, when first EV generations reach their EOL, a considerable market for second-use LIB starts to develop. Nevertheless, this requires the clarification of existing regulations and the introduction of supportive regulations.

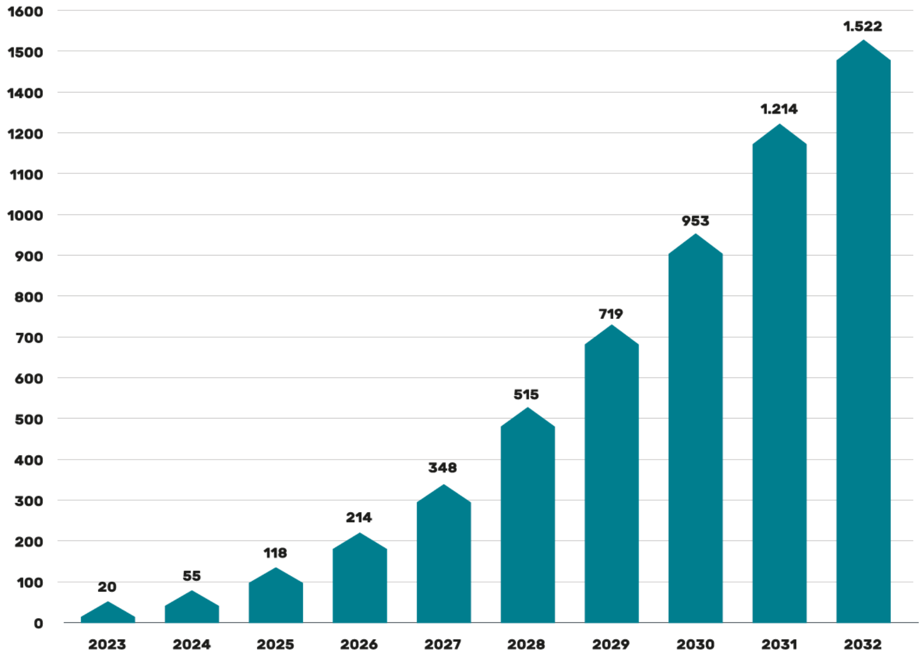


Figure 33: Estimated global second-use-battery energy [GWh] (source: Berylls (2018)).

An aspect that could accelerate a second-use market would be a specific design for second-use-applications already considered in the battery production. First, this relates to a facilitation of the dismantling of the battery system down to the cell, which might improve technical and economic feasibility of second-use. Second, this relates to an improved battery management system and SOH determination, so that the process of separating “good” cells (EOL not yet reached, SOH high enough for second-use) from “bad” cells (EOL reached, SOH too low for second-use) is facilitated. Further, that would reduce the risk of repurposing cells for second-life applications that could have still be used in the first-life application. Requirements for battery management and SOH determination, in a second-use context, are further elaborated and discussed in Task 7. According to experts, a range of 40 to 80 percent of first-life batteries might be reused.

3.4. Subtask 3.4 - Local Infrastructure (barriers and opportunities)

The aim of this subtask is to identify barriers and opportunities relating to the local infrastructure needed for the operation of batteries in EVs and ESS, e.g.:

- Energy: reliability, availability and nature
- Installers, e.g. availability, level of expertise/ training
- Physical environment, e.g. possibilities for product sharing

3.4.1. Energy: reliability, availability and nature

The demand for ESS in residential but especially in commercial applications largely depends on the availability and costs of technologies for renewable energy generation. The cheaper PV systems get, the more residential ESS might be sold. An increase of renewable energy, which is highly fluctuating and dependant on weather conditions will lead to a more instable electricity grid and require more commercial ESS to stabilize the grid or to compensate fluctuations in energy generation and consumption. Further EVs as well as ESS could be used for providing demand-side flexibility, however this would depend on the availability and conditions of time-dependent electricity tariffs for demand-side-flexibility applications. Further new market designs for financing the grid might be required, due to increasing decentralised energy generation and storage.

3.4.2. Charging Infrastructure for EV

For EVs, the availability and costs of charging infrastructure have a high impact on batteries energy efficiency. An increasing charging power might lead to faster battery aging, which reduces overall battery efficiency. Further, a high density of charging infrastructure might lead to lower battery capacities, since the distances between charging points decreases. Beyond that, the impact on load profiles and therefore on durability, e.g. fast charging vs. overnight charging, as well as on peak demand in grids might be an issue

3.4.3. Installation, e.g. availability and level of know-how

The limited availability of qualified personnel or suitable maintenance and repair infrastructure, especially for battery replacements, might be a barrier to second-life and repurposing concepts.

3.4.4. Lack of trust in second-hand products

Especially end customers might not be willing to buy second-hand product (used EVs/batteries) because they do not trust in their quality and well-functioning. However, the use of second-life batteries might also have a positive impact on a company's sustainable image.

3.4.5. Availability of CE marking and producer liability in second-life applications

A big, yet still unsolved issue is the question of CE marking in second-life applications and the question of liability. The cell OEM and the car OEM know best, via BMS or other systems, how the battery has actually been used and can make a good estimate on the battery's state of health. However, they do not want to be liable in case of failure or damage.

3.5. Subtask 3.5 – Summary of data and Recommendations

The summary of all important data and assumptions can be found in Table 10.

Further, we want to address the consistency and compliance of that study with the Product Environmental Footprint Pilot. The definition of the battery system and its components is consistent with the PEF approach, especially since the thermal management system and chargers are not in the primary scope of neither PEF nor our study. Also all vehicle and energy system components are beyond the scope. The wording, but also the calculation formulas for application service energy and quantity of functional are derived from the PEF and only slightly adapted and facilitated. However, it has to mentioned, that the PEF is not designed for the consideration of second-life applications.

Based on the analysis in this task, several main observations can be made:

- Power electronics (inverter, converter etc.) and drivetrain efficiency are not to be included in the product scope, however they will have substantial impact on the overall efficiency.
- Further, the charger is also not to be included in the product scope, since it is not built together with the battery and usually provided by another supplier.
- The active cooling/heating system is mostly closely linked to the battery and might even be provided by the battery supplier. However, regarding cooling and heating systems, car manufacturers consider the vehicle as an entire system and besides the thermal management of the battery; the passenger compartment has to be adequately tempered. For the vehicle's thermal management system currently also thermal heat pumps are discussed, thus energy consumption can hardly be differentiated to the battery and passenger compartment
- However, the substantial losses due to charger and cooling and heating requirements might be worth a deeper analysis.

Table 10*: Summary table of all relevant data (Sources according to the preceding section*

	Passenger BEV (medium to large)	**Passenger BEV (small)**	**Passenger PHEV**	**HDT BEV**	**HDTU PHEV**	**Residential ESS**	**Commercial ESS**
Economic lifetime application [a]	13	14	13	14	12	20	20
Annual vehicle kilometres [km/a]	14,000	11,000	14,000	50,000	100,000		
All-electric annual vehicle kilometres [km/a]	14,000	11,000	7,000	50,000	50,000	-	-
Fuel consumption [kWh/100km]	20	16	18	120	140	-	-
Recovery braking [% fuel consumption]	20%	20%	20%	12%	6%	-	-
All-electric range [km]	320	200	50	240	86	-	-
Annual number of full cycles [cycle]	120	120	120	300	600	250	250
Maximum DOD (stroke) [%]	80%	80%	75%	80%	75%	80%	80%
Typical system capacity [kWh]	80	40	12	360	160	10	30,000
Minimum system sapacity [kWh]	60	20	4	170	n/a	2,5	250
Maximum system capacity [kWh]	100	60	20	1,000	n/a	20	130,000
Application Service Energy	**43,680**	**29,568**	**19,656**	**940,800**	**890,400**	**40,000**	**120,000,000**
Quantity of functional units (QFU) over application service life	**96,000**	**48,000**	**18,000**	**576,000**	**360,000**	**64,000**	**240,000,000**
Battery cycle life (no calendar aging) [FC]	1,500	1,500	2,000	2,000	3,000	8,000	10,000
Battery calendar life (no cycling) [a]	20	20	20	20	20	25	25

ŋcoul x ŋv = energy efficiency	92%	92%	92%	92%	92%	92%	92%
Energy consumption due to battery energy efficiency [kWh]	**7,680**	**3,840**	**1,440**	**46,080**	**28,800**	**5,120**	**19,200,000**
Self-discharge rate [%/month]	2%	2%	2%	2%	2%	2%	2%
Average SOC [%]	50%	50%	50%	50%	50%	50%	50%
Energy consumption due to self-discharge [kWh]	**192**	**96**	**29**	**864**	**384**	**30**	**90,000**
Charger efficiency AC [%]	85%	85%	85%	92%	92%		
Charge power AC [kW]	3.8	3.8	3.8	22	22		
Charger efficiency DC [%]	93%	93%	93%	93%	93%	98%	98%
Charge power DC [kW]	50	50	50	150	150		
Share AC charge [%]	80%	80%	80%	50%	50%		
Battery efficiency charge [%]	94%	94%	94%	94%	94%		
Energy consumption due to charger energy efficiency [kW]	**13,983**	**6,991**	**2,622**	**46,957**	**29,348**	**1,391**	**5,217,391**
Heating/cooling energy requirements [%]	5%	5%	5%	5%	5%	5%	5%
Energy consumption due to cooling and heating requirements [kWh]	**4,800**	**2,400**	**900**	**28,800**	**18,000**	**3,200**	**12,000,000**

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Preparatory Study on Ecodesign and Energy Labelling of Batteries under FWC ENER/C3/2015-619-Lot 1

TASK 4

Technologies – For Ecodesign and Energy Labelling

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Version history:

Version 1:

- Version made available in December 2018 for the Stakeholders to comment and discussion in the stakeholder meeting.

Version 2:

- is a review based on the input from the stakeholder comments which resulted mainly in a reviewed description of the technology itself and the life cycle stages
- includes several updates on the text and additional figures
- revised version of the BOM according to the stakeholder comments
- includes some recommendations based on the findings of this task at the end of the report.

Version 3:

- Additional information provided for the BOM
- Additional data provided on recycling rates
- Literature sources revised

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Contents

ABBREVIATIONS

Abbreviations	Descriptions
ADR	European Agreement Concerning the International Carriage of Dangerous Goods by Road
Al	Aluminum
BAT	Best Available Technologies
BC	Base case
BEV	Battery Electric Vehicle
BJB	Battery junction box
BMS	Battery Management System
BNAT	Best Not-yet Available Technologies
BOM	Bill-of-Material
CED	Cumulative energy demand
CMC	Carbon methyl cellulose
CNT	Carbon nanotube
Co	Cobalt
CPE	Composite polymer electrolytes
CRM	Critical Raw Materials
DEC	Diethyl carbonate
DMC	Dimethyl carbonate
DOD	Depth of Discharge
EC	European Commission
EC	Ethylene carbonate
EMC	Ethyl methyl carbonate
EoL	End-of-life
EPTA	European Power Tool Association
ESS	Electrical Energy Storage Systems
EU	European Union
EV	Electric Vehicle
Fe	Iron
FU	Functional Unit
GWP	Global Warming Potential
HE	High-energy
HEV	Hybrid Electric Vehicle
HV	High-voltage
IATA	International Air Transport Association
IMDG	International Maritime Dangerous Goods Code
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCO	Lithium-ion Cobalt Oxide
LCV	Light commercial vehicles
LFP	Lithium-Ion Phosphate
Li	Lithium
LIB	Lithium ion battery
LMNO	Lithium-Ion Manganese Nickel Oxide
LMO	Lithium-Ion Manganese Oxide
LMP	Lithium-Metal-Polymer

LTO	Lithium-Ion Titanate Oxide
LVD	Low Voltage equipment
MEErP	Methodology for Ecodesign of Energy related Products
Mn	Manganese
NCA	Lithium Nickel Cobalt Aluminium
Ni	Nickel
NiCd	Nickel-Cadmium
NiMh	Nickel-Metal hydride
NMC	Lithium-ion Nickel Manganese Cobalt Oxide
P	Phosphor
Pb	Lead
PC	Passenger car
PE	Polyethylene
PHEV	Plug-in Hybrid Electric Vehicle
PP	Polypropylene
PV	Photovoltaic
PVD	Physical vapour deposition
R&D	Research and Development
SASLAB	Sustainability Assessment of Second Life Application of Automotive Batteries
SEI	Solid-electrolyte interphase
Si	Silicon
SOC	State of Charge
SPE	Solid polymer electrolyte
TIM	Thermal interfacial material
TRL	Technology Readiness Level
UN	United Nations
UNECE	United Nations Economic Commission for Europe
WEEE	Waste electrical and electronic equipment
ZVEI	Zentralverband Elektrotechnik- und Elektronikindustrie e. V.

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4. Task 4: Technologies

Summary

Battery systems are built up on a range of cells technologies, which are evolving rapidly in order to improve efficiency, energy density, performance or reliability. Furthermore, improvements on component side as e.g. the housing or BMS (Battery Management System) allow a broad spectrum of different combinations to design a battery system. Anyhow, taking as a reference year 2018, the lithium-ion technology can be expected a suitable base case, for applications as battery-electric passenger car (PC BEV), plug-in-hybrid passenger car (PC PHEV), battery-electric light commercial vehicles (LCV BEV), battery-electric medium-duty tractor unit (Truck BEV), plug-in-hybrid heavy-duty tractor unit (Truck PHEV), Residential storage and Grid stabilization.

Furthermore, lately a number of competing lithium-ion cell chemistries and designs have subsequently been commercialized and could be candidates for Best Available Technologies (BAT). These comprise cells, which use cathodes, with a higher content of Ni or which are renouncing on using a blend of materials. While e.g. for the anode a percentage of silicon is added to the former pure graphite anode. However, new cell technologies are evolving as for example high voltage spinel, high energy NMC (Nickel Manganese Cobalt Oxide) or Ni-rich cathode materials as well as solid-state batteries[1]. Those, also not yet available on the market can be considered for Best Not-yet Available Technologies (BNAT).

Current batteries on the market are not designed for circularity, meaning easy to disassemble, repair, refurbishment and recycling. They are not considered to be easily opened and usually designed to be only opened at end of life by mechanical intervention. Such irreversible design severely limits not only the potential for repair/refurbishment potentials, but also the recovery of valuable materials or the reuse of components. There are only currently limited examples of module design to support ease of disassembly or dismantling for recycling.

Despite of the outstanding needs from recyclers and of the advancements in technological research, there are currently a clear lack of business incentives for manufacturers to implement design-for-circularity.

In summary, the following Base cases (BC), BAT and BNAT were identified[2]. The cell technology is proposed as starting point for defining the combinations because it is fundamental to achieving performance improvements. Therefore, it has to be considered that we are dealing with a flexible product, consisting of different cell chemistries.

- The Base Case e.g. (BC1) is an average performing EV battery system for BC1.
- A BAT Case is combing one or more measures as listed in Table 2 (see chapter 4.1.3) for "Today"
    - Higher share of Ni (in case of NMC but nor already NMC 811 Ni-rich).
    - Silicon added graphite anode and an increased layer thickness compared to previous versions of the cells.
    - Reduced thickness of the separator

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[1] Other than LMP

[2] An in-depth analysis of the base cases will be conducted in Task 5

  - Optimization of inactive materials: Reduction of inactive materials such as binders, or the reduction of current collector thickness.
  - Housing improvements regarding isolation, weight and more.
- BNAT- is a battery system based on future improvements (see 4.1.3), thus the BNAT is expected to include battery technologies as:
  - All-solid-state batteries
  - High-voltage spinels or
  - High energy NMC

4.1. Subtask 4.1 - Technical product description

Task 4 provides a technological description of the products in scope of the study. Thus, it serves two different purposes: On the one hand it is intended to inform the policymakers and stakeholders about the product and its components from a technical perspective, on the other hand it serves to define the Base Cases and also works towards the definition of Best Available Technology (BAT) and state-of-the-art Best Not yet Available Technology (BNAT). While the Base Case represents an average product on the market today in terms of resources efficiency, emissions and functional performance, the BAT and BNAT will also be assessed in terms of environmental improvement potential. The BAT represents the best commercially available product with the lowest resources use and/or emissions. The BNAT represents an experimentally proven technology that is not yet brought to market, e.g. it is still at the stage of field-tests or official approval. The assessment of the BAT and BNAT provides the input for the identification of the improvement potentials in Task 6. The data for the base cases will serve as input for Task 5.

4.1.1. Existing products

4.1.1.1. Description of the key components of a battery system

A battery system builds up from different subcomponents, which are depicted in the following Figure 1. The electrode is thereby often seen as the smallest joint unit within a battery system.

A cell contains, depending on its final purpose, a certain number of electrodes. Since, the energy of a single cell is in most cases not sufficient for performing the function of a product; several cells are connected in parallel or in series to form modules. The individual modules are then provided with a mechanical support structure and connectors. Several modules in a row or in parallel are then combined again to form a battery system. The number and type of connected cells and modules finally depends on the desired operating mode of the application (Ketterer et al. 2009).

Figure 1: Schematic overview of the key components of a battery system after (Hettesheimer 2017)

In order for the cell or battery system to fulfil its intended function safely and optimally, further additional components are required on battery system level. The housing with the associated cooling system and battery management system shields the partially sensitive active and passive components of the accumulator system (BMS) from harmful environmental influences (water, dust, etc.) (Rahimzei et al. 2015).

After giving this short overview of the structure of a battery system, a detailed description of the mentioned key components will be given in the following.

4.1.1.2. Key components on cell level - Elements of a cell and cell formats

The components of a battery cell that are needed to fulfil its function are the cathode, anode, separator, electrolyte and the housing as well as further safety components. The functional structure of a cell and of the key components is exemplarily displayed in the following Figure 2. The components will be briefly described while an outlook of their future improvement potentials will be given later.

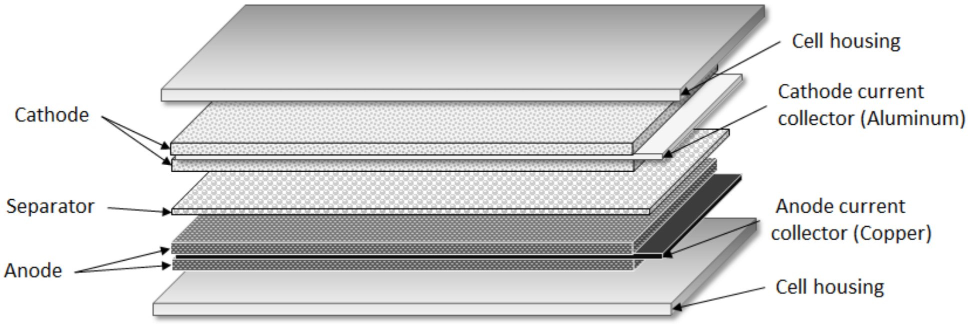

Figure 2: Exemplary structure of a battery cell (Hettesheimer 2017)

Cathode

The cathode (positive electrode) consists of mixed oxides applied to an aluminium foil (or aluminium current collector). The cathode material consists of the active material, a polymeric binder which is usually polyvinylidene difluoride and a conductive additive as carbon black. The cathode materials currently used are lithium nickel cobalt manganese oxide (NMC), lithium nickel cobalt manganese oxide (NCA) or lithium iron phosphate (LFP). In addition, these cathode materials are also mixed with lithium manganese oxide (LMO) to form LMO-NCM and LMO-NCA (Thomas et al. 2018; Rahimzei et al. 2015).

Manganese spinel oxides ($LiMn_2O_4$, LMO for short) are characterized by high safety in the event of overcharging, high thermal stability and low material costs. Their specific capacity is about 120 mAh/g. Difficulties arise due to undesired side reactions, like Mn dissolution, which lead to a reduction in service life.

Lithium nickel cobalt aluminium oxide (LiNiCoAlO2, NCA for short) has a high power density and long service life as well as a high specific capacity of 160-180 mAh/g. Disadvantages are the low thermal stability as well as high material costs, whereby depending on the development of nickel and cobalt prices there is still price reduction potential.

Compared to NCA, lithium nickel manganese cobalt oxide (LiNiMnCo2, NMC for short) is characterized by higher thermal stability and lower costs, while the specific capacity of 150 mAh/g (NMC 111) is somewhat lower. Compounds with a higher share of Ni as NMC 532 are achieving a higher energy density of somewhat 170 mAh/g. Furthermore, there are also chemistries with still higher energy capacities available and under development, which will be described later on.

The lithium iron phosphate batteries (LiFePO4, LFP for short) have a higher chemical stability than the oxides. This ensures a long service life and safety[3]. It is also environmentally friendly and relatively inexpensive. The specific capacity is approx. 160 mAh/g and thus roughly corresponds to that of NMC, but at lower voltage of 3.3 V (Anderman 2013; Mock 2010; Wallentowitz and Freialdenhoven 2011; Peters et al. 2013).

The following table provides a summary of the properties of different cathode materials.

Table 1: Properties of different cathode materials (Rosina 2016)

	LMO	**LFP**	**NMC**	**LTO**	**NCA**
Nominal voltage	3.80 V	3.30 V	3.65 V	2.3 V	3.60 V
Charge limit (Vmax)	4.20 V	3.60 V	4.20 V	2.7	4.20 V
Cycle life	>1000	>2000	1000 -2000	>5000 Up to 15 000+	2000 -3000
Specific power (W/kg)	Medium/high	Medium/high	High	High	High
Thermal stability	Fairly stable	Stable	Fairly stable	Stable	Least stable
Cost	Medium	Medium-to-high	Medium-to-high	High	Medium-to-high
Pros	•Cost •Safety •Power	•Safety •Materials cost •Life expectancy	•Energy density •Range of charge	•Safety •Cycle time	•Energy density •Lifetime
Cons	•Lifetime	•Low temp. performance •Processing cost	•Safety •Cost	•Low voltage •Energy density	•Cost •Safety •Low thermal stability
Supplier	LG, Chem, Samsung SDI, AESC	BYD, A123, Saft	Panasonic, Kokam, Saft	Leclanché, Toshiba, Microvast, ATL	Panasonic, Saft

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[3] Under the prerequisite that the cell is also constructed in a safe manner.

Anode

The anode (negative electrode) of the typical li-ion cell consists of a copper foil (or copper current collector) and graphite or a lithium alloy material. Natural or synthetic graphite anodes are currently the most common choice because of their low electrode potential and low volume expansion when Li^+ ions are intercalated. For high performance and safety requirements, lithium titanate as an additional option is also available, going along with disadvantages in terms of cost and energy density. Common binders here are: e.g. carbon methyl cellulose (CMC) or polyacrylic acid (Rahimzei et al. 2015). In the case of an all solid Lithium-Metal-Polymer (or LMP®) cell, the anode is made of a thin film of metallic lithium that serves simultaneously as an electrochemical anode and a current collector

Separator

The LIB separator isolates the two electrodes from each other in order to prevent a short circuit and to prevent malfunctions. The pores of the separator are filled with the electrolyte in liquid or gel form. The separator is mostly made of a porous plastic composite of polyethylene (PE) and polypropylene (PP). But PP/PE has the disadvantage of a low melting temperature (approx. 165 °C). However, another choice to enhance thermal resistance, are ceramic or ceramic coated separator. In addition, nonwovens and glass fibre separators are used in research (Rahimzei et al. 2015). For the LMP technology, the separator is a thin polymeric film that contains the lithium salt. It serves simultaneously both the purposes of separator and electrolyte.

Electrolyte

Electrodes are wetted by liquid electrolyte, which enables Li-ion transport. The electrolyte is required to be stable electrically in a typical LIB voltage range from 0 to 4.5 V and must have a high ion conductivity over a wide temperature range (from -40 °C up to +80 °C). Usually a liquid electrolyte consists of mixture solutions such as ethylene carbonate (EC), diethyl carbonate (DEC), dimethyl carbonate (DMC), and ethyl methyl carbonate (EMC) dissolved lithium salts (e.g. $LiPF_6$). Besides the most common fluid electrolyte, also polymer electrolytes are used. Since it is not possible for the polymers to escape, the use of stiff containers is not necessary and thus a lighter construction possible. The disadvantage, however, is the lower conductivity (Rahimzei et al. 2015; Thomas et al. 2018).

4.1.1.3. Cell housing and cell formats

Li-ion cells differ not only in the cell chemistry used, but also in their cell geometries, which directly influence the shape of the cell housing. Currently, three different cell formats are used in practice: the cylindrical cell, the pouch cell and the prismatic cell.

The basic elements of a cell described in Figure 2 represent the starting point of any cell geometry. Depending on the shape of the cell housing, the cell is inserted differently into the housing during the production step of cell assembly. While pouch cells can be stacked or wound, cylindrical and prismatic cells are usually wound. The different cell shapes as well as a cross-section (A, B & C) of the respective cells are illustrated in Figure 3.

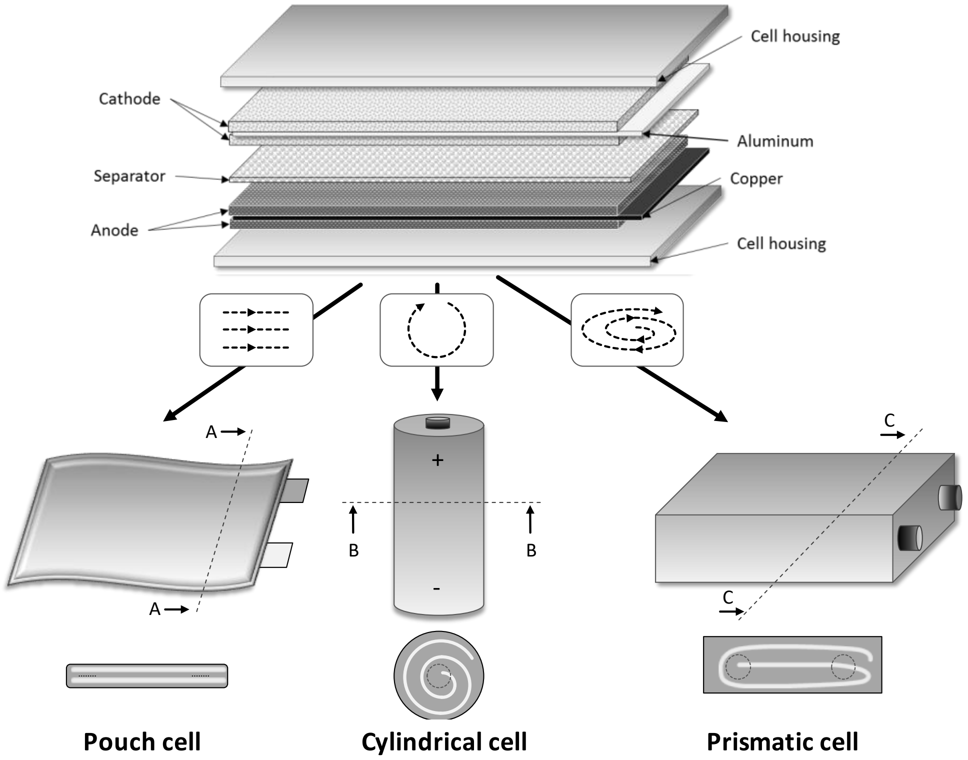

Figure 3: Possible cell formats: pouch, cylindrical and prismatic cell format

Depending on the geometry used, the cells have different advantages and disadvantages. The highest volumetric energy density of cylindrical cells is due to the basic geometry highest, but the energy density of large-format pouch cells has approached or reached a similar energy density to that of small-format lithium-ion cells in recent years. Depending on the module design, the cylindrical cell loses some of its advantage over the prismatic and pouch cell at the module level due to the packing density. The stiffness of the cylindrical cells is regarded as highest. A middle way trade-off between stability and size is the prismatic cell, which is produced with the help of a flat winding, similar to the cylindrical cell, and then inserted into a solid housing. With the pouch cell, the stiffness is not given by the pouch foil and must be supplemented with a frame when inserted into the module. All three cell shapes can be well thermally controlled. The main differences lie in the necessary cooling effort and the possibilities of dissipating and conducting heat. The pouch cell enables good heat dissipation via the current collectors and thus offers the best cooling performance. In the cylindrical cell, the heat generated in the core during charging processes can only be dissipated to a limited extent via the cell housing and the cell lid. This disadvantage can also be seen by the prismatic cell format. These are commonly cooled via the bottom, whereby cooling between the prismatic cells is also conceivable (Michaelis et al. 2018; Hettesheimer et al. 2017).

The pouch cell material is an aluminium-polymer composite that forms a soft cell container. Cylindrical and prismatic cell containers are hard cases. Cylindrical cell containers are commonly made of steel or aluminium, while prismatic cell containers are made of polymers or aluminium (Thomas et al. 2018).

4.1.1.4. Key components on module level

Even though the formats of the cells are geometrically very different, the outer appearance of a module for prismatic or a pouch cells looks quite similar (see Figure 4). The type of components on module level are also more or less the same (also the number of the specific components installed may differ). The cells are stored in a casing to provide them mechanical support. The casing is thereby mostly made of aluminium or PP/PE. Furthermore, the cells are connected on the tabs by busbars, mostly made of aluiminum. For temperature, regulation sensors are applied and cooling channels provided. Finally, each module has terminals to interconnect it with other modules.

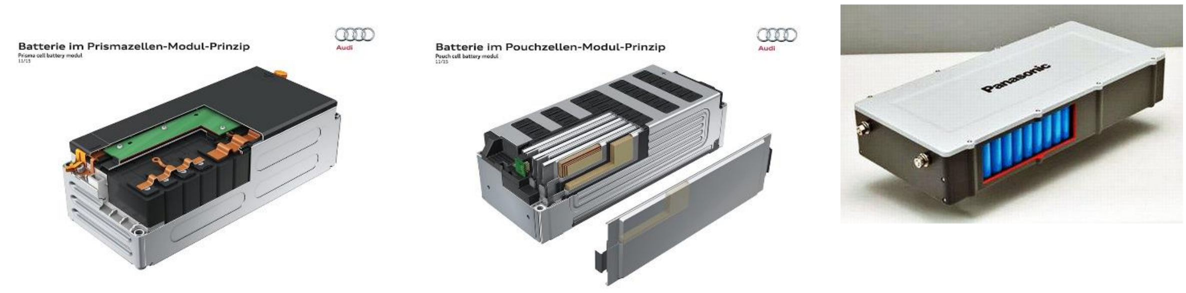
Prismatic format (Source: Audi) Pouch format (Source: Audi) Cylindrical format (Source: Panasonic)

Figure 4: Exemplary module structures for different cell formats

4.1.1.5. Key components on system level

Battery management system (BMS)

The task of the battery management system is the intelligent and optimised operation of the battery, which increases the service life, reliability, safety and economy of the battery system. For this reason, various sensors for temperature, voltage or current measurement are integrated in the individual modules. The current battery condition, also known as "State-of-Charge" (SOC), can be derived from this. And, for example in the case of EV, conclusions can be drawn about the remaining range of a vehicle based on the SOC. A further important task of the BMS is the charge and discharge control, since extreme imbalances between the cell charge states could occur during the respective processes without targeted control, which would make it impossible to charge the serially following cells again. For optimum service life and operation, it is therefore necessary to balance the cells. As part of safety management, short circuits are detected and battery operation is prevented by a safety circuit. Ultimately, the battery management system is also responsible for operating the battery in its optimum temperature range and the associated thermal management. According to Majeau-Bettez et. al. the BMS contains electronic circuits, software, and internal/external connections as well as wires used to operate the battery. The BMS consists of approximately 10% printed wire (circuit) boards, 40% steel, and 50% copper by weight (Majeau-Bettez et al. 2011b).

Thermal management

In lithium-ion batteries, thermal management has the task of controlling cell temperature efficiently and reliably, since cell performance and ageing are strongly dependent on temperature. Increased temperatures lead, for example, to faster degradation of the materials and faster aging of the battery. If not controlled, higher temperatures may also lead to the triggering of a thermal runaway phenomenon[4]. Low temperatures can lead to an obstruction

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[4] In the case of all-solid LMP cells, safety concerns are raised only when cell temperature reaches the melting temperature of lithium at 180°C.On the contrary they need to be operated at a minimum temperature of 60°C or more depending on the ionic conductivity that the application requires.

of the current flow, as the conductivity in the electrolyte is reduced. The system may therefore be cooled at high temperatures or heated in colder weather conditions to ensure normal operation, optimum power output and service life. Depending on the application, both functions can have considerable effects on the total power consumption and thus e.g. in the case of EV on the purely electrical range. The cooling system is either operated with air, water or other liquid coolants as e.g. Ethylene-Glycol and is often based on a heat-pump system for also cooling or heating the cabin. Furthermore, a TIM (Thermal interfacial material) is also used between cell and pack bottom. The cooling system consists mainly of aluminium and partly of steel. The aluminium radiator is thereby the main component (Rahimzei et al. 2015; Hettesheimer 2017; Ellingsen et al. 2014).

Housing and additional components

As described above, the housing shields the active and passive components of the battery system, from harmful environmental influences. It also shields service personnel from high-voltage components and provides temporary fire protection. It is therefore crucial for safe, reliable and long-term operation. Especially in the case of EV traction batteries, which are usually housed in the floor area of the vehicle, the housing may be exposed to extreme influences such as rockfall, splashing water, etc. High mechanical stability and corrosion resistance are therefore important. When designing the battery system for EV, attention must be paid not only to the housing but also to internal and external mounting systems, which must be able to withstand the sometimes high mechanical and thermal loads. In addition, the housing, together with the components contained therein, also serves as a stabilizing element for the body of some "Purpose Design" vehicles. Since the housing must not only offer a high protection but has to be light weighted too, it is usually made of aluminium and/or PP/PE.

In addition to the components mentioned above, there are numerous other elements to complete the battery system. Busbars connect the modules together and fuses protect the components from damage due to power surge or contactors which are isolating the battery system from the vehicle. Closed upon completion of safety tests and opened in the event of a crash or battery fault (Rahimzei et al. 2015).

4.1.2. Discussion on battery technology improvement (design) options

Defining standard improvement options for battery systems in the sense as for other products listed in the Ecodesign working plan is quite difficult. Since the LiB was continuously improved in the past years it can already be considered as a quite mature product and a thus standards improvement options are already state-of-the-art. Anyhow, improvements were mostly made on the component level and regarding the efficient operation of the battery. Potential may still be found in the engineering of the battery; e.g. LG was able to increase the energy density of its cell by 50% without changing the chemistry (Rosina 2016). Another major point of improvement is the reduction of passive components and materials within the cell and the system to reduce the weight, material content and thus reduce the environmental impact and increase the energy density. This can be reached by using thinner conductors or separators, reducing the dead volume within the cell or by using lightweight components for the battery tray (Takeshita et al. 2018; Thielmann et al. 2017).

However, in the upcoming years some relevant improvements are expected regarding Li-based batteries other battery types as for example non-polymeric all-solid-state batteries using metallic lithium. To define a BAT and a BNAT it is necessary to take a closer look on the future development prospective by means of the different battery components. This procedure differs from MEErP in which sections on standard improvement, BAT and BNAT are usually described in sequence. Anyhow, in this specific case for battery systems it seems rather expedient to focus on components and their improvement potentials. Based on this, subsequently a classification regarding BAT or BNAT can be made. A quite detailed outlook on the developments on component level is given by means of a roadmap from (Thielmann et al. 2017) which was developed under cooperation of German actors from science and industry and is listing mayor improvement options until the year 2030. In the following Figure 5 different technological developments and therefore improvement, options will be described for the different system components until the year 2025. The study will thus include Li-ion technologies up to generation 3b (as e.g. high voltage spinel cathodes or carbon-silicon anodes).

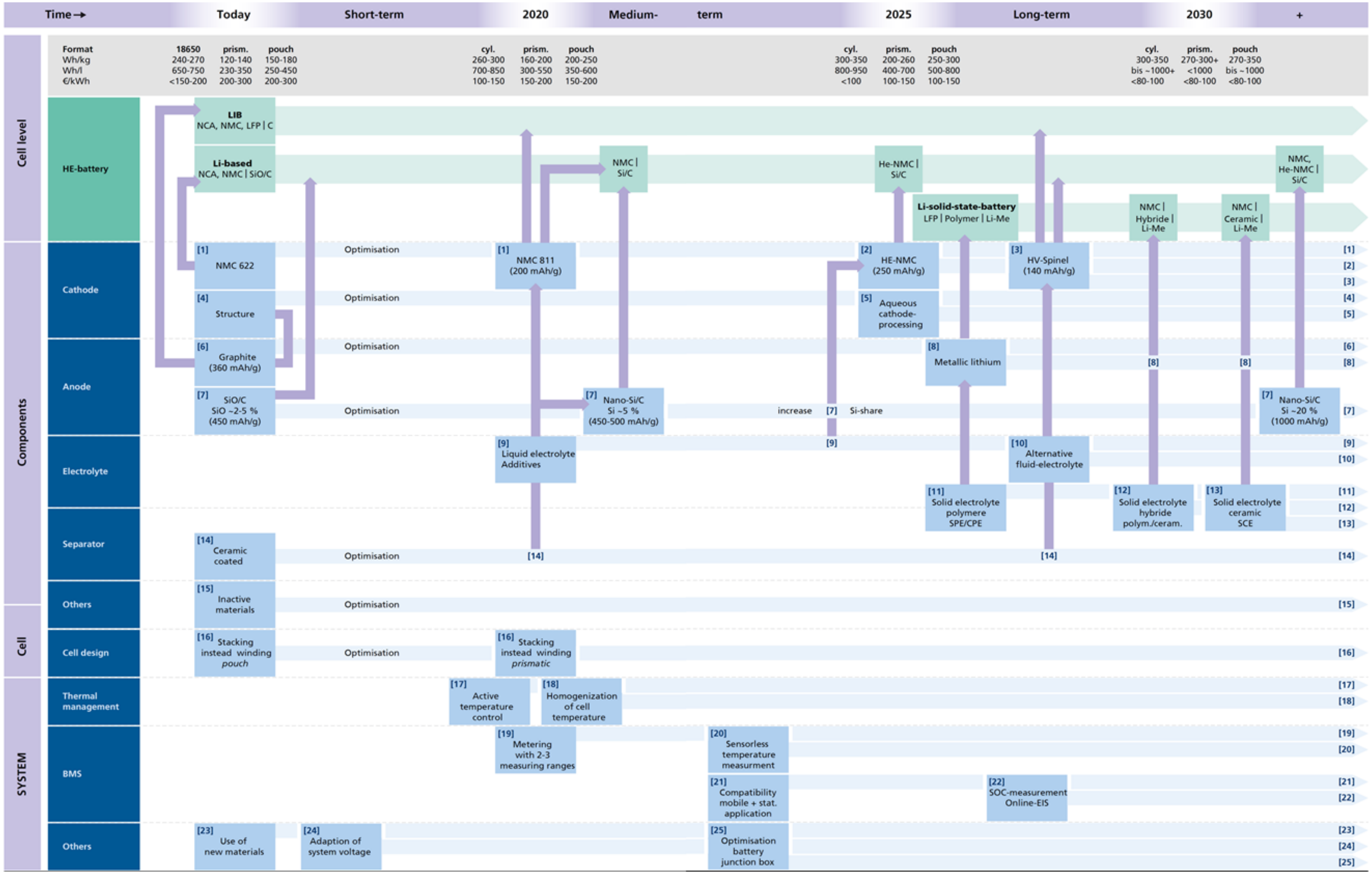

Figure 5: Definition of improvement options (Thielmann et al. 2017)

The classification regarding BAT and BNAT will be made after the description of the improvement options in Table 2 (in section 4.1.3).

4.1.2.1. Cathode[5]

4.1.2.1.1. Nickel-rich materials

Nickel-rich materials are defined as NCA with more than 80% nickel, or NMC with a composition of 811.

Target and suitable cell formats

The aim of using nickel-rich materials is, on the one hand, to dispense with Co or at least to reduce the Co content of the active materials. This leads to a reduction in material costs and resource requirements. On the other hand, it also results in an increase in material performance, as the electrical conductivity and Li^+ diffusivity increase with an increased Ni content.

Bottlenecks and solutions

The central bottleneck for reaching market maturity is an increase in the service life of the materials. However, this can be achieved with a low to medium R&D effort. This is analogous to what has already happened with NMC materials such as 532 or 622, which now represent the state of the art. The reason for the reduced service life is that the surface of the nickel-rich materials is more reactive to the electrolyte (the unreacted residual Li source on the cathode surface can react with the binder to make gelation during slurry mixing process). Coatings, for example, can be a solution to this problem and for protection of crack and cation mixing causing new surface areas with structural unstable weakness of High Ni cathode. In addition, care must be taken during processing to ensure that the room humidity < 50% is maintained.

Advantages and disadvantages

Extremely high energy densities can be achieved with nickel-rich materials, as these materials or powders can theoretically be compacted almost to the level of LCO. Co-free materials have a higher electrical conductivity compared to NMC 111. This offers the possibility to save conductive additives and thus to reduce the inactive part in the cathode or to save further costs. Overall, the costs (per kWh) are considerably lower than with state-of-the-art systems or NMC 622.

Furthermore, the approach provides an advantage with regard to resource availability, especially with regard to cobalt which is classified by the EC as a critical raw material[6]. On the other hand, the higher moisture sensitivity is disadvantageous compared to NMC standard materials. However, this is still at a manageable level, although production costs are rising.

Effort and producibility

Producibility goes hand in hand with minor adaptations.

Maturity and market entry (in automotive application)

The approach is currently still in the range of prototypes to demonstration. First samples can however already be sampled by the customer. The market maturity for nickel-rich materials

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[5] The following improvement options are based on Thielmann et al. 2017. For this reason the source will not be listed after each abstract.

[6] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52017DC0490

(NMC 811) is expected to be reached around 2020. Thus, this approach can be classified as BNAT or even BAT.

4.1.2.1.2. High-energy NMCs

High-energy (density) NMCs are lithium-rich "integrated" composite materials which can be defined as y×Li_2MnO_3 (1-y)×$LiMO_2$ M = (Ni,Mn,Co). The materials offer a theoretically high specific capacity due to an advantageous ratio of Li to transition metal with greater than 1.

Aim and suitable cell formats

In practice, specific capacities of about 280 mAh/g are currently being achieved. The use of high-energy NMC thus aims to increase energy density. Furthermore, high energy NMC has a price advantage over nickel-rich materials due to its high Mn content and thus offers additional cost reduction potential. The cell format plays no role for the use of high-energy NMC.

Bottlenecks and solutions

Bottlenecks currently form the electrolyte availability as well as the electrolyte costs, which are comparatively high as standard electrolytes are no longer sufficient. Furthermore, the washing out of Mn can also impair the service life of the materials. Mn precipitates in the cell and the cathode material degrading its performance. Particle coatings are a possibility to prevent the washing out.

Advantages and disadvantages

There is a very high cost advantage at cell level due to the high Mn content. In addition, the energy density is better than with NMC-111 systems, but lower than with nickel-rich materials. The porosity of the powders, on the other hand, is similar, although the intrinsic density is lower, which results in a lower overall density in the comparison with nickel-rich materials. Thus high energy NMC is very advantageous in terms of cost, but not the best solution in terms of high energy densities. The use of high-energy NMC therefore also depends on the application and the available installation space, as well as on how much one is dependent on the high energy densities.

Apart from this limitation, electrode balancing with the anode is problematic (different specific capacities of cathode and anode). The anode would have to be very thick to completely absorb the lithium from the cathode. However, this in turn limits performance and has a negative effect on producibility. However, this aspect can be largely compensated by the use of silicon-containing anodes.

Effort and producibility

For the use of HE-NMC a higher R&D expenditure has to be considered until the product is finally ready for the market. This also concerns the producibility, for which a small expenditure can be assumed.

Degree of maturity and market entry

At present the manganese-rich materials are still in the area of applied research up to prototypes, possibly already with the customer sampling. The market entry of High Energy NMC could take place in the year 2025 provided that all difficulties are overcome. Thus, this approach can be classified as BNAT but may be out of time scope.

4.1.2.1.3. High-voltage spinels

High-voltage spinels are lithium-manganese based oxides with a cubic structure. As nickel doped oxides, they are classified as "5V" materials (e.g. $LiMn_{1.5}Ni_{0.5}O_4$, 4.8V against Li/Li^+). The capacity of the high-voltage spinel is approximately 140 mAh/g.

Target and suitable cell formats

The material is comparatively well available and inexpensive, which can result in cost advantages. At the module level, a smaller number of cells can be used to achieve a high battery voltage, thus reducing costs and increasing energy density if necessary. As with the approaches already mentioned, the use of high-voltage spinels is independent of the cell format.

Bottlenecks and solutions

Challenges on the way to market maturity relate in particular to electrolytes. The electrode materials are rather unstable at this high voltage operation. Mn is dissolved into the electrolyte and accumulate on anode surface during charging as side products by reaction with electrolyte. The central bottleneck is therefore cathode material stability, electrolyte stability and manganese leaching. The electrolyte stability causes the decomposition products of the electrolyte to deposit on graphite anodes and continue to react. This ultimately leads to cell death through dendrite formation and possible punctuation of the separator or faster degradation the cell performance.

The electrolyte thus has a significant influence on the service life of the cell. State-of-the-art carbonate-based electrolytes are stable up to about 4.5 V against Li/Li+. This stability must therefore be further increased in the future, since e.g. High voltage - NMC requires a stability up to 5 V against Li/Li^+. Alternatively, coatings for these active materials are also being developed to compensate for these disadvantages.

Advantages and disadvantages

A major advantage of using high-voltage spinels is the price advantage for the cathode material resulting from the elimination of cobalt and the high proportion of manganese in combination with the higher average voltage compared to standard NMC. In addition, the energy density can be increased compared to conventional anode materials due to the possible high potential. However, not at the level of nickel-rich materials. The disadvantage of using high-voltage spinels is the availability of suitable electrolytes and the separator stability.

Effort and producibility

The R&D expenditure of this approach is to be classified as high. The adjustments to producibility are rather small or even drop-in capable.

Maturity level and market entry

HV technology is currently in the field of applied research. The market entry of high-voltage spinels could take place between 2025 and 2030. Thus, this approach can be classified as BNAT but is out of time scope of this study.

4.1.2.1.4. Layer thickness

With regard to the layer thickness, the optimization of the electrode is not considered from the raw material perspective, but from the conceptual point of view of how the electrode is designed. The charge of a cathode is currently around 40-100 Ah/m^2 (coated on both sides with aluminium). The central influencing variables for an increase in energy density are layer thickness, porosity and tortuosity. The layer thickness influences the processability, flexibility, stability and thus also the service life of the cell. In addition, high layer thicknesses impair the thermal conductivity of the electrode. Passivated (isolated) areas can form and drying becomes more time-consuming. The tortuosity can be changed by micro-structuring the electrode accordingly. The porosity is currently even worse than hexagonal closest ball packing, while the total density is already close to the limit, as the conductive additive and the binder are still required.

Aim and suitable cell formats

The general goal of an increased layer thickness of active materials is to increase the energy density by increasing the ratio of active to inactive materials. The approach of increased layer thicknesses is in principle suitable for all cell formats.

Bottlenecks and solutions

The most important bottleneck on the way to an increased layer thickness is the difficult processability. Increasing the layer thickness in order to obtain a few percent more energy density at the system level already leads to a considerable increase in expenditure. Accordingly, further development activities must be undertaken in the area of processability (e.g. with regard to the drying of thick layers, powder coating processes, the handling of the thicker electrode, for example when winding through the thicker bending radii, when filling, etc.). Another bottleneck is the usable capacity of thick layers. The thickness has a negative effect on conductivity and electrolyte distribution, which means that it takes much longer to supply the cathode material with lithium ions or to transport them away.

Advantages and disadvantages

The advantage lies in the higher energy density due to the configuration of the electrodes and the relatively lower proportion of inactive materials. The disadvantage, however, is the poorer processability due to the reduced mechanical flexibility. The lower conductivity of thick material layers leads to a poorer fast charging capacity of the cells. Furthermore, also the available power at a low SOC will be affected. Active materials with increased layer thickness are already on the market, and the approach is constantly being further developed.

Effort and producibility

The effort required to optimize the layer thickness can be regarded as high, the adjustments to the producibility as low.

Maturity and market entry

The maturity is to be seen between the applied research up to the prototype. Approaches to optimizing layer thickness are already state-of-the-art today and will continue to be pursued and continuously improved in the future. Thus, this approach can be classified as BAT.

4.1.2.1.5. Aqueous cathode production

Aqueous cathode production describes the substitution of organic solvents by water.

Aim and suitable cell formats

The aim of using aqueous media during electrode manufacturing is to reduce manufacturing costs and to make LIBs much more environmentally friendly by eliminating the use of organic solvents. Aqueous cathode production is suitable for all formats.

Bottlenecks and solutions

An essential bottleneck lays in the quality of aqueous electrodes/cells and their electrochemical performance. Many of the cell components, such as highly nickel-rich systems or the electrolyte, are very sensitive to water. Even small residual amounts in the ppm range can have a significant effect on the performance and service life of the cells. The processability can also still be regarded as difficult at present, as there is no corresponding process route in place to allow the water supplied during processing to be completely dried out of the electrodes again. One solution on the material side would be to hydro-phobize the material, which is, however, very costly.

Advantages and disadvantages

The advantage of an aqueous cathode production lays in the reduction of costs through the saving of organic solvents and their recovery as well as in the positive environmental aspects. While the higher energy consumption for drying and the water sensitivity of various active materials represent a disadvantage of this process. Especially with nickel-rich and lithium-rich materials, there is a risk of Ni and Li being washed out.

Effort and producibility

The R&D expenditure to be carried out in the field of aqueous cathode production can be regarded as high. The adjustments to producibility are likely to be rather small.

Degree of maturity and market entry

The maturity can currently still be located in basic research. Aqueous binders are therefore still more of a research topic. However, if material-related problems (such as cathode powder or binders) are solved, a market launch could be possible from 2025. Thus, this approach can be classified as BNAT but is out of time scope of this study.

4.1.2.2. Anode

4.1.2.2.1. Graphite

Natural and synthetic graphite represent the status quo as anode material and has a specific capacity of approx. 360 mAh/g.

Aim and suitable cell formats

Until now, almost exclusively natural and synthetic graphite was used as anode materials for LIBs, and LTO was used for special applications. The further development of energy densities on the cathode side will in future also require new active materials on the anode side in order to enable meaningful electrode balancing. Another driver for the increasing substitution of graphite is the desired fast charging performance of future batteries.

The concrete aim is a further increase of the energy density, for example by increasing the density in the electrode layers or by using graphite-containing composites.

Bottlenecks and solutions

Graphites are used today as active materials in all cell formats and currently represent the state of the art, with no further massive improvements to the material or electrode to be expected. With regard to thickness optimization, graphite is already close to the theoretical limit. On the other hand, there is still development potential in the field of electrode development, e.g. by structuring the electrode or by mixing different types of graphite, conductive carbon black, conductive CNTs or similar.

Advantages and disadvantages

Overall, there are probably no other major advantages or disadvantages. It is an established system. With regard to increasing the energy density, however, graphite anodes are exhausted.

Effort and producibility

The expenditure of a further optimization is to be seen as a means, since there are hardly any optimization possibilities and further improvements are very complex. The producibility is given.

Maturity and market entry

Today, graphite products represent the state of the art and are available on the market.

4.1.2.2.2. Si/C composites

The transition from pure intercalation materials in LIBs to mixed systems with a low content of alloying materials such as silicon can represent a possibility to significantly increase the specific capacity of pure carbon anodes (372 mAh/g corresponding to LiC_6). Si offers a theoretical capacity of about 3578 mAh/g (corresponding to $Li_{15}Si_4$). Like graphite, the material has very good raw material availability and low toxicity. With a redox potential of less than 0.5 V against Li/Li^+, a good compatibility to graphite-based anodes is given. Due to the high-volume change of Si in the alloy with Li of up to 300 %, electrodes with a high Si content are exposed to strong mechanical loads. Si/C composites can partially absorb this effect. With a mixture of 20 % Si and 80 % carbon, capacities of about 1000 mAh/g can be achieved.

Aim

Si composites with content of < 5 % Si are already being used commercially in High Energy-LIBs (HE-LIBs). Composites with a content of 20 % are currently in applied research (TRL 4-5) and could, in combination with NMC, enable a gravimetric or volumetric energy density of 300-350 Wh/kg and 1000 Wh/l in the future. From the point of view of performance, possible charge currents of 1 C - 3 C to 80 % SOC are predicted.

Bottlenecks and solutions

The change in volume leads to two types of degradation: The high mechanical load can lead to a reduced mechanical stability of the electrode and thus to the loss of the electrical contact of the particles. On the other hand, the volume change of the Si-particles causes a repeated breaking-up and rebuilding of the SEI (Solid-Electrolyte Interphase). The resulting loss of electrolyte and active material results in an irreversible loss of capacity.

Further optimization of the material and electrode architectures is necessary to cushion the volume expansion. Approaches exist in the nanoscaling of the Si particles or a porous and flexible structure of the composite structure. An important contribution to this is also seen in the further development of compatible binders. Porous C-structures can absorb about 10 % volume changes. With a volume change of 50-100 %, a strong influence on the service life is assumed with the current state of the art.

In order to increase the stability of the SEI during cyclisation, electrolyte improvements could contribute. Other approaches are seen in the production of coated Si particles, e.g. core/ shell structures. The lithium loss associated with the repeated build-up of the SEI could be compensated by a partial pre-lithiation of the anode.

Advantages and disadvantages

The main advantage of Si/C composites is the increase in both gravimetric and volumetric energy densities. As described above, a reduction in cell life seems inevitable.

Effort and producibility

The compatibility of existing electrode and cell production processes with Si/C materials is assessed as good. The suitability of the materials is seen in particular for cylindrical and prismatic cells, since in these formats a favourable external pressure can be applied to the electrode stack to mitigate expansion effects. Due to the easy aggregation of Nano-Si, strategies for the production of stable and processable dispersions have to be developed. At the material level there are currently various concepts for the production of complex structured composites with partly very good electrochemical properties. Scalability to industrial scale has yet to be proven in some cases.

There is a need to optimize materials at the level of applied research. The expenditure for the development of anodes with > 5 % Si content is regarded as low, for anodes with Si content >20 % considered to be high. The increase in the number of cycles is not considered mandatory. A certain reduction in cycle life appears acceptable if the capacity can be increased to the same extent through the use of Si/C composites.

Maturity and market entry

The technology is on the market. It is assumed that the share of Si will increase continuously. The further development path of the materials are pure Si anodes or anodes with a Si content of about 80 %. Thus, this approach can be classified as BAT or as BNAT, depending on the share of Si.

4.1.2.2.3. Lithium metal

In this approach anodes made of Li-metal are used instead of graphite or silicon. Conceptually, a very thin Li layer can be used. The Li of the anode is not necessary for the electrochemical reaction, since all the Li required is already present in the cathode material. The initial Li layer thus serves as a "starting point" for further Li intercalation during the charge of the cell.

Aim

Compared to other material concepts, metallic lithium is the anode with the highest specific capacity. The aim of this approach is to increase the energy density. For lithium-based materials, a cylindrical cell is best suited, as it best tolerates volume changes. The existing LMP technology, uses a prismatic cell design within a housing that controls volume changes cumulated on a bundle of cells through mechanical means. The order is here (as with Si/C-composites): Cylindrical is better than prismatic and this is better than pouch.

Bottlenecks and solutions

When using a lithium metal anode, there is a bottleneck in dealing with volume change and dendrite growth, especially at higher current densities. This leads to a structural loss of the anode, which on the one hand requires larger electrolyte volumes and on the other hand creates the risk of an internal short circuit if the dendrites penetrate the separator. Solution approaches consist in the use of solid electrolytes or appropriately added liquid electrolytes, which are intended to limit the loss of structure of the Li anode. Another bottleneck is that there are currently no commercial thin lithium foils available. In addition, contacting without carrier films is very difficult with regard to handling and further processing is also relatively difficult (reactivation of Li with air and water).

Advantages and disadvantages

The advantages of this approach are increased energy densities, but at the same time also disadvantages due to the change in volume and the associated effects on the service life.

Effort and producibility

The R&D expenditure for the implementation of the Li-metal anode is estimated to be high. New production concepts are needed to be able to produce the anode. This is because concepts for the processing of Li-metal anodes, such as their passivating coating to enable processing in the presence of oxygen or water in the atmosphere, are currently lacking. Cell design requires other techniques in order to cushion the volume expansion of the Li-metal anode.

Maturity and Market Entry

Lithium metal in the broad scale (with exception of the LMP technology) currently only works in the laboratory, but not in the product, and can therefore rather be classified as applied research. Li-metal anodes are not expected to enter the market before 2025. Thus, this approach can be classified as BNAT and may be out of time scope of this study.

4.1.2.3. Stable separator

The development of stable separators concerns separators that are thermally and mechanically stable in cell production and in field use. This applies in particular to so-called ceramic separators or ceramic-coated membranes.

Aim and suitable cell formats

The fundamental goal is to reduce the thickness of the separators while improving the safety of the cell as much as possible. Ceramic separators are currently 21-28 µm thick, ceramic-coated separators approx. 12-24 µm. The aim is to produce future thicknesses significantly thinner than 20 µm, but without safety losses, while simultaneously using high-energy electrodes. Currently, polyolefin membranes are coated with inorganic particles or separators are designed with a continuous layer of inorganic particles. No problems can be detected with the format if the inorganic particles are bonded well to the carrier and there is sufficient tensile strength for the winding/stacking process.

Bottlenecks and solutions

An essential bottleneck is the homogeneity of the coating and the processability of the separator. At the same time, the manufacturing processes must be presented in such a way that the costs of the separators can be developed in line with market requirements.

Advantages and disadvantages

In addition to higher thermal stability, a stable separator offers a high degree of safety (e.g. during nail test, overload test, hot box test). Another advantage is the increased cycle stability. The wetting and high- temperature processing of all-ceramic separators is also significantly better than with conventional membrane-based separators. The disadvantages are the increased costs compared to pure PP or PE. In addition, the ceramic materials are heavier. This means that ceramic-based or modified separators must be comparatively thinner than pure membrane separators in order not to impair the energy densities of the cells.

Effort and producibility

The cost of this approach for ceramic-coated separators is estimated to be low to medium, although small to medium adjustments may also be necessary for the producibility. The costs for the ceramic separators can be classified as medium, as can the adjustments for producibility.

Maturity and market entry

Maturity is at least in the prototype stage, if not even ready for the market.

4.1.2.4. Electrolyte

4.1.2.4.1. Additives

The electrolyte has a significant influence on the life of the cell. State of the art are currently the $LiPF_6$-based electrolytes in carbonate solvents. These have electrochemical stability up to about 4.4 V. The stability window must be enlarged for the utilization of HV materials, e.g. up to 4.6 V for HE-NMC or 5 V for high-voltage spinels. Many of the difficulties currently encountered in the use of new active materials are due to instabilities in the electrode/electrolyte system. The development of suitable electrolytes can thus be regarded as a decisive "enabler" for all future HE systems.

Electrolyte additives are added to the electrolyte consisting of Li salts and carbonate solvents to improve its properties. For example, additives can improve the stability of the electrolyte or have a protective effect on the surface of active material particles.

Aim and suitable cell formats

The aim of additives is in particular to enable the use of new electrode materials or to increase the service life of such cells. Furthermore, properties such as non-combustibility, the window for operating temperatures (low-temperature electrolyte) or voltage stability can be improved. There are no limitations with the different formats, if the other cell components are adapted accordingly.

Bottlenecks and solutions

Difficulties exist in the search for suitable additives or additive combinations and in optimising their concentration in electrolytes. The lowest possible proportion is desirable in order not to impair the function of the electrolyte as an ion conductor.

Furthermore, cost restrictions apply to additives, which require the development of favourable manufacturing processes. The solution approaches exist in the area of basic research in the search for suitable compounds/materials and in the area of synthesis processes.

Advantages and disadvantages

With the additives suitable for Si anodes and HV cathodes, the advantages consist in enabling higher energy densities at cell level. In addition, lower costs for the silicon additives are to be expected. Compared to a component change, established main components (possibly cheaper or better suited for production processes) can be used.

On the other hand, the efficiency of the additives is a disadvantage in the case of silicon additives and HV additives. Either the additives have to produce a stable SEI or they repeatedly replicate SEI and are consumed in the process, reducing the energy efficiency of the cell. In addition, protective additives contribute nothing to the conductivity of the electrolyte and thus to the "function" of the battery, making them an additional passive element.

Effort and producibility

A distinction must be made between compatible additives for HV cathodes and Si anodes in terms of effort: For Si it can be regarded as low to medium, while for HV it is slightly higher and is quantified as medium to high. Producibility seems possible in both cases, but requires minor process adjustments.

Maturity and market entry

In the case of additives for Si anodes and HV additives, one is in the research area or pre-prototype. A market entry could take place from the year 2020. Thus, this approach can be classified as BNAT.

4.1.2.4.2. Alternative liquid electrolytes

By changing the components of the electrolyte, it should become a non-flammable electrolyte, low-temperature electrolyte or electrolyte for high-voltage materials.

Aim and suitable cell formats

The aim of a component change is to increase the service life of the cell or to improve the application possibilities of LIBs. The exchange of salts or solvents aims, for example, to increase the usable voltage window (> 4.5 V) or to improve chemical stability, which is not available for many new active materials with standard electrolytes. Further goals are the reduction of flammability or the extension of the window for possible operating temperatures. When the components are changed, no problematics can be detected in the formats either, provided that the other cell components are adapted accordingly.

Bottlenecks and solutions

The concrete challenges are strongly dependent on the material/electrolyte system under consideration and depend on the exact objective of the electrolyte development. In HV applications, the oxidation stability must be guaranteed in relation to the active materials. When changing components, compatibility with the anode must also be ensured. Ionic liquids often have a too low conductivity, which limits the maximum current density (power rate). They are also relatively expensive.

Advantages and disadvantages

Enabling the use of HV materials could increase energy density at cell level. Non-combustible electrolytes also provide a higher degree of safety. With an extended operating temperature range, it may be possible to partially dispense with cooling if the stability of the SEI is still guaranteed. If the components are changed, the costs are to be considered disadvantageous.

Organic carbonates are relatively cheap, while all other materials are currently still quite expensive. In addition, the reduced cycle stability and service life of non-combustible electrolytes and low-temperature electrolytes represent a disadvantage.

Effort and producibility

When changing components, a distinction must be made between HV applications and the inhibition of flammability, as it is also the case with addition: The cost for flammability inhibiting electrolytes can be regarded as medium, while it is slightly higher for HV and is classified as medium to high. Producibility should be possible with minor adjustments.

Maturity and market entry

All in all, the approach of a component change in electrolytes is still very young and in the research stage, with the exception of non-flammability and low-temperature electrolyte. Market entry should therefore take place around the years 2025 to 2030. Thus, this approach can be classified as BNAT but is out of time scope of this study.

4.1.2.4.3. Polymer electrolyte SPE/CPE

Aim and suitable cell formats

Polymers can be made ion conductive by complexing with Li salts. The salts are dissolved in polymer chains. Ion transport takes place via the mobility of the chains in the polymer. The best known representative of this class is polyethylene oxide/LiTFSI. SPEs usually have a low ionic conductivity at room temperature, which prevents their practical application. Therefore, they need to be brought to a sufficient operating temperature that will ensure adequate conductivity for a given application (e.g., existing LMP technology operates at a minimum temperature of 60 to 80°C depending on the application). Conductivity of polymer electrolytes can be significantly increased by combining them with ceramic or metallo-organic nanoparticles to form composite electrolytes (CPE composite polymer electrolytes). Among other effects, the presence of nanoparticles inhibits the crystallization of polymer chains and thus increases their mobility.

In combination with a Li-metal anode and LFP cathode, the polymer-based LMP 100% solid batteries are already being used in commercial applications. Other polymer-based solid batteries are also used in test projects and those are considered at the TRL 7. LMP® cells of the current generation operating at 80°C reach performance levels of 240 Wh/kg, 360 Wh/l, 120 W/kg.

The raw material availability for the production of the polymer electrolyte is good. In battery systems, the costs are currently still determined by the Li anode, whose price increases inversely to the layer thickness. The importance of this technology for Europe is estimated to be high. It is assumed that value chains could be established within the EU. In this sense, the EU is regarded as internationally competitive.

Besides the described SPE/CPE, there are also solid polymer-ceramic hybrids and solid ceramic electrolytes (SCE) in development. Due to the reason, that for those technologies the market entry (for automotive applications) is not expected in the short-term, they are not described here in detail.

Bottlenecks and solutions

Weaknesses of the technology result from the low ionic conductivity and the resulting high operating temperature. Compared to SCEs the potential stability of polymer-based electrolytes is worse, so that use with high-voltage cathodes is currently only possible in exceptional cases. Solution approaches exist in the further search for suitable nano filler materials, other polymers or polymer combinations. The use of functional or protective layers can improve the chemical stability of the materials to each other. The R&D expenditure is estimated to be moderately high and lays in the area of material and production development.

Advantages and disadvantages

The main unique selling point of the SPEs/CPEs is the higher safety of cells and the possibility to better transfer the cell energy density to the module level by reducing passive components. By changing the components on the anode and separator/electrolyte sides, a higher volumetric energy density can be achieved. On the cathode side, there is no change compared to LIBs. In general, polymer electrolytes offer the possibility to carry out the preparation process dry or solvent reduced.

The overall high internal resistance of the solid batteries, which requires operation at high temperatures, is regarded as a disadvantage. However, in many of the world climates, very hot or cold, it can instead be an advantage over lithium-ion batteries (LIBs) that need to be maintain around 25 °C for safety, performance and cycle life. In hot climates for example, the solid batteries will require minimal energy to maintain its operating temperature and moreover will not suffer from and ambient at 40 °C or even 50 °C. In colder climate, the solid battery packaging that includes insulation to maintain internal operating temperature and efficient heating systems can also be an intrinsic advantage over LIBs that would also in this context require heating but cannot be overly insulated to enable cooling in warmer months.

Producibility

The producibility of SPE-based solid batteries is given and demonstrated by the latest market entry in 2011 in Europe of the LMP® technology. For production by other manufacturers, minor adjustments in the production technology from cell to module are necessary. Compared to SCE batteries, the flexibility of polymer layers makes them easier to process. There are no restrictions with regard to possible cell formats.

Applications

The use of the technology is seen in particular in applications with regular operation using moderate charge rates, in particular in extreme climates as this facilitates in hot environments or justifies in cold ones the permanent maintenance of the cells at their high operating temperature, part of which is obtained through the actual operation of the battery. Hence, possibilities exist in the area of stationary storage and fleet vehicles such as city buses or last-mile delivery trucks that operate during a portion of the day and are brought back to garages during off-hours.

Future development and vision

The aim of the development is to increase conductivity of the electrolyte to reduce the necessary operating temperature and maintain a uniform lithium deposition in spite of higher charging currents. To increase the energy density it is necessary to increase the voltage stability and decrease thicknesses of cell layers that do not contribute to the energy level, such as the separator and the cathode current collector. For example, in LMP technology, the current development is expected to increase the performance parameters to 250 Wh/kg, 400 Wh/l and 125 W/kg at 2000 cycles and a service life of 10 years by 2022.

Solid-battery technologies may be separated in two groups. The 100%-solid LMP technology first marketed in the early 2000s in North America and approximately a decade later in Europe is classified as a Best Available Technology (BAT) within this new approach of battery design. Other experimentally-proven solid battery technologies are in a second group that can be classified as BNAT.

Further technical improvements are conceivable through the use of so-called "single ion" conductive polymers. Sometimes these have a higher conductivity at a lower operating temperature than currently used systems. Due to the ion transfer number of 1 of such SPEs, the formation of Li dendrites could be prevented by the theoretically possible homogeneous Li transport and the avoided concentration gradients.

4.1.2.5. Cell design and cell formats

4.1.2.5.1. Optimization of inactive materials

In this approach, the current collector and the casing are understood as inactive materials. In addition, protective layers, binders, clamps, springs or pressure relief valves are also considered.

Aim and suitable cell formats

The aim of this approach is to increase energy density through inactive material optimization and material reduction (e.g. binder content). The approaches are very diverse. The reduction of layer and carrier thicknesses is often intended. The weight of inactive components can be reduced by substituting materials. The approach to optimize inactive materials is in principle independent of the format. The concrete strategies can, however, differ considerably, since there are strong requirements for cell design that are dependent on the structural shape (and also size).

Bottlenecks and solutions

Bottlenecks lies particularly in the processability with a reduction of the current conductor thickness or the casing-thickness. In addition, the warranty or proof of safety under the new modification represents a bottleneck.

Advantages and disadvantages

One advantage of optimizing inactive materials is weight savings and space optimization. In addition, the material savings can result in cost advantages. The switch from steel to aluminium, for example, can result in corresponding cost disadvantages due to higher material prices. In some cases, however, this is already state of the art, especially for prismatic cells.

Effort and producibility

The expenditure is to be estimated rather as low to medium. For example when using an aluminium case instead of steel. The producibility can also be achieved by a low to medium effort in the adaptation.

Maturity and market entry

The degree of maturity is generally well advanced and can be located in the area of prototypes/demonstrators to market maturity. Accordingly, some approaches are already on the market. Thus, this approach can be classified as BAT up to BNAT.

4.1.2.5.2. Stacking instead of winding

In the area of the entire cell (prismatic and pouch), the transition from winding the cell to stacking the individual electrode packages represents a considerable opportunity to increase the energy density due to a higher degree of cell filling. There are two different procedures for inserting the electrode packs into the cell housing: Winding the electrode packs and stacking. Winding is currently still predominantly used for prismatic and cylindrical cells, while pouch cells are predominantly stacked. During winding, the coated anode and cathode films are wound separately by the separator, while during stacking (e.g. Z-stacking) individual cathode and anode sheets are inserted laterally into the separator.

Aim and suitable cell formats

The aim of stacking is to increase the filling level by reducing the dead volume in the cell housing. The filling level is comparatively lower during winding, e.g. due to the resulting radii. The stacking process is particularly suitable for prismatic cell formats and also for pouch cells.

Bottlenecks and solutions

The bottleneck, however, is the cycle time for stacking. Since this is a pick-and-place process, it takes somewhat longer. In addition, the stacking process can be differentiated according to the individual processes (e.g. stacking single sheets, Z-folding, etc.), in which the cycle times vary again. Irrespective of the type of stacking process, however, the cycle times and the higher costs for the pick-and-place process represent the central challenges.

Advantages and disadvantages

It is possible to increase the filling degree and thus the energy density by stacking instead of flat winding in prismatic cells. In addition, a better pressure distribution in the cell and, if necessary, easier processing of thicker layers will be achieved due to the higher filling degree, since no more small bending radii are produced. The mechanical stress at the edges is also lower during stacking, which can have a positive effect on the service life of the cell. The disadvantage of the stacking process, on the other hand, is the larger number of cut edges, but otherwise there are rather no disadvantages compared to wound cells.

Effort and producibility

The R&D effort to address these problems can be seen as a means. Producibility still requires medium adjustments.

Maturity and market entry

The stacking process has already been industrialized and the market entry has already taken place. Thus, this approach can at least be classified as BAT.

4.1.2.6. Battery management system (BMS)

4.1.2.6.1. Electricity meter with 2-3 physical measuring ranges

The task of the Battery Management System (BMS) is the intelligent and optimised operation of the battery, which optimises the service life, reliability, safety and economy of the battery system. For this reason, various sensors for temperature, voltage and current measurement are integrated in the individual battery modules. On this basis, four R&D challenges are of particular relevance for the BMS: A total current measurement with 2-3 different physical measurement ranges, sensorless temperature determination of all battery cells, the marriage of specifications for electronics for automotive and stationary applications and online electrochemical impedance spectroscopy. While the first three approaches aim at an optimized recording of the current battery properties, the approach for the development of electronics for automotive and stationary applications rather includes a life-cycle focus and a more economical second use of the system (also the other two approaches may also play a role therefore)[7].

Aim and suitable cell formats

In today's battery systems, electricity meters are usually only able to cover one physical measuring range.

By using electricity meters with 2-3 physical measuring ranges, the currents can be measured more accurately and the SOC of a battery can also be determined more accurately. This allows a better utilization of the capacity and a simultaneous reduction of battery ageing.

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[7] The role of the BMS for 2nd life applications will be further explained in chapter 4.2.4.2 Second-life applications

Bottlenecks and solutions

There are no bottlenecks worth mentioning. Only the effort concerning the hardware integration increases a bit and has to be implemented as cost-optimal as possible. In addition, the costs of the electronics for the electricity meter must be taken into account.

Advantages and disadvantages

If the slightly increased costs for electronics are accepted or reduced, electricity meters with 2-3 physical measuring ranges allow a more accurate estimation of the condition of the battery and especially of the SOC and thus increase the usable capacity and reduce battery aging.

Effort and producibility

The R&D expenditure for this approach is rather low and producibility is largely given.

Maturity and market entry

The degree of maturity can therefore be seen in the area of the prototype/demonstrator. Electricity meters with 2-3 physical measuring ranges are already partly used today. A broad market entry could then take place from 2020. Thus, this approach can be classified as BNAT.

4.1.2.6.2. Sensorless temperature measurement

Until now, measuring the temperature of the cells required complex wiring and the direct physical connection of a temperature sensor to the cells. A new alternative approach therefore pursues temperature determination without direct use of a temperature sensor e.g. via intercept frequency.

Aim and suitable cell formats

The aim of sensorless temperature determination is to determine the condition of a single cell more precisely. This increases the number of measured cell temperatures, which in turn makes it possible to better monitor the battery system in order to detect abnormal behaviour in the event of an error of a single cell at an early stage and to prevent a possible thermal runaway. On the other hand, the approach does not require any additional wiring. Sensorless temperature determination is suitable for all formats, but less relevant for cylindrical battery systems with many small cells connected in parallel, since the large number of cells makes it difficult to determine which cell temperature ultimately deviates.

Bottlenecks and solutions

There are still big problems because of the noisy environment (e.g. because of the motor converter). The disturbances have to be filtered out and the handling of differently aged cells with different internal resistances is a challenge.

Advantages and disadvantages

Despite these bolttlenecks, the advantages of sensorless temperature measurement are high. With regard to battery safety, the indirect determination of the temperature of each individual cell via its voltage and behaviour represents a significant added value. Sensorless temperature determination could also act as an early warning in the event of faults. The disadvantages of such an application are small. There are minor additional costs in electronics as more components are required.

Effort and producibility

The R&D expenditure for sensorless temperature determination can be regarded as medium. Producibility, on the other hand, is given.

Maturity and market entry

The maturity level of this approach is currently still in the field of basic research. Market entry is therefore only likely to take place in the medium term between 2020 and 2025. Thus, it can be classified as BNAT.

4.1.2.6.3. Compatibility of electronics for automotive and stationary applications

The design of electronics in today's battery systems is strongly application-oriented. Accordingly, it can only be used for one application at a time. Which then would be a barrier to ecodesign requirements when products are not designed for both ESS and EVs. The design of the electronics for both automotive and stationary use would make it possible to operate the battery after its use in the automobile also in the stationary area, without having to accept major compromises with regard to the required performance. Therefore, on the one hand, automotive requirements would have to be met. On the other hand, requirements for the stationary sector such as a service life of 20 years and operation 24 hours a day, 7 days a week. The type of cell formats does not play a role in this approach.

Aim and suitable cell formats

The aim of this approach is therefore to use electronics that are suitable both for automotive applications and for subsequent stationary applications. Although there are OEMs who also use their automotive batteries for stationary applications, the batteries are not designed or optimized for this purpose.

Bottlenecks and solutions

As a central bottleneck, the additional costs arising from the fact that different requirements are placed on the electronics can be mentioned here. These, however, are to be regarded as low.

Advantages and disadvantages

The resulting advantage from the compatibility of electronics for automotive and stationary applications can be classified as a means, provided that Second-Life as an application will also be relevant in the future. The potentially high costs for second life applications can be seen as a disadvantage. How decisive these are, however, ultimately depends on the respective Second Life business model.

Effort and producibility

The expenditure is rather small. The producibility is also given.

Degree of maturity and market entry

The approach is still more in the area of basic research. The time of market entry is strongly dependent on the development of business models based on 2nd life concepts. The approach should therefore reach market maturity between 2020 and 2025 at the earliest. Thus, it can be classified as BNAT.

4.1.2.7. Thermal management

4.1.2.7.1. Improved battery temperature control during fast charging

The overriding goal at system level is to make the best possible use of existing capacity (or optimise usable capacity) and to minimise overhead in terms of weight and volume. The central problem here is thermal management, which not only leads to different aging but also to derating of the electrical properties, resulting in lower system performance.

The R&D challenges in the field of thermal management concern rapid charging with simultaneous optimization of the service life and homogenization of the temperature in the battery system over the operating time. The focus of the objectives in the area of thermal management is therefore on increasing or maintaining the service life, especially if the battery is quickly charged and thus high currents and temperatures are generated in the battery system.

During fast charging (up to 350 kW in the future), stronger continuous currents flow through the battery system for several minutes than during driving (more likely 20-40 kW) and lead to a high thermal load. Temperature control of the cells is therefore necessary and will have a considerable effect on the service life of the battery system.

Aim and suitable cell formats

The aim of a suitable temperature control is to limit the reduction in service life and to avoid derating even under the extreme thermal stresses of fast charging. In principle, the format of the cells is irrelevant. All formats can be fast charged. However, the format sometimes has a strong influence on the current carrying capacity of the cell contacts and on the quality of the thermal resistance. For example the cell contacts of a pouch cell are comparatively thin, which leads to a higher resistance and thermal load during charging.

Bottlenecks and solutions

The higher costs for the thermal management and the charging stations as well as the definition of standards for the charging stations are to be seen as an essential bottleneck.

Advantages and disadvantages

The advantage that would result, however, would be faster charging without a drastic reduction in service life. In return, however, the high costs of creating the infrastructure must be taken into account.

Effort and producibility

The R&D effort to be undertaken in relation to fast charging is estimated to be high to very high, especially when the system needs to be cooled, for example at rest areas where the charging stations are frequently used. The cost of producibility is also very high and requires new production concepts.

Maturity and market entry

At present, fast charging as defined above (up to 350 kW), in vehicles (excluding buses) can still be seen in the stage of basic research (also the Tesla Supercharger v3 will be able to charge with 250 kW peak). However, market entry could be expected from 2020. Thus, this approach can be classified as BNAT.

4.1.2.7.2. Homogenization of temperature

The cells in a battery system may have different temperature levels during operation. This primarily depends on how the cells are connected and loaded. Depending on the temperature level, their performance changes at different speeds. Each cell has its own temperature distribution. However, homogenization ensures that this temperature distribution is identical for all cells and that the ageing of each cell progresses at the same rate.

Aim and suitable cell formats

This homogenization leads to an even ageing of the cells. Through the battery system, this reduces the need for cell derating and increases both uptime and life. In addition, the internal cell resistances and thus the equal cell aging, have a positive effect on the fast charging performance. The homogenization of the temperature is rather independent of the cell format and can therefore be applied to all formats, but with different effort.

Bottlenecks and solutions

There are currently no larger bottlenecks.

Advantages and disadvantages

If the homogenization of the temperature is successful, the advantage is very high, since a more even cell aging is achieved. The internal resistance of the cells thus also changes uniformly in all cells and with it also the power consumption capacity of the cells. This means that the balancing effort can be reduced, as the cells only drift further apart to a limited extent than has already been the case in production. These advantages are at the expense of slightly higher material costs, whereby the absolute amount cannot yet be conclusively quantified. In addition, there is a higher expenditure in the cooling system.

Effort and producibility

There is still room for improvements to a certain extent, but at the same time it requires some extensive changes (e.g. direct cooling of cells), although the effort involved is rather small. Producibility is given.

Degree of maturity and market entry

In terms of maturity, the approach is in the field of applied research or prototype/demonstrator. There are already some commercial applications. For example, Tesla currently already has a liquid cooling system with which 1C charging is possible. However, it is still controversial whether this will affect the service life. The overriding aim of this challenge is therefore to achieve uniform cooling of the cells without reducing the service life. This could be achieved by the year 2020. This approach can thus be classified as BNAT.

4.1.2.8. Housing and additional components

4.1.2.8.1. Use of new materials

The housing of the battery system encloses and protects the internal components of the battery system, as well as the outside of the vehicle. R&D challenges in this area include the use of new materials to make the case lighter or smaller in volume, and the design and material optimization of the battery junction box to achieve the same goal. The use of new materials for or within the housing, covers a wide range of possible materials such as mica, supra thermal insulators, lightweight materials or phase change materials for thermal insulation.

Aim and suitable cell formats

The aim of using these new materials is to reduce both weight and volume overhead, regardless of the material. Finally, such a reduction makes it possible to increase e.g. the range of the vehicle.

Bottlenecks and solutions

There are currently no serious bottlenecks visible. However, a large number of tests are still necessary before a market launch in order to investigate and demonstrate the advantages of the materials, depending on the type of cell and application.

Advantages and disadvantages

The resulting advantages can be considered medium to high, as the materials have a positive influence on weight and ageing. The only disadvantage could be low additional costs.

Effort and producibility

The effort required for material development depends on the specific case. However, it can tend to be classified as high to very high. New production concepts may also have to be developed in some cases in order to achieve producibility.

Maturity level and market entry

Most of the materials mentioned are currently still in the pre-development stage. Nevertheless, some materials are already on the market, so that the market launch of individual materials has already taken place. This approach can therefore be classified as BAT and BNAT depending on the considered material.

4.1.2.8.2. Change in system voltage (48V, 800V)

A further R&D challenge at system level is to design the battery voltage of a BEV to 800V instead of common 400V. This increase in voltage is intended to noticeably improve the performance of the battery system in terms of power consumption and output. Alternatively, a trend towards lower system voltages, i.e. 48V, is currently being observed.

Aim and suitable cell formats

The aim of the voltage increase is to increase the performance of the battery system. The approach is suitable for all cell formats. The voltage reduction to 48 V aims at a cost reduction of the battery periphery and the BMS.

Bottlenecks and solutions

The bottleneck to series production readiness of 800V systems is the guarantee of safety, since some of the components have yet to be developed and their safety must be proven accordingly. Power electronics for 48V systems are available in principle, but challenges still have to be solved by the higher currents.

Advantages and disadvantages

The advantage of using 800V systems lays in the increased performance of the battery system through more power and braking force, which is particularly relevant for applications in the high-performance and premium automotive segments. The disadvantage resulting from this measure is the increased costs. In terms of maturity, is the 800 V system developed in parallel with the 400V or 600V system.

The main advantage of 48V systems is the lower cost of automotive electronics and powertrain. However, significant disadvantages result from the high currents, which tend to have a negative effect on the power efficiency of the overall system and generate higher power transmission costs.

Effort and producibility

The R&D expenditure to be carried out for 800V systems can be classified as very high. It is expected that medium adjustments will be necessary for producibility.

48 V drives differ fundamentally from 400V or 600V systems. It is assumed that 48V systems will not be used in previous xEV models. The R&D expenditure is estimated to be moderately high.

Maturity and market entry

To date, the first 800V prototypes are already available, but no series production has yet been reached, which means that the maturity is in the prototype/demonstrator range. It should be possible to reach market maturity in the short term. Battery systems with a higher voltage of 800 V should enter the market by 2020. The use of 48 V systems is seen in particular for industrial applications (transport, industrial trucks) and for small vehicles (scooters, small xEV in particular PHEV). First prototypes and small series are already available. The approach can therefore be seen as BAT (48V) and BNAT (800V).

4.1.2.8.3. Optimization of the battery junction box and new solutions for contactors

The battery junction box (BJB) contains electrical-mechanical components such as BMS or contactors and relays. Their design and material optimisation (e.g. all-solid-state relays) is the focus of this approach.

Goal and suitable cell formats

The aim of optimizing the BJB is to reduce weight and volume, but also costs. The approach is suitable for all formats and independent of cell size or cell format.

Bottlenecks and solutions

The bottleneck, which has to be solved here, lies in the guarantee of safety. For example, in the case of a mechanical contact, it is easy to ensure that it is open, as opposed to a semiconductor switch.

Advantages and disadvantages

The solution of the bottleneck is opposed by a large cost saving for the components of the BJB as well as a reduction of the volume and weight of the BJB with no recognizable disadvantages.

Effort and producibility

However, the effort required to solve this bottleneck is high. New production concepts are likely to be necessary.

Maturity and market entry

Research in this area is between basic research and applied research. Market entry could take place in the medium term between 2020 and 2025. So far, the bottleneck on the subject of security still stands in the way of the breakthrough. Thus, this approach can be classified as BNAT.

4.1.3. Overview of the improvement design options and classification regarding BAT and BNAT and expected timeline

Based on the previous section the following BAT and BNAT is identified including a timeline for which it can be expected to enter the market, see Table 2.

Table 2: Expected timeline for the market entry of the improvement options

		Today (BAT)	2020 (BNAT)	Until 2025 (BNAT)	From 2025 (out of time scope)
Cathode	Nickel-rich materials	■	■		
	High-energy NMCs			■	■
	High-voltage spinels				■
	Layer thickness	■	■	■	
	Aqueous cathode production				■
Anode	Graphite	■			
	Si/C composites	■	■	■	■
	Lithium metal			■	■
Electrolyte	Additives		■		
	Alternative liquid electrolytes				■
	Polymer electrolyte SPE/CPE			■	
Separator	Stable separators	■			
Cell design and cell formats	Stacking instead of winding	■			
	Optimization of inactive materials	■	■	■	
Battery management system (BMS)	Electricity meter with 2-3 physical measuring ranges		■		
	Sensorless temperature measurement			■	
	Compatibility of electronics for automotive and stationary			■	
Thermal management	Improved battery temperature control during fast charging (-> 350 kW)		■	■	
	Homogenization of temperature		■		
Housing and additional components	Use of new materials	■	■	■	
	Change in system voltage (48V, 800V)	48V	800V		
	Optimization of battery junction box/ new solutions for contactors		■	■	

Following the description given before, a BAT Case (considered on component level) may contain some or all of the following improvement options as listed in Table 2 for "Today".

- Higher share of Ni (in case of NMC but nor already NMC 811 Ni-rich).
- Additives to the graphite anode
- Increased layer thickness compared to previous versions of the cells.
- Thickness of the separator is further reduced-
- Reduction of inactive materials such as binders, or reduction of current collectors' thickness.
- Isolation, Insulation and weight reduction of housing.

A BAT may include all or most of these options depending on the intended application. As BNAT can be considered those technologies and improvement options that have not entered the market yet but might be available until the year 2025. Table 2 depicts the following improvement options:

- On side of the cathode this will be the Ni-rich materials (NMC811) but also the High voltage spinels and High energy NMC might be an option.
- For the anode, it can be expected that, even there will still be pure graphite anodes, the anode will be composed with a certain share of Si.
- Additives in the electrolyte will be an issue, probably together with alternative and polymer electrolytes as described before.
- The separator will be further improved regarding safety and thickness.
- Regarding the cell design it can be expected that the reduction of inactive materials will be further proceeded, while for the prismatic cell format also the stacking process might become more and more common.
- The BMS and sensoring of the cells might be improved by measuring more than one physical range to improve the cell management and increase the service life of the battery system. Also a sensorless measurement is thinkable, which would reduce the wiring and therefore improve the energy density and reduce the costs (materials and production). Furthermore, when considering second life application, it might be an option to use electronics suitable for both, automotive and stationary applications.
- Another step regarding improving the service life is to improve the thermal management to homogenize the cell temperature and thus to increase the whole battery systems service life. It has also to be considered that fast charging-capability will play a more prominent role in the future. The thermal management has therefore to be able to deal with the high currents going along with that.
- Finally, the whole housing will be further improved (as on cell level) by eliminating inactive materials or by using new materials offering a higher value regarding safety, weight or costs. This will especially address the junction box and contactors. Additionally, the whole battery system may be adapted to new system voltages as e.g. 48V or even 800V.

Since the added value of an improvement option strongly depends on the intended application, a BNAT may include one or more of these options depending on the application.

4.2. Subtask 4.2 - Production, distribution and end-of-life

4.2.1. Product weight and Bill-of-Material (BOM)

Based on the insights of Task 2 and Task 3 the following applications can be identified as a potential baseline to build the base cases[8].

Table 3: Key parameters of market products used to build the Base case

Application Parameters	Passenger car BEV large (80 kWh)	Passenger car BEV small (40 kWh)	Passenger car PHEV	Truck BEV (40 t)	Truck PHEV(40 t)	Residential Storage	Grid stabili-sation Storage
Economic lifetime of application [year]	13	14	13	14	12	20	20
Typical capacity of the application	80	40	12	360	160	10	30 000
Nominal battery system capacity [kWh]	80	40	12	30	20	10	10
Number of cycles per year	120	120	120	300	600	250	250
Maximum calendar lifetime of the installed battery (no cycling ageing)	20	20	20	20	20	25	25
Maximum number of cycles for battery system until EoL (no calendar ageing)	1500	1500	2000	2000	3000	8000	10 000
SoH @ EoL of battery system relative to declared capacity	70%-80%	70%-80%	60%-80%	70-80%	60-80%	50-70%	60-70%

For the base case definition, we are looking at the different applications to define the system capacity and the system designs. The battery systems of the applications are thereby using different cell chemistries as already described in task 3. Therefore, on cell level typical battery cells on the market are used as a database for the BOM. But due to the high heterogeneity of products on the market it is not possible to identify a reliable base case for the applications, since they wouldn't be representative in terms of cell chemistry or cell format. To come to a base case which can be seen as representative for the products on the market and therefore could be considered as a base case, a virtual battery system for each of the above-mentioned

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[8] The corresponding values listed below should not be considered as an exact value but rather as a typical example for the application. For sake of transparency, the values are therefore not given in a range but listed, as they will be used for the calculations in task 5.

applications is build. The different share of cell chemistries in the product thereby reflects its market share within the specific application.

Therefore, the following distribution of cell chemistries is estimated, based on the results of Task 3 and, where no reliable information could be gained, on own estimations.

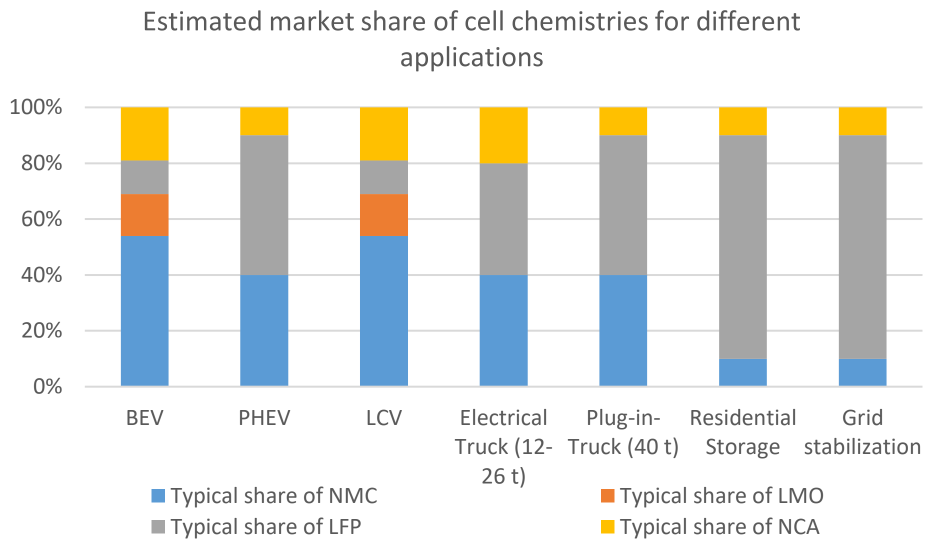
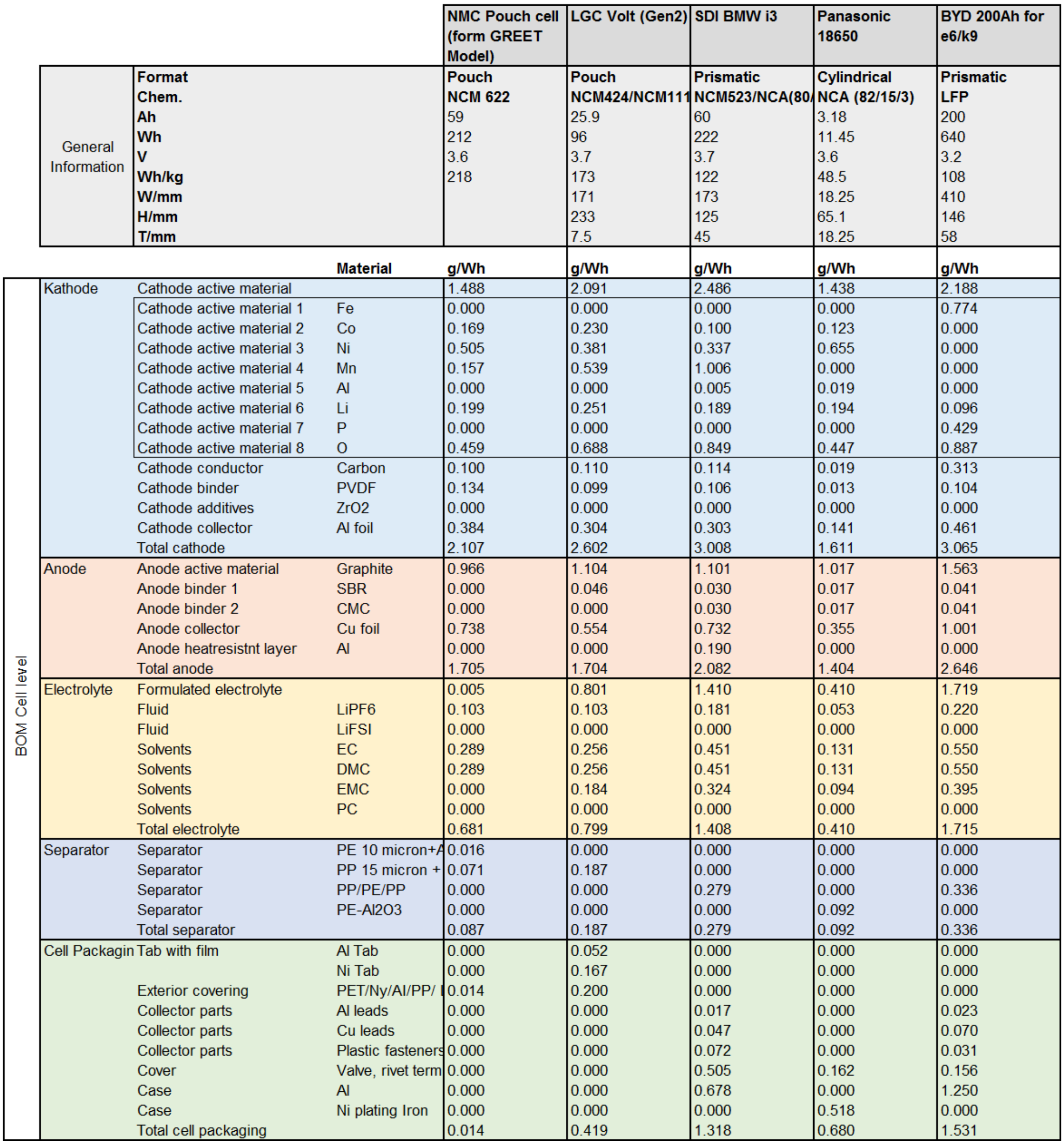


Figure 6: Distribution of cell chemistries within the different Base Cases (based on Pillot 2017; Hill et al. 2018 and own assumptions)

However, the BOM for the cells within the base cases is based on common cells on the market. To reflect a typical product for the different applications by the mixture of those cells, the cells where chosen to cover the most common cell chemistries and also the most common cell formats as described in the previous chapters. The following table depicts the considered cells as well as their corresponding BOM.

Table 4: Specifications and BOM of the considered cells as database for calculating the base cases (mainly based on information from Takeshita et al. 2016, 2018)



				NMC Pouch cell (form GREET Model)	LGC Volt (Gen2)	SDI BMW i3	Panasonic 18650	BYD 200Ah for e6/k9
	General Information	**Format**		**Pouch**	**Pouch**	**Prismatic**	**Cylindrical**	**Prismatic**
		Chem.		**NCM 622**	**NCM424/NCM111**	**NCM523/NCA(80/**	**NCA (82/15/3)**	**LFP**
		Ah		59	25.9	60	3.18	200
		Wh		212	96	222	11.45	640
		V		3.6	3.7	3.7	3.6	3.2
		Wh/kg		218	173	122	48.5	108
		W/mm			171	173	18.25	410
		H/mm			233	125	65.1	146
		T/mm			7.5	45	18.25	58
			Material	**g/Wh**	**g/Wh**	**g/Wh**	**g/Wh**	**g/Wh**
BOM Cell level	Kathode	Cathode active material		1.488	2.091	2.486	1.438	2.188
		Cathode active material 1	Fe	0.000	0.000	0.000	0.000	0.774
		Cathode active material 2	Co	0.169	0.230	0.100	0.123	0.000
		Cathode active material 3	Ni	0.505	0.381	0.337	0.655	0.000
		Cathode active material 4	Mn	0.157	0.539	1.006	0.000	0.000
		Cathode active material 5	Al	0.000	0.000	0.005	0.019	0.000
		Cathode active material 6	Li	0.199	0.251	0.189	0.194	0.096
		Cathode active material 7	P	0.000	0.000	0.000	0.000	0.429
		Cathode active material 8	O	0.459	0.688	0.849	0.447	0.887
		Cathode conductor	Carbon	0.100	0.110	0.114	0.019	0.313
		Cathode binder	PVDF	0.134	0.099	0.106	0.013	0.104
		Cathode additives	ZrO2	0.000	0.000	0.000	0.000	0.000
		Cathode collector	Al foil	0.384	0.304	0.303	0.141	0.461
		Total cathode		2.107	2.602	3.008	1.611	3.065
	Anode	Anode active material	Graphite	0.966	1.104	1.101	1.017	1.563
		Anode binder 1	SBR	0.000	0.046	0.030	0.017	0.041
		Anode binder 2	CMC	0.000	0.000	0.030	0.017	0.041
		Anode collector	Cu foil	0.738	0.554	0.732	0.355	1.001
		Anode heatresistnt layer	Al	0.000	0.000	0.190	0.000	0.000
		Total anode		1.705	1.704	2.082	1.404	2.646
	Electrolyte	Formulated electrolyte		0.005	0.801	1.410	0.410	1.719
		Fluid	LiPF6	0.103	0.103	0.181	0.053	0.220
		Fluid	LiFSI	0.000	0.000	0.000	0.000	0.000
		Solvents	EC	0.289	0.256	0.451	0.131	0.550
		Solvents	DMC	0.289	0.256	0.451	0.131	0.550
		Solvents	EMC	0.000	0.184	0.324	0.094	0.395
		Solvents	PC	0.000	0.000	0.000	0.000	0.000
		Total electrolyte		0.681	0.799	1.408	0.410	1.715
	Separator	Separator	PE 10 micron+A	0.016	0.000	0.000	0.000	0.000
		Separator	PP 15 micron +	0.071	0.187	0.000	0.000	0.000
		Separator	PP/PE/PP	0.000	0.000	0.279	0.000	0.336
		Separator	PE-Al2O3	0.000	0.000	0.000	0.092	0.000
		Total separator		0.087	0.187	0.279	0.092	0.336
	Cell Packagin	Tab with film	Al Tab	0.000	0.052	0.000	0.000	0.000
			Ni Tab	0.000	0.167	0.000	0.000	0.000
		Exterior covering	PET/Ny/Al/PP/ I	0.014	0.200	0.000	0.000	0.000
		Collector parts	Al leads	0.000	0.000	0.017	0.000	0.023
		Collector parts	Cu leads	0.000	0.000	0.047	0.000	0.070
		Collector parts	Plastic fasteners	0.000	0.000	0.072	0.000	0.031
		Cover	Valve, rivet term	0.000	0.000	0.505	0.162	0.156
		Case	Al	0.000	0.000	0.678	0.000	1.250
		Case	Ni plating Iron	0.000	0.000	0.000	0.518	0.000
		Total cell packaging		0.014	0.419	1.318	0.680	1.531

While the database for determining the BOM on cell level can be considered as appropriate, it becomes quite challenging on the module or system level, since there are manifold design options differing from OEM to OEM and by application. BOM for those levels can hardly be found and if so, because of their low number or the date of release, they could hardly be seen as a base case in terms of a representative product. However, different literature sources were reviewed, mostly in the context of LCA studies to gain information about the BOM on module and system level (Ellingsen et al. 2014; Kim et al. 2016; Majeau-Bettez et al. 2011a; Yuan et al. 2017; Cusenza et al. 2019).

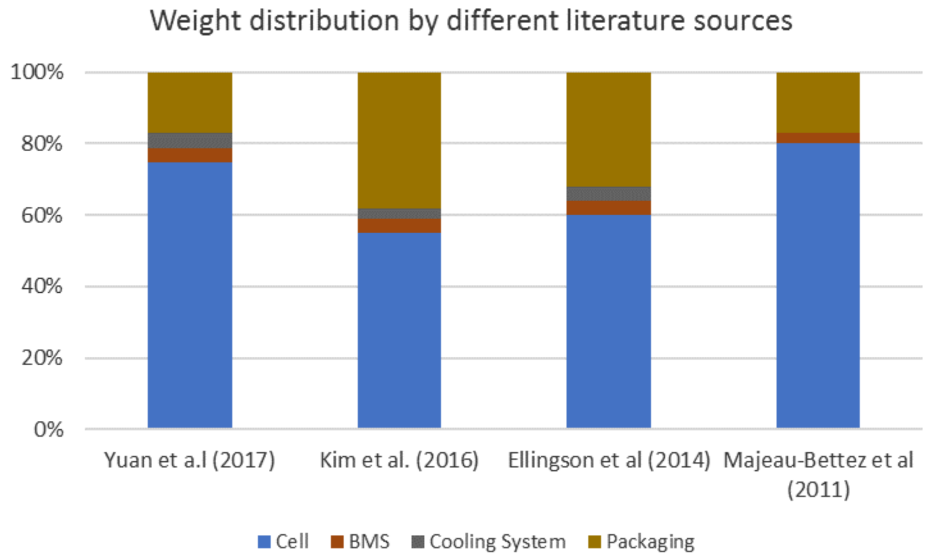


Figure 7: Weight distributions given in literature

Considering the weight distributions given in literature for different battery systems, shows that the weight of the cells (incl. cell housing) has the highest share in total battery system weight. It furthermore visualizes, that the BMS and Cooling system typically has a weight of 3-5 %. Anyhow, regarding the share of the packaging varying opinions exist. A part of the explanation for the comparatively high share of packaging in the case of Ellingson might be that the system is intended for a PHEV application wherefore a lower number of cells is needed and thus the share of the packaging is relatively increased. For Kim et al. the reason may lay in the high number of 430 low-capacity cells, which have to be packed into modules and thus the high corresponding volume needed to be covered by the system housing. For a better interpretation of the value in the previous table, the following Table 5 gives an overview of the key parameters for the battery systems used in the reviewed studies:

Table 5: Overview of the key parameters for battery systems used in reviewed studies

	Yuan et a.l (2017) LMO	Kim et al. (2016) LMO/NMC	Ellingson et al (2014) NMC
Capacity	24	24	26.6
Cells	192	430	360
Total weight	167	303	253
Nom. voltage	3.85	3.7	3.65
Cell Ah	32	15	20

It becomes obvious, that the cell capacity of the battery cells is quite low compared to today, This again leads to a higher number of cells in the modules by a comparatively low system capacity. Since todays system capacities are higher, information about the weight distribution of today's state-of-the-art battery systems can hardly be transferred from these studies. For this reason some own analyses were conducted by using the BatPaC-model (Nelson et al. 2017). The modelling was conducted with the aim to receive information about the sensitivity of the weight distributions depending on the cell chemistry (NM333, NMC 622, LFP and LMO), the system size (40 kWh and 80 kWh) and the application (PHEV or BEV). The modelling results are depicted below.

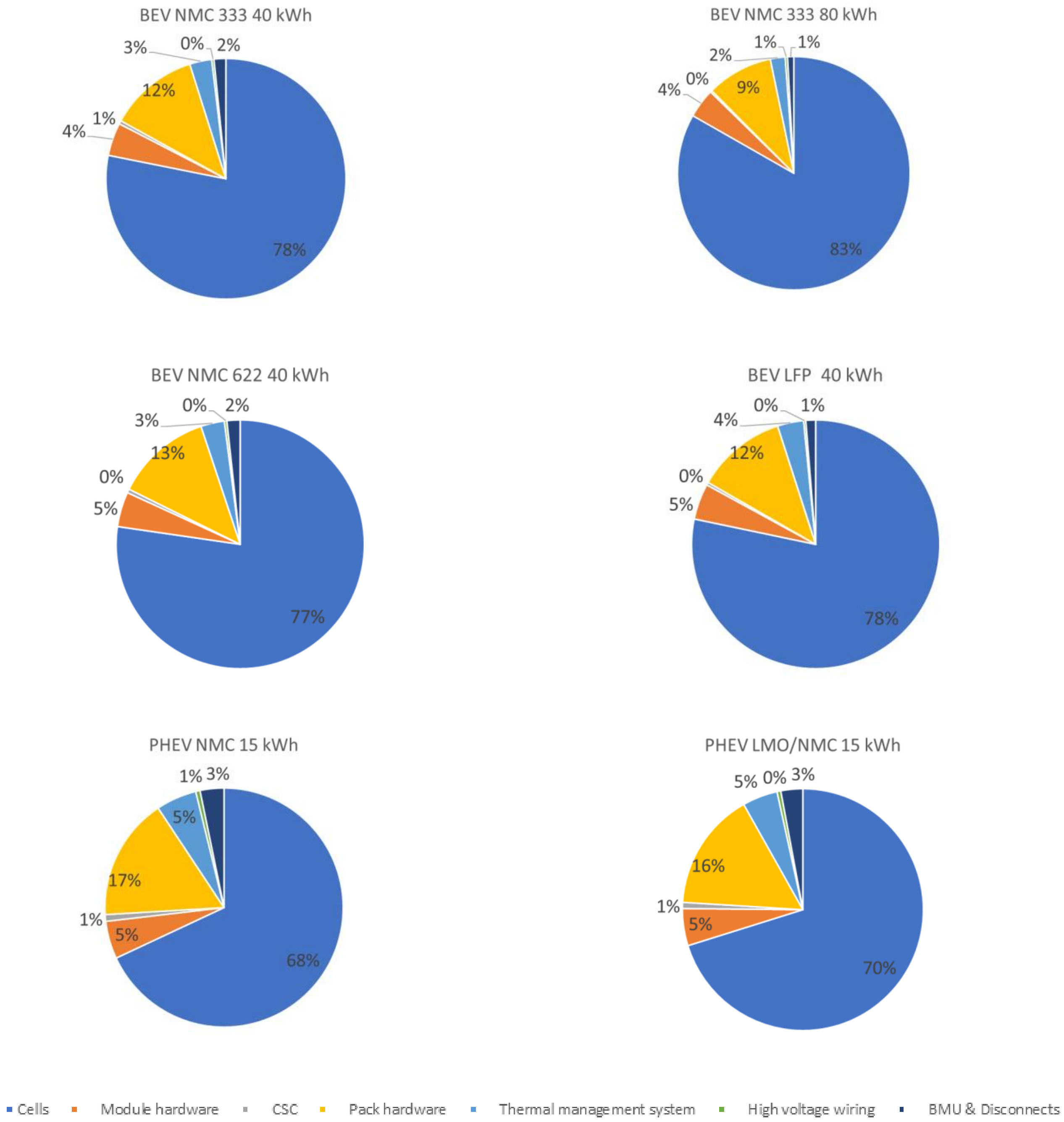
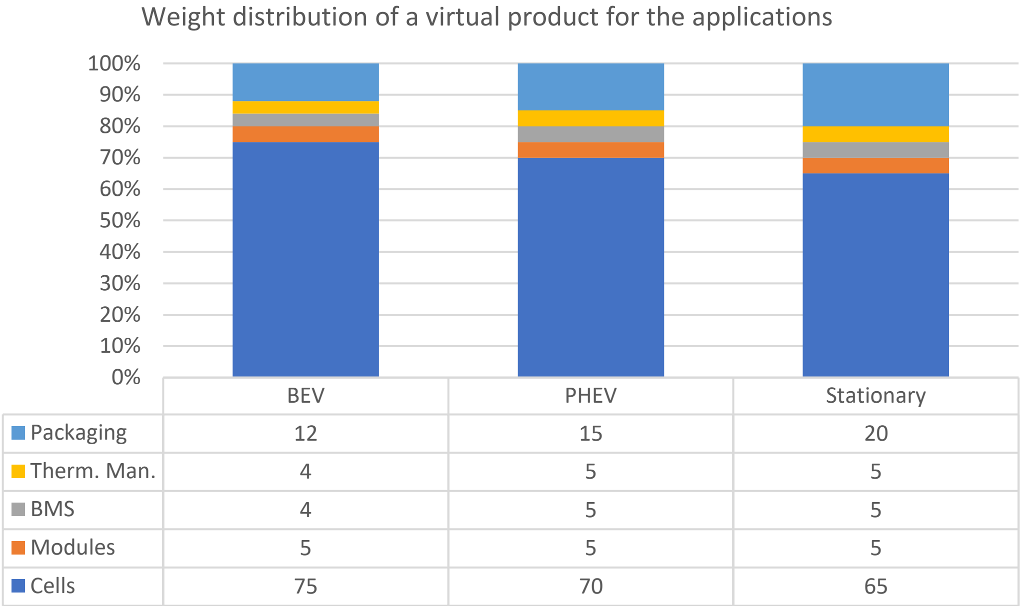


Figure 8: Analyse of the weight distributions by different system capacities, cell chemistries and applications (own analyse based on Nelson et al. 2017)

The modelling results on the one hand stress out, that the share of the BMS and thermal management also is approximately 4-5 % of the total battery system weight (as also indicated by the literature review). On the other hand they depict that, as already expected, the share of cell weight is comparatively lower for PHEV applications than for BEV. However, also an influence depending on the system capacity becomes visible, while a significant difference regarding the cell chemistry cannot be observed. A major take away is thus, that the module (also the cell format stays the same) has an equal share of ~5%. The share of the packaging therefore differs slightly for BEV and PHEV, due to the previously described relation between cells and packaging volume. Thus considering the results of the literature review (Figure 7) and the modelling (Figure 8), thee following weight distributions as shown in Figure 9 are estimated for the different applications (also no further differentiation is made between BEV for Passenger car LCV or Truck, PHEV for passenger and Truck or residential and grid stabilization application).



	BEV	PHEV	Stationary
Packaging	12	15	20
Therm. Man.	4	5	5
BMS	4	5	5
Modules	5	5	5
Cells	75	70	65

Figure 9: Weight distribution of a virtual product for the applications (own assumptions based on Figure 7 and Figure 8)

After defining the weight distributions on different levels for the applications, the concrete share of materials has to be determined. Here again, the heterogeneity of products and the availability of reliable up-to-date data is not given. Based on available in-house information the following estimations are made for the share of different materials in the module. Thereby a differentiation according to the cell formats has to be considered. For the modules, the material compositions as depicted in Figure 10 were assumed for a virtual product on the market.

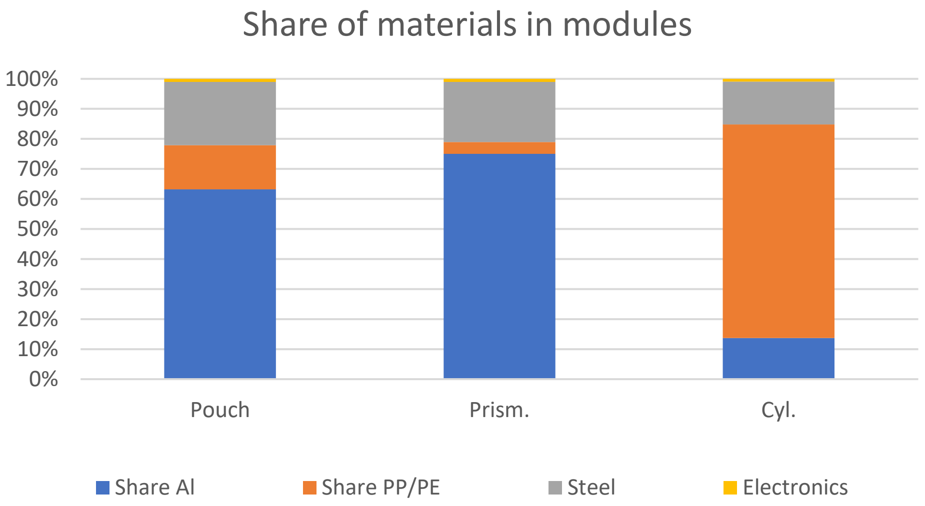
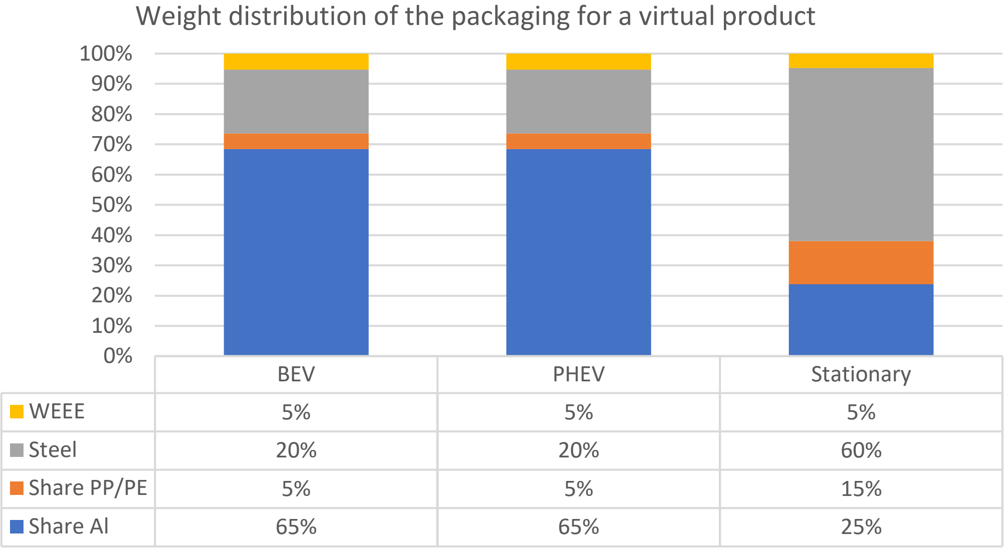


Figure 10: Share of materials in modules due to different cell formats (own assumptions based on internal data)

Regarding the material composition a relatively high share of Al is estimated in case of the pouch or prismatic format as e.g. for the casing or cooling plates. Also steel plays a prominent role, since it is also used as an alternative to Al-casings or e.g. for the tightening of pouch cells. Furthermore, the share of plastics is considered comparatively high for the cylindrical cells especially because of the cell brackets. Furthermore, often parts of the module as e.g. the lids are made of plastics. The share of plastic is also considered higher for pouch cells than for prismatic cells due to the reason that they have to be put into frames to provide them the necessary stiffness.

Finally, also the share of materials for the packaging has to be defined and is depicted in Figure 11. Here it is assumed that no significant difference regarding the relative share of materials is made between BEV and PHEV applications. The assumptions are based on the previously described sources. However, since for stationary applications, the weight is not seen as critical as for mobile applications, a higher share of steel is assumed.



	BEV	PHEV	Stationary
🟨 WEEE	5%	5%	5%
◼ Steel	20%	20%	60%
🟧 Share PP/PE	5%	5%	15%
🟦 Share Al	65%	65%	25%

Figure 11: Weight distribution of the packaging for a virtual product[9]

Based on the described data and assumptions, the BOM for the different applications was calculated based on the BOM from Table 4 and information from Figure 9 to Figure 11. The resulting BOM for the different applications is displayed in the following *Table* 6. [10]

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[9] Distribution for BEV based on previous reviewed literature. PHEV and Stationary based on own assumptions)

[10] Please note that the BOM aims to determine the amount of different materials contained in a battery pack. Since a virtual product is calculated, the BOM of different cells from Table 4 are aggregated according to their market share in the specific application. This also leads to an effect that for some cells, the materials e.g. aluminium are listed for each component (collector, casing, etc.), while for other cells only the total amount of aluminium is given. Thus, specific values in the lines might seem comparatively low at some points, while the total amount of materials is correct.

Table 6: BOM for the defined Base Cases (own calculation)

		Base Case		BC 1	BC 2	BC 3	BC 4	BC 5	BC6	BC7
		Long Description		Passenger Car - BEV high battery capacity	Passenger Car - BEV lower battery capacity	Passenger Car PHEV	Truck BEV	Truck PHEV	Residential ESS	Grid supporting ESS
		Pack capacity	Wh	80 000	40 000	12 000	30 000	20 000	10 000	10 000
		Pack capacity	kWh	80	40	12	30	20	10	10
Level	Component	Material								
Cell	Cathode	Fe	g	9 293	4 646	4 646	9 293	7 744	6 195	6 195
		Co	g	9 555	4 778	1 254	2 765	2 090	292	292
		Ni	g	35 923	17 961	2 613	9 988	4 355	1 160	1 160
		Mn	g	17 112	8 556	2 589	1 888	4 315	157	157
		Al	g	510	255	23	113	38	19	19
		Li	g	14 440	7 220	2 014	4 704	3 357	1 162	1 162
		P	g	5 153	2 577	2 577	5 153	4 294	3 435	3 435
		O	g	46 224	23 112	9 160	18 831	15 267	8 004	8 004
		Carbon	g	8 785	4 393	2 428	5 069	4 047	2 620	2 620
		PVDF	g	7 130	3 565	1 115	2 941	1 859	981	981
		Al foil	g	24 847	12 424	4 397	10 991	7 329	4 215	4 215
	Anode	Graphite	g	87 281	43 641	15 895	36 445	26 492	14 483	14 483
		SBR	g	1 247	623	487	593	812	345	345
		CMC	g	1 247	623	266	593	444	345	345
		Cu foil	g	52 933	26 467	9 093	23 004	15 155	9 103	9 103
		Al	g	2 283	1 142	-	-	-	-	-
	Electrolyte	LiPF6	g	9 373	4 687	1 875	4 195	3 125	1 916	1 916
		LiFSI	g	9	4	-	3	-	0	0
		EC	g	24 406	12 203	4 688	10 852	7 813	4 820	4 820
		DMC	g	24 406	12 203	4 688	10 852	7 813	4 820	4 820
		EMC	g	10 903	5 451	3 370	5 310	5 616	3 257	3 257
	Separator	PE 10 micron+AL2O	g	517	258	-	194	-	16	16
		PP 15 micron + AL2	g	2 258	1 129	899	847	1 499	71	71
		PP/PE/PP	g	7 381	3 691	2 016	4 032	3 360	2 688	2 688
		PE-Al2O3	g	2 201	1 100	110	550	183	92	92
	Cell Packaging	Al Tab	g	-	-	250	-	417	-	-
		Ni Tab	g	-	-	800	-	1 333	-	-
		PET/Ny/Al/PP/ Lamin	g	435	218	961	163	1 601	14	14
		Al leads	g	487	243	141	281	234	188	188
		Cu leads	g	1 406	703	422	844	703	563	563
		Plastic fasteners/cov	g	1 240	620	188	375	313	250	250
		Al, Steel, Valve, rivet	g	11 828	5 914	1 132	2 850	1 887	1 412	1 412
		Al	g	23 135	11 568	7 500	15 000	12 500	10 000	10 000
		Ni plating Iron	g	12 430	6 215	621	3 107	1 036	518	518
Module		Al	g	15 861	7 931	3 814	7 272	6 357	3 975	3 975
		PP/PE	g	8 510	4 255	1 182	2 914	1 969	1 094	1 094
		Steel	g	5 749	2 875	1 242	2 474	2 070	1 263	1 263
		Electronics	g	304	152	63	128	105	64	64
System	BMS	Steel	g	9 736	4 868	2 521	4 092	4 201	2 558	2 558
		Copper	g	12 170	6 085	3 151	5 115	5 251	3 198	3 198
		Printed circuit board	g	2 434	1 217	630	1 023	1 050	640	640
	Thermal management	Al	g	21 906	10 953	5 671	9 208	9 452	5 756	5 756
		Steel	g	2 434	1 217	630	1 023	1 050	640	640
	Packaging	Al	g	51 114	25 557	13 233	21 484	22 055	5 116	5 116
		PP/PE	g	3 651	1 826	945	1 535	1 575	3 837	3 837
		Steel	g	14 604	7 302	3 781	6 138	6 301	15 349	15 349
		WEEE	g	3 651	1 826	945	1 535	1 575	1 279	1 279

The approach for defining the BOM for the bases cases will be summed up again in the following, In a first step, depicted in Figure 12, the base cases were built by first reviewing common cells (using different cell chemistry and cell formats) and their BOM on the market (seeTable 4). For these different cells the materials in g/Wh was calculated and based on that a virtual product (virtual cell) was built based on the market share of different cell chemistries in the considered application (Figure 6).

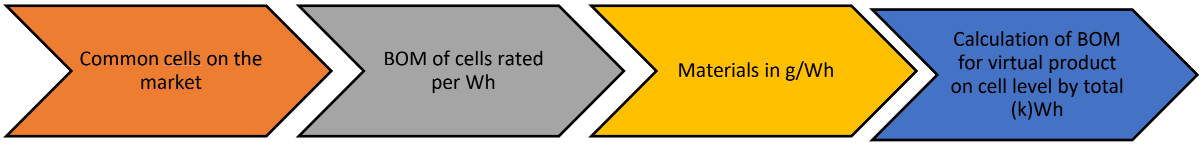

Figure 12: Approach for defining a virtual product (on cell level)

After having defined the virtual product on cell level, the great heterogeneity in the case of module and system design has to be captured. Since detailed information, regarding a representative BOM for the modules and system level is hardly available. Therefore, a bottom-up approach was used to build the system around the defined common cells, based on the typical distribution of battery systems and the share cell materials. The process is depicted in the flow chart below (Figure 13).

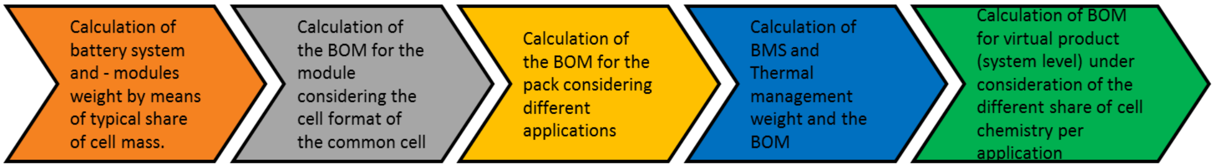

Figure 13: Approach for defining a virtual product on the battery systems level

Based on the total cell mass of the common cells, the mass of the corresponding module and system (packaging) was calculated. Therefore first some values given in literature were reviewed (Figure 7) and also own battery systems were modelled considering different capacities, cell chemistries or mobile applications (Figure 8). Based on these insights finally the weight distribution of a virtual product for the applications was defined (including share of mass of cells, module, BMS, Thermal management and system packaging). After having defined the weight proportion for the module, system packaging, BMS and Thermal management. The corresponding BOM were calculated. For the BOM of the modules the cell format of the (common) cell was considered (Figure 10). While for the systems packaging especially the application play a crucial role and therefore was considered (Figure 11). The BOM for the BMS and Thermal management is considered as similar for all applications. The virtual products for each application, forming the BOM our Base Cases Table 6) is finally again calculated according to the share of cell chemistries within the application.

4.2.2. Assessment of the primary scrap production during sheet metal manufacturing

4.2.2.1. Production process of a LiB

The manufacturing process of a LiB can be roughly divided into four parts: Electrode production, cell assembly, module assembly and battery system assembly. Each of these sub-areas comprises a series of production steps that can easily diverge depending on the desired cell geometry and the intended use of the battery system. The process of battery system production is therefore described exemplarily in the following Figure 14.

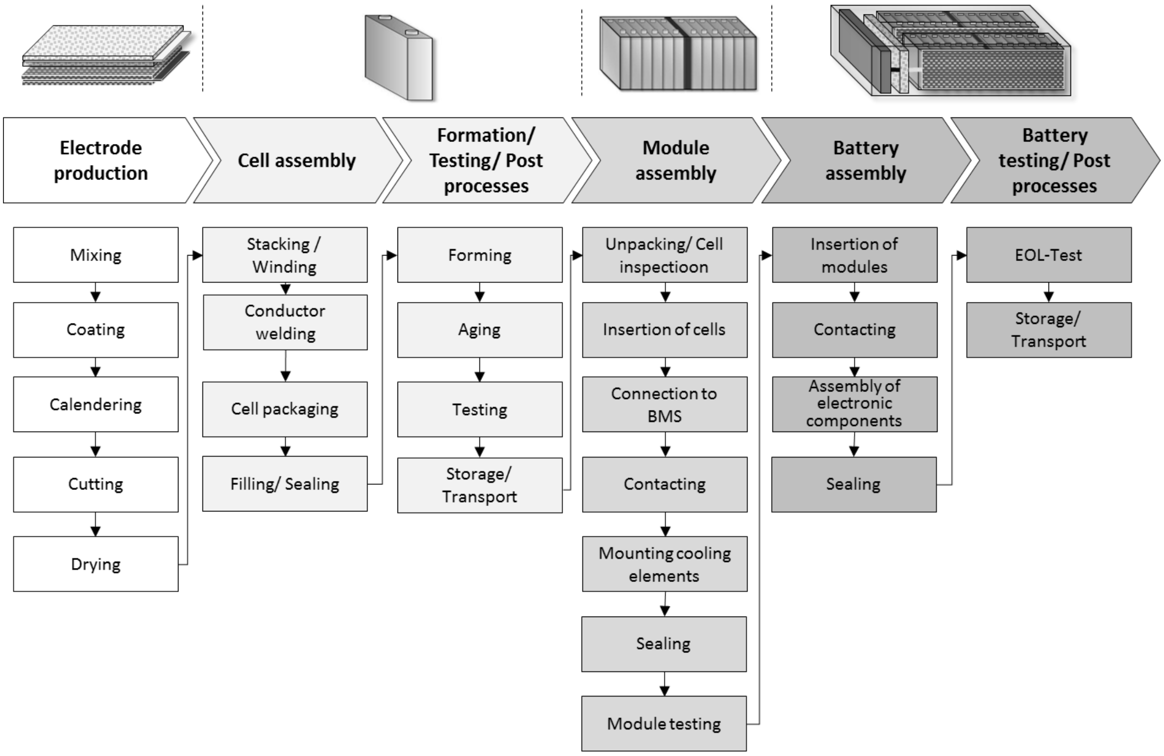

Figure 14: Exemplary lithium ion battery manufacturing process (Hettesheimer et al. 2013)

The individual process steps will be explained in more detail in the following.

Mixing

The starting point of any cell production is the manufacturing of the electrodes. The chemical components of the electrode coating are mixed with binding agents, solvents and additives to form a paste. The mixing process can be carried out in different ways by mixing and dispersing. The difficulty in this process step lies in achieving a high degree of homogeneity despite the disperse solids and maintaining this until the drying process, without the formation of agglomerations (Michaelis et al. 2018; Hettesheimer et al. 2013; Heimes 2014).

Coating and drying

In this process, the coating paste (also called "slurry") is applied to both sides of the carrier films. In the case of the cathode, this is aluminium, while the carrier foil of the anode usually consists of copper. The typical values for the wet layer thickness are between 200-250 µm. The coating width with several application nozzles can be up to 1500 mm. The challenge is to create a homogeneous layer thickness across the entire web width. The drying phase immediately follows the coating process. As a rule, the ovens are between 30 m and 50 m long. Drying not only reduces the moisture content of the slurry, but also evaporates the previously added solvents and either recovers them or recycles them thermally. Compared to coating, drying is the production process that determines the speed. The drying time depends on the thickness of the coating, the solids content of the suspension and the solvent used. Today, circulating air dryers are generally used, partly in combination with infrared dryers. Gentle drying is achieved using temperature profiles with different zones (Kwade et al. 2018; Michaelis et al. 2018; Hettesheimer et al. 2013; Heimes 2014).

Calendering

After drying, the electrode material is wound into so-called "coils". During subsequent calendering, these are unwound again after transport and the electrode thickness is compacted by rotating rollers at a pressure of around 1500 N/mm until a predefined porosity is achieved. The foils are then rolled up again into coils. A homogeneous layer thickness is again important, which is why pressure-controlled calenders are usually used to compensate for any unevenness by varying the pressure accordingly (Hettesheimer et al. 2013; Heimes 2014).

Slitting

After calendering, the coils have a width corresponding to that of the coating line. During cutting, the coils are then cut into 100 mm to 300 mm wide foil strips by means of a rolling knife or laser beam and either rewound into coils or further subdivided into individual sheets. If the cut is made by a rolling knife or punching, there is a risk of the active material peeling off, while laser cutting involves the introduction of heat into the active material and can initiate metallurgical processes. The processing speeds for punching are up to 0.2 s/sheet. Laser cutting achieves speeds of up to 1200 mm/sec (Hettesheimer et al. 2013; Heimes 2014; Michaelis et al. 2018).

Vacuum drying

The later cell quality and life is closely related to the residual moisture of the electrodes during cell assembly. For this reason, the electrodes are separated after cutting, dried for several hours in vacuum ovens according to polarity in stacks and removed again in the drying room for cell assembly (ANL 2012).

Cell assembly

The previously described steps of electrode production are essentially independent of the later cell geometry. However, this changes during the cell assembly phase. After cutting, the cells are either stacked (described in the following) or they are wound. The subsequent packaging and filling/insertion phases are essentially the same for all cell geometries. In the following, the focus is on the assembly of a pouch cell. The entire process of cell assembly takes place in the drying room for reasons of correlation of moisture in the cell with the service life and performance of the battery (Hettesheimer et al. 2013; Heimes 2014).

Stacking

First, the sheets cut from the roll in the previous process are stacked on top of each other. Several layers consisting of anode, separator, cathode, separator, anode etc. are formed. The separator is often folded in rolls after each sheet so that the individual sheets are inserted separately from the side, but the separator remains in one piece until the desired cell thickness is reached. The process is a typical pick & place application where high stack accuracy is required (+/- 0.2 mm) (Kampker 2014; Heimes 2014).

Packaging, electrolyte filling and sealing

Packaging describes the process of inserting the stack of electrodes into the intended packaging. Whereas in the case of pouch cells it is an aluminium foil, rigid cell containers are used for the prismatic cell. After the stack has been inserted, the cell is partially sealed for the subsequent filling process. The main requirement for the cell packaging, which is usually a purchased part, is that it must be impermeable to water vapour diffusion throughout its entire service life. The cell is filled with the electrolyte under vacuum. The precise dosing of the electrolyte and the resulting complete wetting of the electrodes and the separator are of great importance in this process. They are ensured by weight control. The cell is afterwards temporarily sealed (vgl. ANL 2012; Hettesheimer et al. 2013; Heimes 2014).

Formation, aging and testing

After the cell has been sealed, formation and all subsequent process steps can take place outside the drying room again. Previously, the cell was uncharged. This now changes due to the initiation of the electrochemical reaction. The lithium ions begin to be embedded in the graphite of the anode and the solid electrolyte interphase (SEI) is formed. The forming process takes around 24 hours (up to 10 days) and significantly determines the service life and safety of the lithium-ion cell. The cell can be contacted either manually or automatically, whereby the cell is charged and discharged several times. Depending on the cell manufacturer, the current strength and the intermediate rest phases vary. The formation is relatively time-consuming and capital-intensive. The final cell sealing takes place after the last formation. The cells are then stored for a longer period during the aging process and tested for self-discharge (ANL 2012; Hettesheimer et al. 2013; Heimes 2014; Michaelis et al. 2018).

Module assembly

The finished cells are interconnected to modules in the further process. The module assembly is determined by rather typical assembly activities and therefore they will not be explained in detail. The first step in module assembly consists of fixing the cells in the module and contacting. This is usually done by laser beam or ultrasonic welding or by mechanical locking using a spring mechanism. Subsequently, further electronic components are added to monitor the module. In the final step of module assembly, heat conductors may be attached to the module to dissipate the heat generated during operation. Finally, the module is closed and transferred to a quality inspection (vgl. ANL 2012; Kampker 2014).

Battery assembly

All modules that have successfully passed the quality test are assembled into battery systems or battery packs. For this purpose, the modules are anchored in a prefabricated battery case, either in a row or in parallel rows, depending on the battery design. The individual modules are then contacted again (e.g. by a contact rail or busbars). In addition, the battery management system and cooling system are installed and wired. Finally, the finished battery system is sealed and tested (ANL 2012; Hettesheimer et al. 2013; Thomas et al. 2018).

All-solid electrodes production

The production of all-solid battery electrodes has similarities as well as key differences with the production of LIB electrodes as it is described above. For example, in LMP® technology or other all-solid batteries, the metallic lithium film is laminated on a roll mill to required final thickness. The lithium metal anode does not need a carrier and acts as its own current collector.

The cathode as well as the separator chemical components require mixing in solution for coating or through an extrusion screw. Drying is needed for coating. Homogeneity of composition as well as thicknesses across the film width is as critical as with lithium-ion electrodes. Calendaring may or may not be used depending on the process capability to control thickness. Production of the electrodes in dry rooms may be used to limit the moisture content.

Electrodes “coils” are typically slit into the required width for subsequent cell assembly and packaging. Electrode sheets are typically stacked as for lithium-ion pouch cells, with a repeated sequence of anode – separator – cathode. There is no need to fill the cell with electrolyte as the polymeric ion-conducting medium is built directly into the cathode and separator films. For that reason, voltage is measured across the cathode and anode as soon as they are put into contact and self-discharge may be monitored across the subsequent production steps. There is also no need for the “formation” step to build the Solid Electrolyte Interface (SEI).

In all-solid technology, individual cells do not require a housing. A group of cells connected together typically in series may however be housed in some form of casing, emptied of moisture and sealed to block water vapour diffusion into this battery module envelope hence preventing the premature degradation of the metallic lithium anodes. Battery modules are typically connected in a series that provides the targeted voltage for the battery application. Such strings of modules may moreover be connected in parallel to form larger battery systems.

4.2.2.2. Energy consumption of battery production

The question of energy use for battery production has been considered in particular in the context of LCA analyses, whereby greenhouse gas emissions are mostly determined in kg CO_2 equivalent per kWh of battery capacity produced (kg CO_2 eq/kWh). Industry data from battery production can hardly be obtained, so that studies from 2011 to 2016 (as in Romare and Dahllöf 2017) pursue different approaches to determining greenhouse gas emissions and energy use in battery production. "Bottom-up approaches" try to estimate the energy input of individual process steps from battery production. The energy input is considered to be rather low (0.4-1.4 kWh/kg per battery pack produced or less than 3 to more than 10 MJ/kWh (Romare and Dahllöf 2017; Yuan et al. 2017; Ellingsen et al. 2017), while "top-down approaches" also include other (auxiliary) processes and are considered more complete. Thereby energy inputs in the range of 350 to 650 MJ/kWh (30 to over 250 kg CO_2 eq/kWh) are estimated (Romare and Dahllöf 2017 and the literature cited therein as well as Hall and Lutsey 2018).

Depending on whether the focus is on the assessment of the energy input in battery cell- and pack production or even on the total primary energy demand for the production of all components (including battery materials), energy requirements of approx. 200 - 2500 MJ/kWh are calculated. In the studies, it is often unclear to what extent only process steps and the electricity demand are taken into account or whether material processing is already/partially included.

A comparison of several studies (Romare and Dahllöf 2017; Pettinger and Dong 2017; Yuan et al. 2017) shows that the extraction and processing of raw materials results in comparatively low emissions The studies also show no clear differences when considering different cell chemistries. With regard to the energy input for battery materials (components) vs. battery production (processes), it can be seen that both contribute to the energy input in approximately the same dimension. Depending on the study, the contribution of "cell material" vs. "cell production" is between a ratio of 30:70 - 70:30 and is therefore also rather unclear (however, the estimated order of magnitude is the same).

Peters et al. 2017 provides an overview of existing assumptions regarding the energy demand for the production of LiB. For this purpose, 36 LCA studies were analysed and differentiated according to cell chemistry and the approach for identifying the energy demand (top-down, bottom-up or no information). Thereby the cumulative energy demand (CED) of 19 studies was identified and is shown in the following figure at battery pack level.

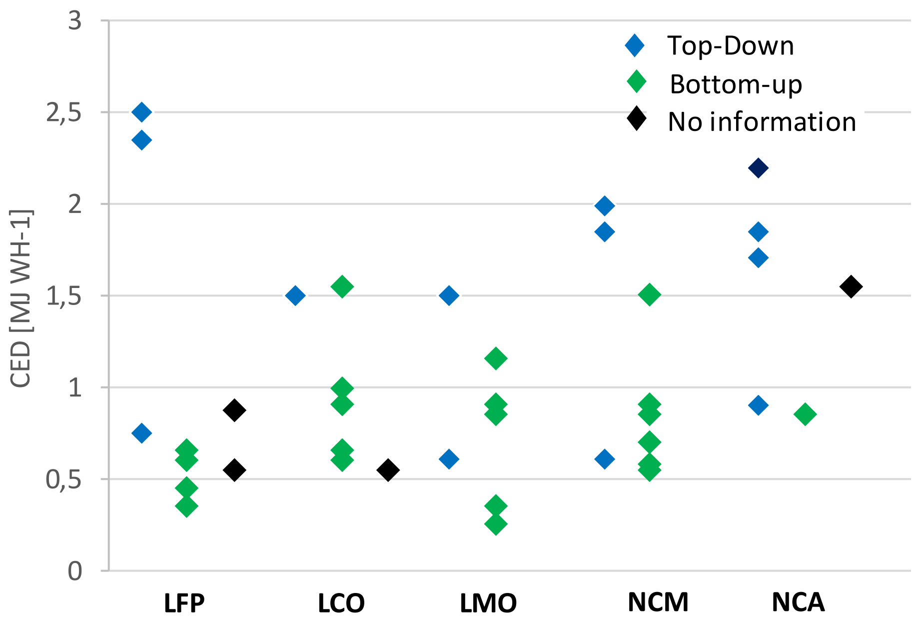

Figure 15: Cumulative energy demand at battery pack level for different cell chemistries (based on Peters et al. 2017)

The figure illustrates again the difficulties mentioned before with regard to the exact quantification of energy demand. Accordingly, there is also a lack of further detailed information on the energy demand in the individual production steps. However, many of the studies point out the fact that the production of battery materials has a large share in energy demand during the electrode production (especially cathode production, see Romare and Dahllöf 2017). For the other (usually less energy-intensive) components, the results of the studies vary. Electrode coating and drying processes (Pettinger and Dong 2017; Yuan et al. 2017) or drying rooms are thereby among the most energy-intensive steps in battery production. Pack production (including electronics, etc.) seems to require just as much energy, while the pack assembly is estimated to be less energy-intensive.

In summary, an energy consumption of 350 to 650 MJ/kWh (less than 100 to max. 200 kWh el. energy for the production of 1 kWh battery) can be assumed for battery production (process steps) (400-600 MJ/kWh are relatively frequently determined in studies). For battery materials or components, the same order of magnitude is assumed again (ratio 30:70 to 70:30 depending on the study, but mostly a lower energy demand on the part of the battery materials is estimated or calculated).

4.2.2.3. Improvement options on side of the battery production

As concluded in the previous section, coating and drying, forming and providing conditioned drying room atmospheres are the most energy-intensive process steps and they account for the major share of energy consumption in cell production. In the following, some improvement options are listed to tackle the main drivers of the energy consumption within these production processes:

Energy efficiency during production - Coating, drying and formation

On the coating and drying side, there are several starting points for reducing energy consumption. On the one hand the solvent content can be reduced up to a dry coating, on the other hand the drying process can be further optimized. A significant cost and energy saving can be achieved by shortening the time in the drying process. The aim is to produce suspensions with a higher solids content. Dry coating might be available for the mass market from 2025 onwards. An alternative approach might also be the PVD coating. An acceleration of the drying process and a multiple use of the drying section would also be thinkable in order to reduce investment and energy costs. This means an "initial drying" of the first side, so that carrier rollers can be used for transport and after the subsequent coating of the second side, the total drying of both sides can take place simultaneously (Michaelis et al. 2018).

Potential for energy efficiency and cost savings during formation can be achieved due the fact that forming plants have high-connected loads in continuous operation. For this reason, it is necessary to reduce energy losses during forming as much as possible. The concept of using the energy released during the discharge of one lithium-ion cell to charge another is being applied already (Michaelis et al. 2018).

Design for disassembly and design for recycling

Although this is not a part of the production of battery systems, the possibility for remanufacturing and recycling of batteries is strongly determined during the production phase. To facilitate the disassembly and later on the reuse or the recycling of the battery packs, a "design for disassembly" and "design for recycling" could offer a high benefit. Improvements in this direction could address different issues as how different components are connected, how cells or packs are designed and to what degree information about the pack or the cell is made transparent.

Currently, the state-of-the-art technologies used to connect the structural components are screwing, bonding and welding of the individual elements. Especially the bonding and welding could be considered as unfavourable in terms of "design for disassembly" compared to reversible joints (Michaelis et al. 2018).

In addition, considering the steady growing number of battery systems considerable for a later disassembly, recycling or reuse, automation will play a major role to manage these large amounts in an economical way. Hereby the large variety of battery cells, battery modules and battery system systems currently in use constitutes a major challenge for automated dismantling (Michaelis et al. 2018). There may be variations in the materials used, the design, the location of the battery and the shape of the battery pack. Although a full standardisation is considered as unrealistic, a number of basic standards could make battery disassembly and recycling less time-consuming. For example, tools or lifting parts (e.g. eyelets or mounting threads) could be installed as standard in future battery packs. This would allow standard lifting to be used to disassemble the battery pack (Thomas et al. 2018; European Environment Agency 2018). Considering the specific cell designs, the cells could also be designed in a way that the material can be recovered in its processed form (Romare und Dahllöf 2017).

Another issue is the marking of the cells to provide transparent information about the materials used in the battery pack or cell. The design requirement in this respect is a way to also enable easier recycling with a potentially higher material recovery and higher quality (Romare und Dahllöf 2017).

Thus, by adapting the design, the disassembly and recycling process could be simplified and the recovery of materials optimized. However, the demands on installation space and performance are countering this development. Modularization, substitution of adhesives and a reduction of the module voltage are conceivable, but contrary to the current development

(Michaelis et al. 2018). A more detailed section about the requirements to support disassembly, recyclability and reusability can be found in the task 7 report[11].

Energy mix

The environmental impact of cell manufacturing is partly dictated by the energy sources used to generate the electricity. Since the greenhouse gas emissions associated with the use of energy are highly dependent on the energy mix, the environmental impact of battery production improves accordingly with the proportion of renewable energies in the electricity mix (Thomas et al. 2018).

4.2.3. Packaging materials

The transport of dangerous goods and articles in Europe is arranged in the ADR by UNECE (ECE/TRANS/257)[12] and the IATA[13]. Batteries fall under class 8 (corrosive products) or, for lithium and Li-ion batteries under class 9 (miscellaneous).

Lithium batteries are classified in Class 9 – Miscellaneous dangerous goods as:

- UN 3090, Lithium metal batteries; and
- UN 3480, Lithium ion batteries

or, if inside a piece of equipment or packed separately with a piece of equipment to

power that equipment as:

- UN 3091, Lithium metal batteries contained in equipment; or
- UN 3091, Lithium metal batteries packed with equipment; and
- UN 3481, Lithium ion batteries contained in equipment; or

UN 3481, Lithium ion batteries packed with equipment.

For lithium (ion) batteries a specific section exists in the ADR (§2.2.9.1.7) with exigencies to these batteries:

- Lithium cells and batteries have to pass ‘Manual of Tests and Criteria, part III, sub section 38.3’.
- Cells and batteries must have a safety venting device or being designed that no violent rupture can occur.
- Each cell and battery are equipped with an effective means preventing external short circuit.
- Each battery with cells or strings of cells in parallel are equipped with an effective means preventing a dangerous current in the opposite direction, e.g. by diodes or fuses.
- Cells and batteries must be manufactured under a production quality management system.

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[11] Please note, that furthermore JRC (DG JRC-B.5) is conducting research activities related to the assessment of material efficiency aspects of other Energy-related Products (ErP) and the analysis and development of methods supporting the definition of product-specific requirements http://susproc.jrc.ec.europa.eu/E4C/index.html

[12] https://www.unece.org/fileadmin/DAM/trans/danger/publi/adr/adr2017/ADR2017E_web.pdf

[13] https://www.iata.org/whatwedo/cargo/dgr/Documents/lithium-battery-guidance-document-2017-en.pdf

Table A in the ADR prescribes the needed marking, the special provisions and the packaging possibilities. Chapter 6 prescribes the packaging tests and pass criteria.

For lithium batteries a distinct category is made for damaged or defective cells or batteries, defined as that they do not conform to the type tested according to the provisions of the Manual of Tests and Criteria.

- Cells or batteries must be protected against short circuits.
- Cells or batteries must be secured in the packaging to prevent damage for protection against movement (e.g. vibrations)
- Robust outer packaging, according to packaging group II
- Clearances within the packaging must be filled with cushioning materials of non-conductive material, non-flammable material can be lined
- shall not be transported through Category E tunnels.
- are classified and marked accordingly:
    - Lithium ion batteries, UN 3480 WASTE LITHIUM-ION BATTERIES, Class 9, II
    - Lithium-ion batteries UN 3481, packed in devices or with devices,
    - Class 9, II
    - Battery-powered vehicle / battery-powered device UN 3171, Class 9
- require additional transport documents and permits (e.g. ADR transport permit), and special driver training courses

A guide of the EPTA (European Power Tool Association) has been published in cooperation with the ZVEI (Zentralverband Elektrotechnik- und Elektronikindustrie e. V.), which provides the most important information on the transport of batteries. Although this guide refers explicitly to the transport of electric tools and electric gardening equipment, it reflects in a very general way the conditions for the transport of batteries. The following flow-chart gives a structure to determine the appropriate packaging (ZVEI & EPTA 2018).

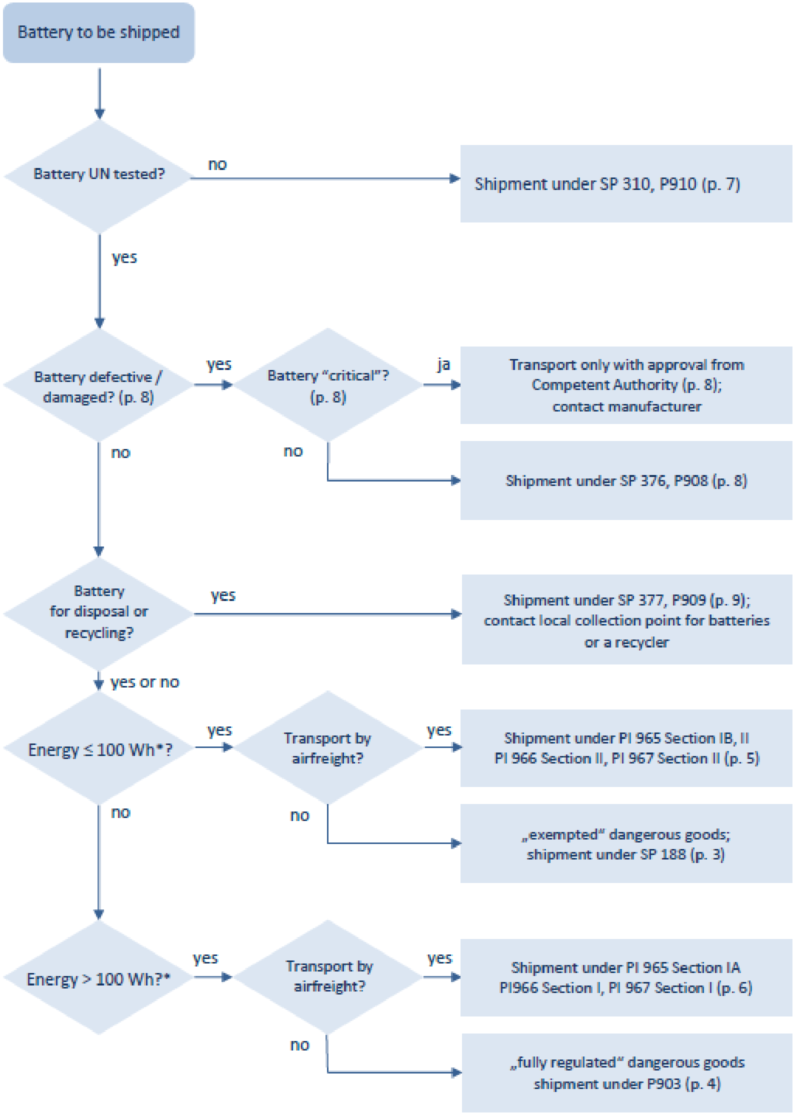


Figure 16: Flow-chart to determine the appropriate packaging (ZVEI & EPTA 2018)

In particular, the energy content and the different conditions classify which dangerous goods regulations must be observed when transporting lithium-ion batteries. Due to exceptions, simplified requirements apply, e.g. for lithium-ion batteries with an energy content of up to 100 Wh. Lithium-ion batteries with an energy content of more than 100 Wh, on the other hand, must always be treated as fully regulated dangerous goods class 9.

Table 7: Transport issues (Example) (ZVEI & EPTA 2018)

Transportation Mode	**Road / Rail (ADR/RID), Sea Freight (IMDG Code)**		
> 100 Wh (per battery)			
Batteries	(without equipment)	Batteries packed with equipment (at least one battery which is not attached to tool)	Batteries contained in equipment (contained/plugged-in in tool)
Packing Instructions	P903, LP903		
Max. quantity	333 kg per transport unit (truck incl. trailer) for exemptions according to ADR 1.1.3.6		
Weight limit	n/a		
Packaging	Batteries must be placed in inner packaging that completely enclose the battery, batteries must be protected to prevent short circuits. Batteries must be secured against movement within the outer packaging. UN approved packaging (Packing Group II: e.g. UN/4G/Y30/…)	Strong outer packaging Protection against unintentional activation Short circuit protection	
Marking 2	Hazard label № 9A (10x10 cm) ADR: UN 3480 IMDG Code: UN 3480 LITHIUM ION BATTERIES	Hazard label № 9A (10x10 cm) ADR: UN 3481 IMDG Code: UN 3481 LITHIUM ION BATTERIES PACKED WITH EQUIPMENT or UN 3481 LITHIUM ION BATTERIES CONTAINED IN EQUIPMENT	
Sea freight container marking	CONTAINER-PLACARDS (min. 25x25 cm)		
Transport document	UN 3480, LITHIUM ION BATTERIES, 9, (E) Number of packages and packaging type (e.g. 1 Fibreboard box) Battery weight	UN 3481, LITHIUM ION BATTERIES PACKED WITH EQUIPMENT, 9, (E) Number of packages	UN 3481, LITHIUM ION BATTERIES CONTAINED IN EQUIPMENT, 9, (E) Number of packages and packaging type (e.g. 1

	(e.g. xx kg), Shipper & consignee's address Sea freight (IMDG Code): (language English) IMO-DANGEROUS GOODS DECLARATION (SOLAS 74, KAP. VII, REG 5, MARPOL 73/79, ANNEX III REG. 4 OF IMDG-CODE)	and packaging type (e.g. 1 Fibreboard box) Battery weight (e.g. xx kg) Shipper & consignee's address Sea freight (IMDG Code): (language English)	Fibreboard box) Battery weight (e.g. xx kg) Shipper & consignee's address Sea freight (IMDG Code): (language English) IMO-DANGEROUS GOODS DECLARATION (SOLAS 74, KAP. VII, REG 5, MARPOL 73/79, ANNEX III REG. 4 OF IMDG-CODE)

As indicated in the table: "Batteries must be placed in inner packaging that completely enclose the battery, batteries must be protected to prevent short circuits and batteries must be secured against movement within the outer packaging".

Currently different types of boxes are sold for this task. Some are mainly made of wood or fibre box, while others are made of aluminium (especially for used or damaged batteries). Furthermore, company unique variants exist.

4.2.4. Materials flow and collection effort at end-of-life

The following Figure 17 depicts the flow of battery materials as well as different possible end-of-life options for the batteries. In this subchapter the sourcing of raw materials, the possibility of 2nd-life applications and finally the recycling of used batteries will be described in more detail.

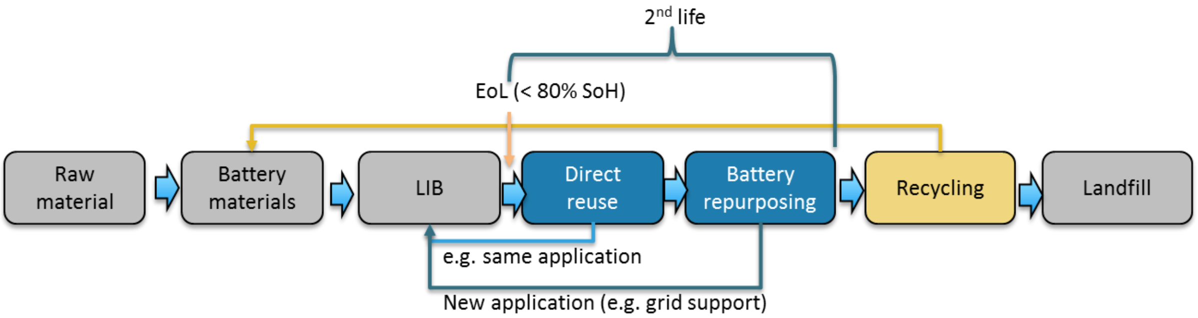


Figure 17: End-of-life options for LiB (based on European Environment Agency 2018)

4.2.4.1. Raw material sourcing

The potential for covering the demand by domestic sourcing in Europe can be considered (apart from cobalt mainly in a refined form) as very limited (see Figure 18). This is especially the case for key materials as nickel, natural graphite manganese or lithium.

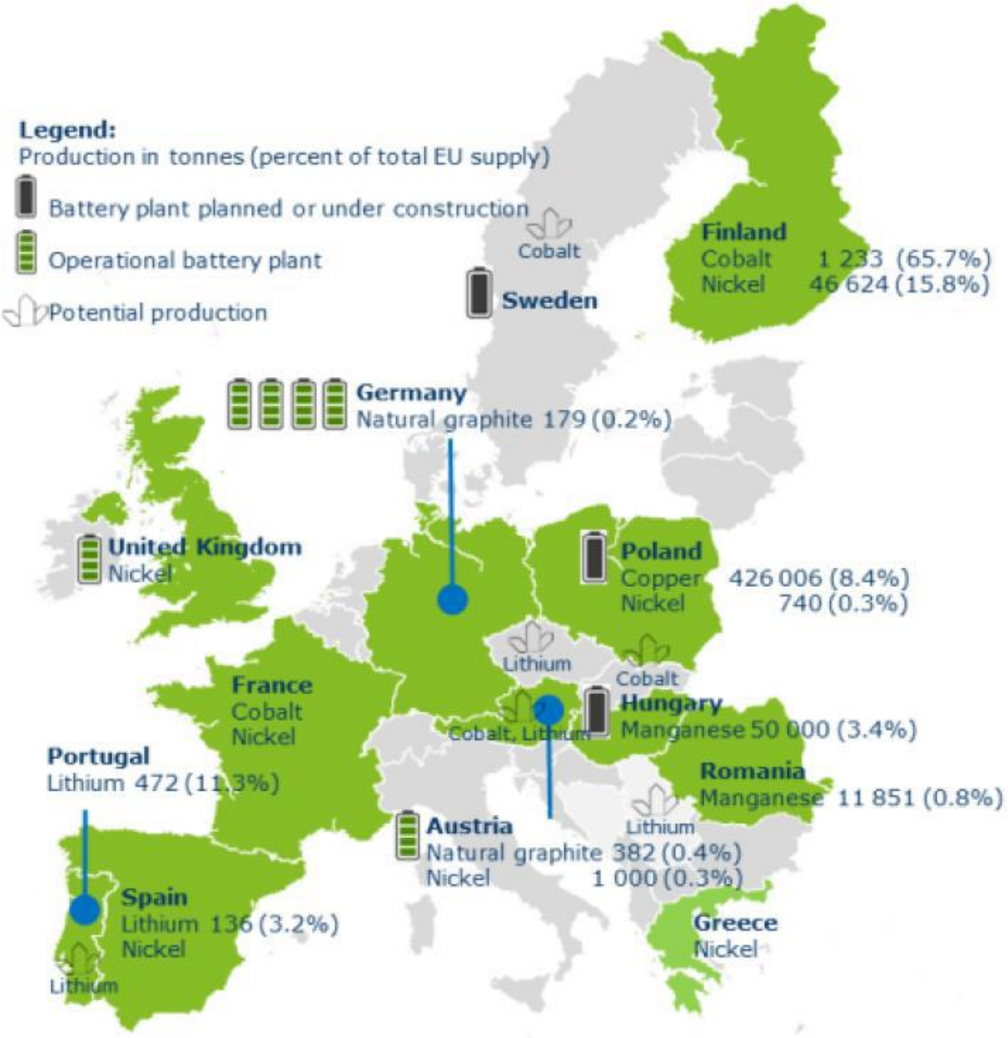


Figure 18: Mine production and potential of battery raw materials, and battery plants in the EU11 (European Commission 2018)

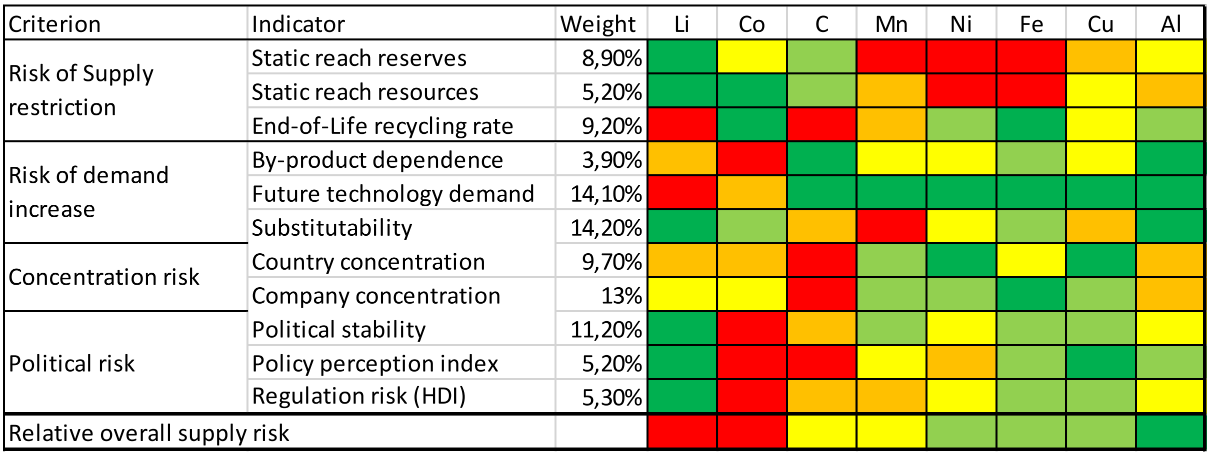
Besides the economic value of these materials most of them, except for lithium, are also considered as "critical raw materials" (Lebedeva et al. 2016). This becomes even more important under the consideration that the global share of EU raw material production for key LiB materials is comparatively low as Table 8 indicates.

Table 8: Production and sourcing of primary battery raw materials (European Commission 2018)

Raw materials	Major global producers	Major sources of EU supply	EU production	Import reliance rate	EoL recycling input rate
Cobalt	D.R. Congo (64%) China (5%) Canada (5%) 135 500t	Finland (66%) Russia (31%) 1900t	Finland	32%	35%
Lithium	Chile (44%) Australia (32%) Argentina (11%) 25 500t	Chile (66%) Portugal (11%) United States (9%) 4200t	Portugal Spain	86%	0%
Nickel	Indonesia (24%) Phillipines (16%) Australia (10%) Canada (10%) New Caledonia (7%) 2 255 500t	Russia (20%) Finland (16%) United Kingdom (13%) Norway (8%) 293 400t	Austria Finland France Greece Poland Spain United Kingdom	59%	34%
Natural graphite	China (69%) India (12%) Brazil (8%) 1 100 000t	China (63%) Brazil (13%) Norway (7%) 95 000t	Austria Germany	99%	3%

The low EU production and thus the high import rate for these key materials also leads to supply risk for those materials. The following table lists the supply risk for different battery materials. The weighting factors hereby indicate the relative importance of each indicator to the overall supply risk score as given in Helbig et al. 2018.

Table 9: Relative supply risk indicator for different raw materials (based on Thomas et al. 2018; Helbig et al. 2018)



Criterion	Indicator	Weight	Li	Co	C	Mn	Ni	Fe	Cu	Al
Risk of Supply restriction	Static reach reserves	8,90%	🟩	🟨	🟢	🟥	🟥	🟥	🟧	🟨
	Static reach resources	5,20%	🟩	🟩	🟢	🟧	🟥	🟥	🟨	🟧
	End-of-Life recycling rate	9,20%	🟥	🟩	🟥	🟧	🟢	🟩	🟨	🟢
Risk of demand increase	By-product dependence	3,90%	🟧	🟥	🟩	🟨	🟨	🟢	🟨	🟩
	Future technology demand	14,10%	🟥	🟧	🟩	🟩	🟩	🟩	🟩	🟩
	Substitutability	14,20%	🟩	🟢	🟧	🟥	🟨	🟢	🟧	🟩
Concentration risk	Country concentration	9,70%	🟧	🟧	🟥	🟢	🟩	🟨	🟩	🟧
	Company concentration	13%	🟨	🟨	🟥	🟢	🟢	🟩	🟢	🟧
Political risk	Political stability	11,20%	🟩	🟥	🟧	🟢	🟨	🟢	🟢	🟨
	Policy perception index	5,20%	🟩	🟥	🟥	🟨	🟧	🟢	🟩	🟢
	Regulation risk (HDI)	5,30%	🟩	🟥	🟧	🟧	🟨	🟢	🟢	🟨
Relative overall supply risk			🟥	🟥	🟨	🟨	🟢	🟢	🟢	🟩

Based on the given indicators it can be concluded, that there is the highest supply risk for lithium and cobalt and a medium risk for the supply with (natural) graphite, manganese, nickel and iron. Considering the potential supply risks, the extension of the service life of the materials/batteries and their return to the material cycle plays an important role.

4.2.4.2. Second-life applications

The performance of lithium-ion battery cells and battery systems, in terms of energy storage capacity and round trip efficiency and power, decreases in the course of time due to cycling, elevated temperature and time-calendar aging (Podias et al. 2018). The battery system of an EV mostly reaches its End of Life when the remaining capacity falls below 70-80% SoH. Automotive lithium-ion batteries as well as LMP batteries offer the possibility of reuse in stationary storage applications after the vehicle's service life (although the electronics might constitute a barrier). When batteries are removed from electric vehicles after their first life, they are likely to retain significant capacity, typically 70%-80% of their original capacity. According to the European Directives (End-of-Life Vehicles Directive 2000/53/EC and Battery Directive 2006/66/EC) batteries must be collected and recycled[14], but their residual capacity could be further used in other applications as e.g. storages for supporting the power grid (Hall and Lutsey 2018). The following figure indicates these different options.

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[14] In particular, 45% of LIBs must be collected and at least 50% of the average weight of LIBs should be recycled.

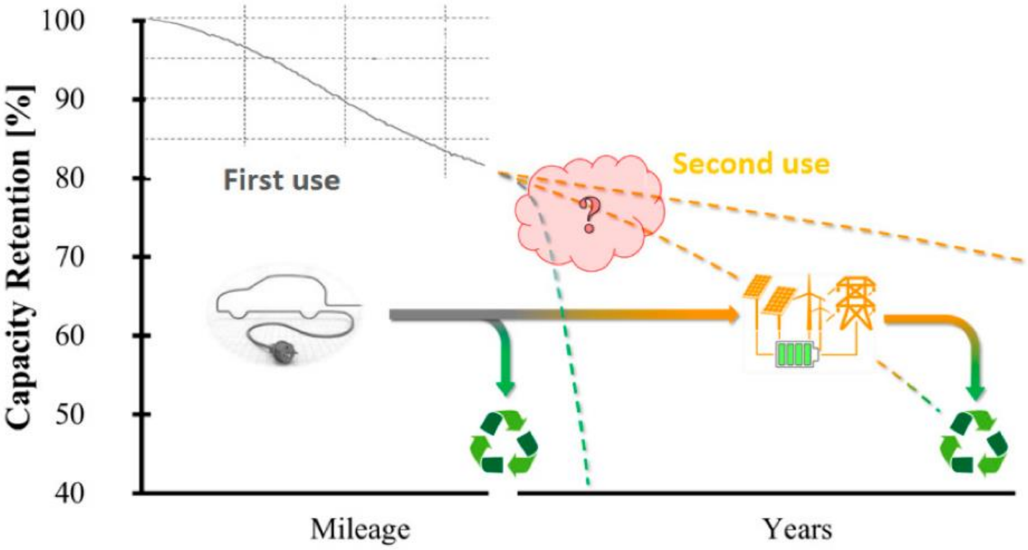

Figure 19: Options after the first-life of the battery (Podias et al. 2018)

In terms of second use it can be distinguished between two different strategies: 1) the battery system is not dismantled, tested and, if suitable for second use, reused directly, 2) the battery system is dismantled at module level and a new battery system is created (Bobba et al. 2018). This second strategy is called "battery repurposing'", while the first strategy is called "direct reuse" (Ardente et al. 2018). The possibility of a direct reuse without dismantling the whole battery system it is the preferable option out of an economic and environmental perspective. If not possible, the battery system can be dismantled and the modules/cells could be tested and repurposed in a new battery system with new materials/components, e.g. BMS. Battery repurposing will require new materials/component, for instance a new battery tray since they are not designed for dismantling, and thus an increase in the costs associated with repurposing step, but the change of use of the battery will be more flexible and designed for specific applications. Paul et al. 2015 define battery repurposing can be defined as a process that includes breaking down packages into modules, checking the hardware of the modules, performing inspection and health benchmark tests on the modules, and certifying that the modules meet a market-defined Second Life standard. After certification of the modules, the second process, repackaging, takes place. In the repackaging process, modules that are considered "good enough" for second use are placed in sub-packaging and packaging that can be shipped for use in stationary systems. It is also possible that very good modules for EVs can be directly reused (Cusenza et al. 2018).

Up to now due to the different possible applications, products (as cell chemistries) or even the energy mix it is hard to give a clear answer on the general advantage of second life applications. Anyhow, some extensive studies have been undertaken to evaluate those possible benefits. In the following the main results of two most grounded studies will be provided. The results from the project: "Sustainability Assessment of Second Life Application of Automotive Batteries (SASLAB)" (Cusenza et al. 2018) and "Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries" (Neubauer et al. 2015).

First of all, in the SASLAB-project, the results have shown that the second use of EV batteries is feasible from a technical point of view. As regards the environmental assessment, an adapted Life Cycle Assessment (LCA) has been developed to assess the environmental performance of EV batteries in secondary use. This method was applied to two different case studies: Peak shaving of an office building in Ispra (IT) and increase of own consumption of photovoltaic (PV) in a residential building in the Netherlands. For the application of the peak shaving, the results indicated that a reusable LMO/NMC battery is only environmentally friendly if it replaces a new battery (either an LMO/NMC or a Lead Acid battery). Adding a repurposed battery in a building where no batteries have been used before does not bring any benefits. Environmental benefits are also observed with increasing PV self-consumption of a residential home: A second-used battery instead of a new one (either LMO/NMC or Lead Acid battery) brings environmental benefits by avoiding battery production (with fresh LMO/NMC battery) or the higher performance of the lithium-ion battery (compared to a PbA battery).

The report from the National Renewable Energy Laboratory identifies that the subsequent service life for the second use is very sensitive to the second life cycle, climate, battery thermal management and other factors, but under favourable conditions and using a discharge cycle depth of 60% of the battery's original capacity may exceed 10 years. The most promising application identified for secondary batteries is the replacement of grid-connected combustion turbine peaker units and the provision of peak shaving services. Compared to automotive service, the use in this application results in relatively advantageous duty cycles, typically significantly less than one cycle per day with discharge times in excess of one hour. Under these conditions, battery life for second use is expected to be in the order of 10 years. Widespread use of batteries in this application would increase the lifetime use of the battery by 72%. Furthermore, it was reported, that technician labour is a significant cost factor for the repurposing that need to be minimised. Therefore, it is not economically viable to replace defective cells within modules, and therefore it is critical to minimize the purchase of modules with defective cells. The use of vehicle diagnostic data to support the purchase of used batteries is therefore of great value to resellers. When such data is available, conversion costs can be as low as 17€/kWh nameplate (Hall and Lutsey 2018; Neubauer et al. 2015).

Up to now there is great uncertainty regarding battery second life performance capabilities and business cases. To enable a successful integration of second-life applications in the products life-cycle still some barriers have to be tackled and improvement options defined:

- If the perspective is the reuse of the xEV battery after its use in EV, a more flexible BMS could ease its use for a potential second-use; in this sense, “design for disassembly” becomes a relevant issue. This refers for example to the to the former mentioned point that the state-of-the-art technologies used to connect the structural components are screwing, bonding and welding of the individual elements. Whereby especially the bonding process could be considered as unfavourable with regard to the reuse (Michaelis et al. 2018).
- Another option is to design the battery to maximize the value throughout its life cycle. The establishment of a BMS in xEVs with the ability to store all important data from the operational history of the battery pack, (e.g. operating temperature, average driving distances, and the habits of individual drivers) at individual battery cell level (in particular temperature, voltage, discharge depth (DOD), state of charge (SOC) is therefore a major issue (Cusenza et al. 2018). By knowing these historical data, for each cell, module or system a suitable application can be defined or they can be grouped according to their individual characteristics, which facilitates an efficient management e.g. by a BMS. Besides the mentioned requirements regarding the available data, also the access to this data has to be enabled.
- The design of electronics in today's battery systems is strongly application-focused. Accordingly, this is only intended for one application at a time. The design of electronics for use in automobiles and in stationary applications would make it possible

to move the battery to its second use without making any major concessions with regard to the required performance. At the same time the electronics must fulfil the automotive requirements such as a service life of at least 10 years, 10,000 operating hours and 300,000 km. On the other hand, also requirements for the stationary applications such as a service life of 20 years and one operation 24 hours a day, 7 days a week (Thielmann et al. 2017).

- Concerning Li-ion xEV batteries, an appropriate and safe removal, handling and transport of such batteries is needed and could minimize the failure rate of repurposing operations. Then, both specialization of operators who can safely manage batteries and strengthening of stakeholders network are two relevant aspects for potentially ease the second-use of xEV batteries (Cusenza et al. 2018).

The role of second life in the future is seen quite different: some expect very few batteries to have a second life, considering that prices for lithium-ion batteries will further drop in the future, while others expect most batteries to have a second life before recycling. Although uncertain, Bloomberg New Energy Finance predicts that by 2025, 27% of these batteries might have a second life in stationary storage, while the remaining 73% would be available for recycling (Drabik and Rizos 2018; Lebedeva et al. 2016).

4.2.4.3. Recycling

Along with the growing number of electric vehicles and stationary batteries, more and more batteries will be available for end-of-life treatment. In the cases where the SoH is too poor, to enable reuse or repurposing, the batteries have to be recycled (Thomas et al. 2018). As mentioned, some of the battery materials are considered as "critical raw materials". Yet, none of these materials is mentioned in the Battery Directive so far. Thus, there are also no requirements (as a specific collection or recycling rate) for the recycling of these materials (Stahl et al. 2018). Currently recycling processes focus on the recovery of the most valuable materials as Ni and Co. Next to the high commodity prices for these materials, a future shortage is expected due to the steadily increasing production of lithium-ion batteries. Thus, battery recycling and circular economy will have an increasingly important role to play and not only valuable materials should be recycled but also those of minor value.

Recycling processes for LIB are a combination of different individual processes: Pre-treatment (deactivation, dismantling and thermal treatment/mechanical separation), pyrometallurgical, mechanical and hydrometallurgical treatment. Thus, different possible recycling routes are existing.

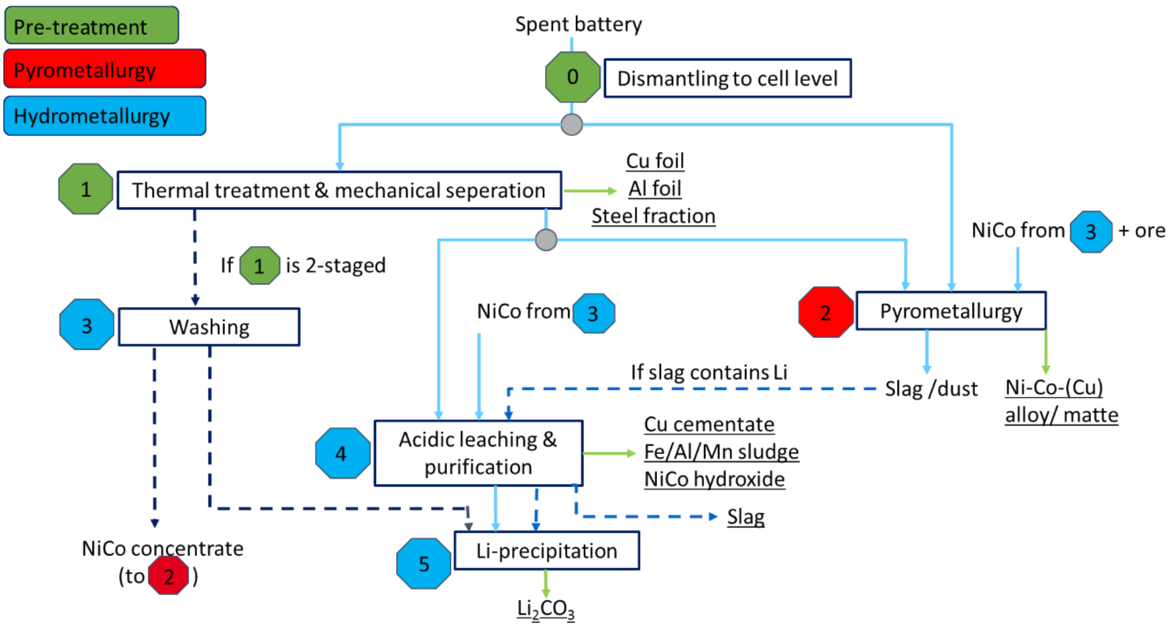

Figure 20: Different possible recycling routes (based on Friedrich and Peters 2017)

The pre-treatment contains several steps as e.g. the deactivation of the system. This can be done by discharging the entire battery system, the battery modules or the battery cells. The dismantling of the battery system and the mechanical separation of the materials. The pyrometallurgical process involves the recovery of metal from the electrode materials with the help of thermal processes, which is why this process is similar to the physical processes. It is an option after the pre-treatment of the batteries and is based on a thermal treatment of the materials. Therefore they are smelted e.g. in a shaft furnace (Gaines 2014) or an electric arc furnace. The treatment binds the heavy metals cobalt, copper and nickel in a melt, while all other contained metal components are completely slagged and subsequently deposited in a landfill. The hydrometallurgical treatment is applied for the direct recovery of metals, such as Co, Ni, Mn, and Li, from the mechanical separated coating materials as well as for the extraction of Al and Li from the slag of pyrometallurgical processes. To achieve this, leaching and several preparation processes are employed (Diekmann et al. 2017). Another possibility is the direct recycling that already has been demonstrated for several cathode types. Thereby the battery materials are recovered for reinsertion into the battery supply chain with little or no additional processing. Discharged cells are placed in a container to which CO_2 is added, and the temperature and pressure are increased to bring the CO_2 above its critical value. The supercritical carbon dioxide extracts the electrolyte from the cells, which can be separated from the gaseous CO_2, and could also be reused after treatment. The electrolyte-free cells are then further crushed under exclusion of water and oxygen. The cell components can be separated by using the different conductivity, density or other properties of the components. Before further use, the cathode materials may require further re-lithiation (Gaines 2014).

Thereby, depending on the selected recycling route (as depicted in Figure 20) different materials can be recovered during the recycling process, what also has an effect on the use of energy, chemicals/additives and the generation of by-products. The following table gives a summary of the different routes, the main processes used and materials recovered.

Table 10: Qualitative assessment of different recycling routes (based on Friedrich and Peters 2017)

Path	Steps	Main processes	Recovered Metals	Energy	Chemicals/ Additives	By-product generation
1	0 (1) 2	Pyrolysis in rotary kiln, EAF & converter	Ni, Co, Cu, (Fe)	high	low	high
2	0 2	Smelting in shaft furnace	Ni, Co, Cu, (Fe)	medium	low	high
3	0 1 2	Thermal treatment + Mechanical separ. Pyrometallurgy	Ni, Co, Cu	high	low	medium
4	2	Direct smelting in EAF	Ni, Co, Cu	high	low	high
5	0 1 4 5	Pyrolysis, Mechanical + Hydrometallurgy	Ni, Co, Cu, Fe, Mn, Li	high	high	low
6	0 (1) 4	Mechanical (inert gas) + Hydrometallurgy	Ni, Co, Cu	medium	high	low

The overall efficiency of battery recycling can be seen as a combination of the collection rate and the recycling efficiency. The collection rate expresses the proportion of lithium-ion batteries produced and collected at the end of their life, while the recycling efficiency is expressed as the percentage by weight of materials that are recovered from the collected waste and then can be reused directly in battery production or in other applications or processes (Lebedeva et al. 2016). While the collection and recycling of batteries is regulated under the Directive 2006/66/EC, which is currently under revision[15]. The current Battery Directive is not providing any further details on the collection of those industrial batteries, which are used by private consumers (e.g. electric vehicles, energy storages or e-bikes). However, the recycling efficiencies for the recycling of Li-ion batteries and their battery materials are estimated to be ~ 95 % for Co and Ni, 80 % for Cu and 50 % for Al, depending on the specific process (Stahl et al. 2018). For the pyrometallurgical process (based on electric arc furnace) Diaz et al. 2018 estimate a 61 % recycling efficiency and the following theoretical values given in Table 11 for the hydrometallurgical treatment by leaching of the electrode powder (step 4 & step 5 in Figure 20).

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[15] The Directive is from 2006, at which time some developments such as high-energy LiB were not foreseeable and the Directive accordingly has shortcomings in the management of these batteries (Stahl et al. 2018).

Table 11: Theoretical recycling efficiency for specific materials (based on Diaz et al. 2018)

Product	**Graphite product**[16]	**Cu-powder**	**Fe/Al residual**	**Co-, Ni-, Mn-hydroxides**	**Li_2CO_3**
Purity	High	Moderate	Moderate	High	High
Recycling efficiency[17]	~100%	~97%	~ 70% for Al/ ~ 90% for Fe	~ 96% for Co, Ni, Mn	> 56%

These values are also mostly in line to assumptions given by Lebedeva et al. 2016. The following table gives an overview of the recycling efficiency of different processes, also considering different cell chemistries:

Table 12: Recycling efficiency of recycling processes (Lebedeva et al. 2016; Hill et al. 2018)

	Combination of pyrom. & hydrom. processes - NMC and LFP [%]	**Purely hydrometallurgical process - NMC only [%]**	**Purely hydrometallurgical process - LFP only [%]**
Lithium[18]	57	94	81
Nickel	95	97	NA
Manganese	0	~100	NA
Cobalt	94	~100	NA
Iron	0	NA	0
Phosphate	0	NA	0
Natural graphite	0	0	0
Aluminium	63	-	-
Copper	41	-	-

Based on the above, the following recycling rates will be applied in this preparatory study.

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[16] Also graphite is mostly not recovered by recyclers and if so not in battery grade quality.

[17] Specific recycling efficiencies refer on specific product in relation to raw material.

[18] In current practice only 1% of lithium is recovered (https://www.eea.europa.eu/publications/electric-vehicles-from-life-cycle) (https://www.eea.europa.eu/publications/electric-vehicles-from-life-cycle)

Table 13: Overview recycling rates Business As Usual (BAU), improved and ambitious scenario (based on diverse literature sources found with EV battery specific data)

Scenario	Cobalt	Graphite	Manganese	Nickel	Lithium
BAU	16.00 (1)	0.00 (1)	0.00 (2)	16.00 (3)	0.00 (4)
Improved: 65% collection rate + combination of pyrom. & hydrom. processes (5)	61.10	0.00	0.00	61.75	37.05
Ambitious: 85% collection rate + purely hydrometallurgical process (5)	84.15	0.00	84.15	82.45	79.90

(1) Lebedeva et al., 2016

(2) Ellingsen & Hung, 2018; Friedrich & Peters, 2017 as quoted in Drabik & Rizos, 2018.

(3) Nickel shows comparable recycling efficiency rates as cobalt (Lebedeva et al, 2016; Hill et al. 2018) and recycled content and recycling rates of a similar order of magnitude in general (meaning based on not EV battery specific data) as cobalt based on the UNEP status report from 2011 on recycling rates of metals. Therefore, the same recycling rate has been applied to nickel as cobalt for the BAU scenario.

(4) Ellingsen & Hung, 2018

(5) The collection rates are taken from Drabik & Rizos (2018) and the recycling efficiency rates from Lebedeva et al (2016) and Hill et al. (2018). The recycling rates are calculated by multiplying the collection rate with the recycling efficiency rate.

The high variance of possible recycling routes also leads to the effect, that most recycling companies have their own specific recycling process. The following table gives an exemplary overview of recycling activities all over the world, as well as information about the recycling process, the recovered materials and the recycling volume.

Table 14: Overview of recycling companies and corresponding recycling processes (Romare and Dahllöf 2017; Lebedeva et al. 2016)

Company	Facility location	Battery types	Recycling process	Materials recovered today	Recycling volume, tonnes of batteries per year
Accurec	Germany (x2)	NiCd, NiMH, Li-ion	Pyrolysis and hydrometallurgy.	Aluminium, copper, iron scrap, iron/magnesium, and nickel/cobalt.	1500-2000
AkkuSer	Finland	NiCd, NiMH, Li-ion, Zn alkaline	Crushing, chemical treatment	Nickel, cobalt, manganese, iron, copper, aluminium	1000 (li-ion) 4000
AERC Recycling Solutions	USA (x3)	All types including Li-ion and Li metal	Pyrometallurgy		
Batrec	Switzerland	Li	Pyrolysis, pyrometallurgy.	Ferromanganese, zinc.	200

Euro Dieuze (Veolia)	France	Li-ion	Hydrometallurgy		200
G&P Batteries	UK	Various (incl. Li-ion)	Pyrometallurgical or hydrometallurgical.		
Glencore (formerly Xstrata)	Canada (x2) Norway	Li-ion	Pyrometallurgical with hydrometallurgical treatment of slag and electrowinning		7000
Hunan BRUNP	China	Various (incl. NiMH, Li-ion)	Hydrometallurgy		3600-1000 >6000
JX Nippon Mining and Metals	Japan	Various (incl. Li-ion)	Pyrometallurgy		5000
Nippon Recycle Center corp	Japan (x3)	NiCd, NiMH, Li-ion, alkaline	Pyrometallurgy		
Recupyl	France Singapore	Li-ion	Mechanical separation, hydrometallurgical leaching and refining.	Aluminium, cobalt, stainless steel, lithium products.	110
Retriev Technologies	Canada USA (x2)	Li metal, Li-ion	Hydrometallurgy		4500
Shenzhen Green	China	NiMH, Li-ion	Hydrometallurgy		2000-3000
SNAM	France	NiCd, NiMH, Li-ion	Crushing, pyrolysis, distillation, pyrometallurgy.	Cadmium, ferronickel alloys, ferro-cobalt alloys	300
Sumitomo Metals and Mining Co	Japan	Li-ion	Pyrom.refining process followed by a hydrometallurgical leaching and refining process	Nickel, copper, cobalt	Sumitomo Metals and Mining Co
Umicore	Belgium	Li-ion, NiMH	Pyrometallurgical smelting followed by hydrometallurgical refining.	Cobalt, nickel	7000
Veolia	France				

Since in the context of this report it is not possible to describe all recycling activities, only some selected European activities will be described in more detail. Umicore uses a pyrometallurgical treatment with a subsequent hydrometallurgical process. The pyrometallurgical treatment produces slag, a liquid metal alloy, flue gas and gas emissions. The slag fraction, which contains aluminium, lithium and manganese, can be used in the construction industry or further processed for metal recovery. Lithium recovery from the slag began in 2017 in collaboration with an external partner. The liquid metal alloy is further refined in hydrometallurgical processes to recover copper, nickel and cobalt by solvent extraction (Thomas et al. 2018).

Accurec recycles cobalt, manganese, nickel and iron while the slag and smoke dust can be treated in additional hydrometallurgical steps for lithium recovery, which is currently not the case due to a lack of economic profit (Thomas et al. 2018).

The recycling process of Recupyl uses mechanical crushing followed by hydrometallurgical treatment. The LIBs are crushed in a housing with defined and controlled atmosphere and pressure. The crushed materials are then filtered into four fractions. Only one fraction, a fine fraction rich in metal oxides and carbon, is further processed. This fraction is sieved to reduce the copper content. The remaining fine powder is further treated in hydrometallurgical steps to obtain solutions of cobalt and lithium salts (Thomas et al. 2018).

The BatRec process is mainly based on a mechanical processing plant. The first step is to crush the batteries in an inert CO_2 atmosphere. Afterwards the crushed batteries are mechanically separated, which leads to a non-ferrous metal-containing metal fraction, a nickel-containing metal fraction, a cobalt and lithium-containing fine fraction and a plastic fraction. The first two metal fractions can be sold to other metal recyclers, while the fine fraction is sold to cobalt and nickel refineries. The plastic fraction can be partially used for energy recovery in a pyrolysis process (Thomas et al. 2018).

So it becomes obvious that most recycling processes focus on the recovery of the valuable cobalt and nickel, while the recycling of lithium or manganese is rather out of scope. Out of an economical perspective, this is reasonable, but this might become a problem when considering the environmental impact: LFP batteries for example contain no economically valuable metals and thus have very low incentive for recycling. Regardless of this the cells still contains aluminium, which has a high greenhouse gas emissions from production and a well-developed recycling chain that is not utilized (Hall and Lutsey 2018).

Romare and Dahllöf compared different potential battery recycling pathways and identified potential net savings of 1–2.5 kg CO_2/ kg.

Table 15: LCA results for different recycling stages (Romare and Dahllöf 2017)

Method	**g CO_2-eq/kg battery**	**Chemistry**
LithoRec (Buchert, et al., 2011b)a) (Prototype scale)	-1035 (hydrometallurgy, see details in Table 23)	35% NMC, 35% NCA and 30% LFP
Libri (Buchert, et al., 2011a) (Prototype scale)	1244 (pyrometallurgy)	35% NMC, 35% NCA and 30% LFP
Umicore (Dunn, et al., 2015) (Industrial scale)	-70% = -1500 g CO_2/kg Co	LCO

Hydrometallurgical (Dunn, et al., 2012)	-2000, mainly from removing need for primary Al	LMO
Intermediate physical recycling (Dunn, et al., 2012)	-2000, mainly from removing need for primary Al	LMO
Direct physical recycling (Dunn, et al., 2012)	-2500	LMO

The results of an LCA thereby depends on the chemistries of batteries (high share off NMC or LFP), the recycling process used and therefore the materials regained and also the quality of the final material output (Romare and Dahllöf 2017). Thomas et al. 2018 gives a summary of the results of different LCA studies regarding the role of recycling. They conclude that recycling concepts that are more dependent on energy consumption as e.g. the pyrometallurgical treatment are likely to have higher greenhouse gas emissions, while recycling concepts that are more dependent on the use of solvents as hydrometallurgical treatment, are likely to have higher impacts in other environmental impact categories. In contrast to the operation phase, EoL emissions associated with battery recycling are unlikely to be affected by changes in the electricity mix, as only a small part of the energy input in EoL treatment processes comes from electricity (Thomas et al. 2018).

4.2.5. Environmental impact of li-ion batteries production

This chapter will briefly highlight the environmental impact resulting from the production of battery systems. Romare and Dahllöf 2017 give a summary of the identified greenhouse gas emission given in the reviewed LCA studies[19] for the different life cycle stages. The values for battery grade material production (including raw material mining and refining) are in a range between 48 -121 kg CO_2-e/kWh, while the most likely value might be 60-70 kg CO_2-e/kWh. The manufacturing process of components, cells and battery assembly has a slightly higher environmental impact. The greenhouse gas emissions are thereby in a range between 20-110 CO_2-e/kWh, with a most likely value of 70-110 k CO_2-e/kWh (Romare and Dahllöf 2017). Anyhow, the ranges indicate that there is a high uncertainty regarding the results but the assessment points out that both, the battery grade material production (including raw material mining and refining) as well as the manufacturing have a high impact on greenhouse gas emissions, while the impact of the manufacturing process can be considered as a bit higher.

As already indicated before, also the choice of the cell chemistry has influence on the material consumption and the energy use for processing. Peters and Weil 2018 gives a good summary of the resulting greenhouse gas emission (in GWP). The following Figure 21 gives an overview of the unified (and original) results of this analysis regarding the relative importance of different battery manufacturing components or stages.

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[19] Ellingsen et al. 2014; Majeau-Bettez et al. 2011a; Kim et al. 2016; Ambrose und Kendall 2016; Amarakoon et al. 2013

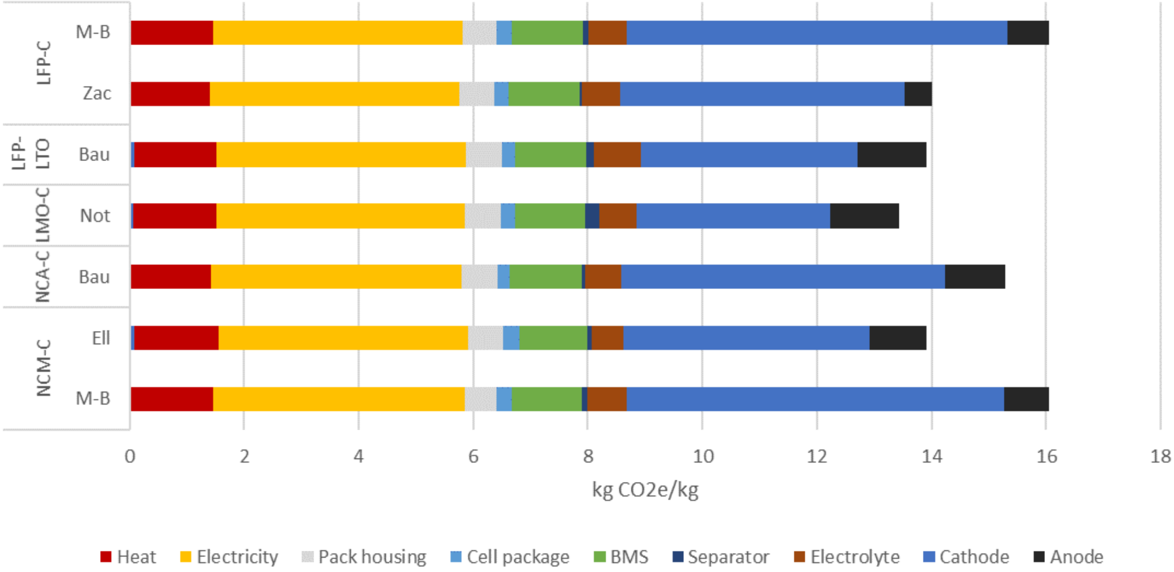

Figure 21: GWP impacts (per kg battery) from the production of Li-ion batteries for different cell chemistries (based on Peters and Weil 2018)

The figure illustrates that especially the cathode materials and the electricity (and heat) have the highest GWP impact. Based on these findings, potential improvements to reduce these emissions focus primarily on a higher energy efficiency in production, the use of low-carbon electricity and the improvement of cell chemicals as well as an increased energy density and battery lifetime (Hill et al. 2018; Romare und Dahllöf 2017; Hall und Lutsey 2018; Peters and Weil 2018).

Hall and Lutsey 2018 state that the energy storage per kilogram of battery, is steadily increasing with an average rate of approximately 5%–8% per year. Although this does not represent an equivalent reduction in materials or energy, they estimate that a 50% increase in battery energy density would lead to a 10%–15% reduction in cumulative energy density. In addition, a longer battery lifetime will lower the initial battery production footprint. As well as the decarbonization of electric grids. Hall and Lutsey 2018 estimate, that a decarbonization of the electric grids around the world (e.g. until 2030) by an average of about 30% will result in approximately 17% lower battery manufacturing emissions by 2030. To quantify the effects of these measures they exemplarily calculated the potential changes in greenhouse gas emissions in g CO_2 e/km in comparison to a reference electric vehicle using this battery in 2017.

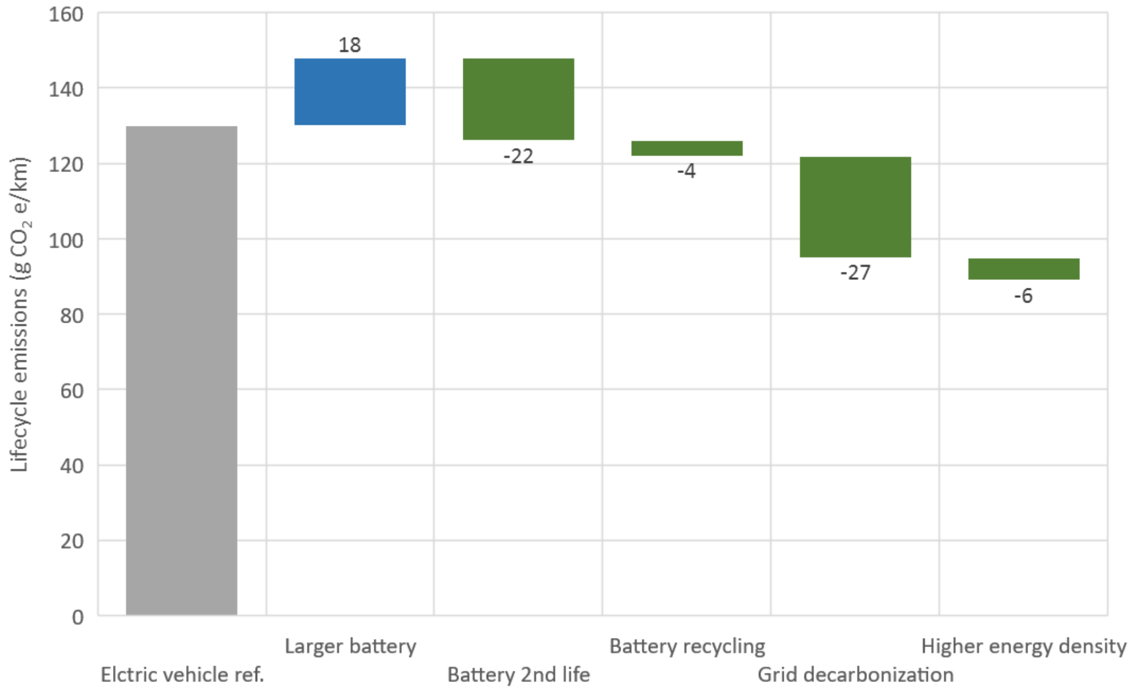

Figure 22: Potential changes in battery greenhouse gas emissions by different measures (Hall and Lutsey 2018)

4.3. Subtask 4.3 - Recommendations

The task 4 report on technologies provides a quite holistic description of the li-ion batteries from a technological point of view as well as over the whole life cycle from the materials sourcing to the end-of-life treatment. Based on the findings in the following some recommendations regarding barriers and opportunities and the following process are listed.

- Due to the rather unsettled market for automotive and stationary li-ion batteries and the great variety of products (cell formats, cell chemistries...) placed on the market a concentration on a "representative cell" is not possible. Thus, for e.g. determining the BOM, an approach based for building a virtual battery is used. The approach allows considering different kind of cells in accordance to their approximate market share and offers a way to deal with this market complexity.
- There is a long list of possible improvement options for li-ion batteries. However, the impact in terms of performance and additional costs, is in the case for most options almost not possible to determine in general way. Thus, extensive investigations would be necessary, considering the specific characteristics of the products and of their intended application. However, in order to be able to make a statement about the effects of improvement options, it is suggested not to consider the improvement options at component level but rather at a higher level. Such an approach seems even more reasonable when looking at different LCA studies which are also rather focusing at this meta-level, e.g.: higher energy density, increased lifetime...).
- Another difference to many other Ecodesign preparatory studies is the possibility of 2nd life applications. This is a quite promising possibility to prolong the service life of a battery and thus to increase the functional unit. This leads to a lower environmental impact per energy service delivered.

- Battery recycling will also play a major role in the future. Anyhow, since this is the specific issue of the Battery directive (which is currently under revision), it makes sense to keep a clear allocation of topics and thus not to consider the subject of recycling any further here, even if some of the technical options may facilitate dismantling and recycling of batteries.

To sum up, the recommendations regarding the scope of the study are to consider the whole battery life cycle, except for recycling which is rather a topic of the Battery directive. Regarding improvement options for a further examination in task 6, the consideration of a prolonged lifetime because of second-life application seems to offer a high potential. Furthermore, the electricity consumed for battery production can have a comparatively high environmental impact and should therefore also be examined close in this preparatory study. Finally, to take account of technological developments, the amount of active and passive materials used to provide a comparative service can be further reduced (also going along with a change in cell chemicals) and should be studied in more depth.

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Preparatory Study on Ecodesign and Energy Labelling of Batteries under FWC ENER/C3/2015-619-Lot 1

TASK 5

Environment & economics – For Ecodesign and Energy Labelling

VITO, Fraunhofer, Viegand Maagøe

Augustus 2019

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Project website: https://ecodesignbatteries.eu/

Version history:

Version 1: version made available in December 2018 for the Stakeholders to comment and for discussion in the first stakeholder meeting.

Version 2 (version made available for the second stakeholder meeting):

- was a more elaborated version with environmental and economic assessments of all seven base cases;
- included several updates on the modelling of battery chemistries and applied parameters based on the updated user parameters, base cases and BOM of Task 3/4.

Version 3 (this version/final version):

- Includes the changes made in the EcoReport tool and LCC calculations, i.e.:
  - lowered the average efficiency of the battery system parameter from 96 % to 92 %
  - corrected the mass imbalance of the extra materials
  - updated the EOL scenario of the “extra materials” category
  - corrected the calculations of the CRM indicator
- Includes textual updates, additions and other corrections

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Contents

List of abbreviations and acronyms

Abbreviations	Descriptions
AD	Acidification
BAU	Business As Usual
BC	Base Case
BEV	Battery Electric Vehicle
BOM	Bill-of-Materials
CAPEX	Capital Expenditure
CF	Characterisation Factor
CMC	Carboxy Methyl Cellulose
CRM	Critical Raw Material
DMC	Dimethyl carbonate
DoD	Depth of Discharge
GER	Gross Energy Requirements
EC	European Commission
EC	Ethylene Carbonate
EMC	Ethyl Methyl Carbonate
EOL	End-of-Life
EPD	Environmental Product Declaration
eq.	equivalent
EU	European Union
EU-28	28 Member States of the European Union
EUP	Eutrophication
FU	Functional Unit
GHG	Greenhous Gases
GWP	Global Warming Potential
HMa	Heavy metals to air
HMw	Heavy metals to water
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCI	Life Cycle Inventory
LCOE	Levelized Cost Of Energy
LCV	Light Commercial Vehicle
LFP	Lithium-ion Phosphate
LiPF6	Lithium Hexaflurophosphate
LiFSI	Lithium bis(fluorosulfonyl) imide
LMO	Lithium Manganese Oxide
MEErP	Methodology for Ecodesign of Energy related Products
MEEuP	Methodology for Ecodesign of Energy-using Products
NCA	Lithium Nickel Cobalt Aluminium
NCM	Lithium Nickel Manganese Cobalt Oxide
NMC	Lithium Nickel Manganese Cobalt Oxide
NiMh	Nickel-Metal hydride
NPV	Net Present Value
OPEX	Operational Expenditure
PAH	Polycyclic Aromatic Hydrocarbons

Abbreviations	**Descriptions**
PM	Particulate Matter
PC	Passenger car
PC	Propylene Carbonate
PCR	Product Category Rules
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
PHEV	Plug-in Hybrid Electric Vehicle
POP	Persistent Organic Pollutants
PVDF	Polyvinylidene fluoride
PWF	Present Worth Factor
QFU	Quantity of Functional Units
Sb	Antimony
SBR	Styrene-Butadiene Rubber
SoC	State of Charge
TOC	Total Cost of Ownership
VAT	Value Added Tax
VOC	Volatile Organic Compounds
ZrO2	Zirconium Oxide
WEEE	Waste Electrical and Electronic Equipment

5. Task 5: Environment and economics

5.0. General introduction to Task 5

The objective of Task 5 is to define one or more average EU product(s) or a representative product category as "Base Case" (BC) for the whole of the EU-28 and calculate the Environmental Impact Assessment and the Life Cycle Costs for consumer for the base cases in business as usual per unit and as EU totals.

Throughout the rest of the study, most of the environmental Life Cycle Assessment (LCA), Life Cycle Costs (LCC) and scenario analyses will be built on these BCs. The BC is a conscious abstraction of the reality, necessary for practical reasons (budgetary and time constraints). The question whether this abstraction will lead to inadmissible conclusions for certain market segments will be addressed in the impact and sensitivity analysis of Task 7.

Task 5 consists of four subtasks:

- **Subtask 5.1 – Product specific inputs**
  The product specific inputs are compiled by collecting the most appropriate information from Task 1 to 4. Based on these inputs BCs are defined; thus the description of a BC is a synthesis of the previous tasks. The following seven BCs are defined within this preparatory study:
    - Passenger car battery electric vehicle with a high battery capacity (PC BEV HIGH),
    - Passenger car battery electric vehicle with a low battery capacity (PC BEV LOW),
    - Passenger car plug-in hybrid electric vehicle (PC PHEV),
    - Truck battery electric vehicle (Truck BEV),
    - Truck plug-in hybrid electric vehicle (Truck PHEV),
    - Residential storage (Residential ESS),
    - Grid stabilisation (Commercial ESS).
- **Subtask 5.2 – Base Case environmental impact assessment**
  An environmental LCA per BC is done with the Ecodesign EcoReport 2014 tool to calculate the consumed resources and materials and the related emissions for the impact categories in MEErP format for the different life cycle stages for all BCs in a BAU, Business As Usual, situation. The GREET2 Model by UChicago Argonne, LLC[1] and the PEFCR on rechargeable batteries[2] are used for the life cycle inventory datasets of some battery specific materials that are not included in the EcoReport tool, but can be added to the EcoReport manually as "extra materials" (more explanation on this is included in section 5.1.3.1). The Critical Raw Material (CRM) indicator is also presented in this subtask. The CRM indicator calculations are done with the formula of the MEErP method[3] but with updated values to calculate the CRM characterisation factors.
- **Subtask 5.3 – Base Case Life Cycle Costs**
  In addition to environmental impacts, the financial impact for the consumer and society are assessed by means of a separate LCC spreadsheet instead of using the EcoReport LCC tool, in order to include more complex functionalities for the calculation.

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[1] https://greet.es.anl.gov/greet.models

[2] http://ec.EURpa.eu/environment/eussd/smgp/pdf/Batteries%20PEFCR%20-%20Life%20Cycle%20Inventory.xlsx

[3] https://ecodesignbatteries.eu/faq

- **Subtask 5.4 – EU totals**
  In the final subtask of Task 5, the data from the LCA and LCC are aggregated to EU-28 level by using the stock and market data from Task 2.

This Task 5 report concludes with a comparison with the Product Environmental Footprint (PEF)[4] pilot on rechargeable batteries (section 5.5), a comparison with other literature sources (section 5.6), and the conclusions (section 5.7).

5.1. Subtask 5.1 – Product-specific inputs

AIM OF SUBTASK 5.1:

This subtask collects the relevant quantitative Base Case (BC) information per BC from Tasks 1 to 4 that is needed for the LCA and LCC.

5.1.1. Selection of Base Cases and Functional Unit

Within the scope of this preparatory study 'High Specific Energy Rechargeable Batteries for Mobile Applications with High Capacity' seven BCs have been defined. An overview of the selected BCs and their technical parameters are presented in Table 1.

The functional unit (FU) is set on the same unit as the one defined within the Product Environmental Footprint Category Rules (PEFCR) on High Specific Energy Rechargeable Batteries for Mobile Applications (version H February 2018) (Recharge 2018).

The **functional unit FU is 1 kWh** (kilowatt-hour) of the total output energy delivered over the service life by the battery system (measured in kWh).

For the LCA and LCC calculations within Task 5, the calculations are done on application level (BC), meaning that the number of batteries needed to deliver the total kWh over the service life required by the application is considered (as described in section 3.3 of the PEFCR). In addition, if a battery system has not reached its end-of-life (EOL) yet while the service lifetime of the application has been fulfilled, then the complete environmental and economic impact of the production and EOL of the not-fully used battery is considered in the calculations and not only the "proportional use" of the impacts of the production and EOL of the battery. This would result in a zero impact allocation to the second life in case a second life would be the case. The complete impact is considered to align the system boundaries of the LCA with the LCC and because second life applications are not considered as BAU yet.

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[4] http://ec.europa.eu/environment/eussd/smgp/ef_pilots.htm

Table 1: Complete overview of technical parameters of selected Base Cases (based on Task 3 and 4)

	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
Economic lifetime of application (Tapp) [yr]	13	14	13	14	12	20	20
Kilometres per year [km/yr]	14 000	11 000	7 000	50 000	50 000	n.a.	n.a.
Electricity consumption [kWh/km]	0.20	0.16	0.18	1.20	1.40	n.a.	n.a.
Application service energy (AS) [kWh/Tapp]	43 680	29 568	19 656	940 800	890 400	40 000	120×10^6
Max. calendar lifetime installed battery (no cycling ageing) [yr]	20	20	20	20	20	25	25
Maximum SoC - maximum DoD (Stroke) [%]	80	80	75	80	75	80	80
Average stroke (SoC - DoD) [%]	24	31	73	50	69	60	75
Energy delivered in first cycle (Edc) [kWh/cycle]	64	32	7	24	12	8	8
Number of cycles per year [-]	120	120	120	300	600	250	250
Max. number of cycles for battery system until EOL (no calendar ageing) [-]	1 500	1 500	2 000	2 000	3 000	8 000	10 000
Service life of battery (Tbat) [y]	14.40	13.43	10.67	8.04	5.33	17.02	17.02
Typical capacity of the application [kWh]	80	40	12	360	160	10	30 000
Nominal battery system capacity [kWh]	80	40	12	30	20	10	10
Number of batteries in the application [-]	1	1	1	12	8	1	3 000

Continuation of Table 1: Complete overview of technical parameters of selected Base Cases (based on Task 3 and 4)

	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
Number of battery application systems per Tapp (Ass) [-]	1	2	2	2	3	2	2
Average efficiency of battery system [%]	92	92	92	92	92	92	92
Charger efficiency [%]	85	85	85	92	92	98	98
Brake energy recovery [%]	20	20	20	12	6	n.a.	n.a.
Thermal management efficiency [%]	99	99	99	99	99	99	99
Self-discharge (@STC) [%]	2	2	2	2	2	2	2
Weight of one battery [kg]	609	304	126	256	210	128	128
Volume of one battery [m^3]	0.16	0.08	0.05	0.08	0.08	0.05	0.05

5.1.2. Economic input parameters and product service life

5.1.2.1. Introduction to Life Cycle Costs and Levelized Cost Of Energy

The MEErP methodology is usually based on an analysis of life cycle costs (LCC). An LCC calculation provides a summation of all of the costs incurred for the end-user along the life cycle of the product. This makes it relevant to consumers because this cost can then be related to potential savings. It is used in Task 6 to find the LLCC, Least Life Cycle Cost, for the identified design options.

The Total Cost of Ownership (TCO) or LCC is a concept that aims to estimate the full cost of a system. Therefore, the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) are calculated. CAPEX is used to acquire the battery system and consists mainly of product costs; cost for decommissioning is also a CAPEX. The OPEX is the ongoing cost of running the battery system and consists of costs for replacement services and electricity costs for energy losses.

The purpose of the discount rate in LCC/LCOE calculations is to convert all life cycle costs to their net present value (NPV) taking into account OPEX for energy and other consumables.

The LCC in MEErP studies is to be calculated using the following formula:

$$LCC[€]= \Sigma CAPEX+ \Sigma(PWF\ x\ OPEX)$$

where,

LCC is the life cycle costing,

CAPEX is the purchase price (including installation) and decommissioning costs or so-called capital expenditure,

OPEX are the operating expenses per year or so-called operational expenditure,

PWF is the present worth factor with PWF = $1/(1+ r)^N$

N is the product life in years,

r is the discount rate which represents the return that could be earned in alternative investments.

The Levelized Cost Of Energy (LCOE) is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment, operations and maintenance, cost of fuel, and cost of capital. The LCOE is defined for the purpose of these calculations as:

$$\mathrm{LCOE}[€/\mathrm{kWh}] = \frac{\text{net present value of sum of costs of electricty stored over its lifetime}}{sum\ of\ electrical\ energy\ delivered\ over\ its\ life\ time}$$

The LCOE calculation of costs per kWh generated aligns with the FU defined in Task 1. In this definition the life cycle environmental impacts of the battery system or component are normalized to 1 kWh of electricity stored.

As a consequence there is a direct relationship between LCOE, LCC and the quantity of FUs (QFU) of a battery system:

LCOE = LCC/QFU [euro/kWh]

Using this approach will allow that comparison in Task 6 for improvement options will be done per in LCC per functional unit or in other words in LCOE.

5.1.2.2. Consumer expenditure data for Base Cases

An overview of the assumed values for CAPEX and OPEX of the seven BCs are shown in the next table.

Table 2: Overview of CAPEX and OPEX assumptions of the Base Cases (based on Task 3)

	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
CAPEX battery system cost per declared initial capacity [EUR/kWh]	206	206	254	220	212	683	683
OPEX battery replacement [EUR/service]	700	700	700	400	400	100	100
CAPEX decommissioning at EOL [EUR]	1 200	600	180	450	300	150	150

5.1.2.3. Market stock and/or sales data for calculation EU totals

Based on Task 2 the sales and stock data of the year 2018 are presented in Table 3. The number of units per BC are calculated by dividing the total amount of GWh capacity installed by the capacity per battery system or application.

Table 3: Overview of the sales, stock, capacity, and service life of the Base Cases (based on Task 2 and 3)

	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
Sales [GWh]	2.76	5.99	2.58	0.02	0.03	0.95	0.50
[Units of battery systems]	34 552	149 694	214 974	825	1 600	95 105	49 964
[U. of bat. appl. systems]	34 552	149 694	214 974	69	200	95 105	17
Stock [GWh]	6.79	18.89	10.04	0.20	0.16	6.83	2.27
[Units of battery systems]	84 877	472 348	836 283	6 600	8 000	682 811	226 510
[U. of bat. appl. systems]	84 877	472 348	836 283	550	1000	682 811	76
Nominal battery system capacity [kWh]	80	40	12	30	20	10	10
Typical capacity of the application [kWh]	80	40	12	360	160	10	30 000
Service life of application [yr]	13	14	13	14	12	20	20
Service life of battery [yr]	14.40	13.43	10.67	8.04	5.33	17.02	17.02

5.1.2.4. Battery system service life and link to the economic lifetime of the application

Definitions:

An application can require several battery systems over its economic lifetime, in order to explain the relationships and assumptions the following definitions will be used:

- AS = The application service energy which is the energy required by the application per service life [kWh]
- Tapp = The economic lifetime of the application in years [y]
- Edc = The energy delivered in the first cycle [kWh/cycle]
- Ass = The number of battery application systems during Tapp [-]
- Tbat = The lifetime of the battery system in years [y]

Calculation of the application service energy (AS)

For the xEV BCs the AS is calculated by multiplying Tapp with the annual kilometres, the electricity consumption, and the additional battery loading due to regenerative braking. For example for BC1:

- the AS = 13 yr * 14 000 km/y * 0.20 kWh/km * (1+20 %) = 43 680 kWh.

Table 4 gives an overview of the assumed parameters needed to calculate the AS for BC1-B5.

Table 4: Overview of the assumptions to calculate the application service energy of the xEV BCs (BC1-BC5).

	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV
Economic lifetime of application (Tapp) [yr]	13	14	13	14	12
Kilometres per year [km/yr]	14 000	11 000	7 000	50 000	50 000
Electricity consumption [kWh/km]	0.20	0.16	0.18	1.20	1.40
Brake energy recovery [%]	20	20	20	12	6
Application service energy (AS) [kWh/Tapp]	43 680	29 568	19 656	940 800	890 400

The AS of the ESS BCs (BC6 and 7) are calculated differently. It is calculated by multiplying Tapp with Edc, the number of cycles per year, and the number of batteries in the application. The number of batteries in the application is determined by dividing the typical capacity of the application by the nominal battery system capacity. E.g. in case of BC7:

- the number of batteries in the ESS application = 30 000 kWh / 10 kWh = 3 000 batteries and
- the AS = 20 yr * 8 kWh/cycle * 250 cycles * 3 000 batteries = 120 000 000 kWh.

The assumptions for calculating the AS of BC6 and BC7 is shown in the table below.

Table 5: Overview of the assumptions to calculate the application service energy of the ESS BCs (BC6-BC7).

	BC6 Resid. ESS	BC7 Comm. ESS
Economic lifetime of application (Tapp) [yr]	20	20
Energy delivered in first cycle (Edc) [kWh/cycle]	8	8
Number of cycles per year [-]	250	250
Typical capacity of the application [kWh]	10	30 000
Nominal battery system capacity [kWh]	10	10
Number of batteries in the application [-]	1	3 000
Application service energy (AS) [kWh/Tapp]	40 000	120 000 000

Calculation of the number of battery application systems for the economic service life of application (Ass)

To calculate the Ass, the service lifetime of the application (Tapp) is divided by the service lifetime of the battery system (Tbat) and rounded up:

- Ass = Int (Tapp / Tbat) + 1

Tbat is calculated by taking the inverse of the inverse of the maximum calendar lifetime of the installed battery plus the inverse of maximum number of cycles for the battery system divided by the multiplication of the number of cycles per year and average stroke. For example the calculation of Tbat of BC1 looks like:

- Tbat = 1 / (20^-1 + (1 500 / (120 * 24 %))^-1) = 14.40

This formula is an early approximation open to a significant margin of error depending on the specific Li-ion battery design.

Table 6: Overview of the assumptions to calculate the number of battery application systems of the BCs

	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
Max. calendar lifetime installed battery (no cycling ageing) [yr]	20	20	20	20	20	25	25
Max. number of cycles for battery system until EOL (no calendar ageing) [-]	1 500	1 500	2 000	2 000	3 000	8 000	10 000
Number of cycles per year [-]	120	120	120	300	600	250	250
Average stroke (SoC - DoD) [%]	24	31	73	50	69	60	75
Service life of battery (Tbat) [yr]	14.40	13.43	10.67	8.04	5.33	17.02	17.02
Economic lifetime of application (Tapp) [yr]	13	14	13	14	12	20	20
Number of battery application systems per Tapp (Ass) [-]	1	2	2	2	3	2	2
Number of replacement battery application systems during Tapp [-]	-	1 [5]	1	1	2	1	1

The battery at the end of life of Tbat and Tapp still has potential left to be reused in other cars or applications (see section 4.2.4.2 of the Task 4 report for general information on second-life applications). This is relevant to explore for second life improvement options in Task 6.

5.1.2.5. Other economic parameters

Discount rate:

The ‘discount rate’ is set at 4 %, following the MEErP. This will be applied to all costs apart from electricity[6]. For electricity, the applied electricity rates in this study are based on the more

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[5] In practice, this replacement will probably not be executed, given the small difference between Tbat and Tapp.

[6] The MEErP methodology (2011) also introduced a so-called escalation rate that corrects the discount rate for electricity, if 4 % escalation rate is used, it will cancel the 4% discount rate (i.e, calculate with 0% discount rate).

up-to-date PRIMES model (energy price data provided by the European Commission) and are already recalculated to the Net Present Value of year 2015 (see Table 7), therefore no discount rate needs to be applied.

Table 7: Decomposition of electricity generation costs and prices (€ per MWh) historical and forecast values (based on PRIMES with data supplied by the EC services) (inflation corrected to reference year 2015)

	Prices reference Year 2015									
	END USER PRICE (in c€/kWh)									
	2005	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Electricity										
Average price	12.0	13.9	14.7	15.6	16.1	16.4	16.9	16.8	16.7	16.6
Industry	8.6	9.9	9.8	10.0	10.1	10.2	10.3	10.4	10.3	10.3
Households(HH)	15.9	17.5	19.4	20.7	21.3	21.7	22.1	22.0	21.5	21.3
Services	12.9	15.1	16.0	17.4	18.0	18.3	18.7	18.6	18.4	18.2

Electricity cost:

The energy rates applied in the analysis are based on the PRIMES forecasted end user prices for industry and households. Based on Table 7, the following end user prices for 2025 are taken as a representative average price during the economic lifetime of a battery application:

- Industry: 0.101 EUR per kWh.
- Households: 0.213 EUR per kWh.

5.1.3. Product life cycle information

This section includes the data used to model the following life cycle stages:

- Production phase, i.e. raw materials use and manufacturing,
- Distribution phase,
- Use phase,
- End-of-life phase.

5.1.3.1. Production phase

The EcoReport contains life cycle impact assessment (LCIA) data of 55 common materials, such as certain plastics and metals. However, those materials do not cover all the materials needed to manufacture battery cells properly. The latest version of EcoReport dating from 2014 (original EcoReport was developed in 2011) enables the user to enter LCIA data for other materials as “extra materials”.

The extra materials which have been added for this preparatory study were modelled and calculated in SimaPro version 8.52 with version 3.4 of the ecoinvent database. The source of the life cycle inventory (LCI) data of the different battery chemistries is the 2018 version of the

GREET2 Model by UChicago Argonne, LLC[7]. In addition, the PEFCR on rechargeable batteries[8] was used to determine the LCI data records for most of the other extra materials. GREET2 was used to model the chemistries, as GREET2 contains LCI data of more different chemistries than PEF and therefore it was possible to model all the needed chemistries based on GREET2 instead of using a mix of the two sources. An overview of the data set used for the extra materials is shown in Table 8 and Table 9. The LCIA data of the extra materials are presented in Annex A.

In the calculations of the production phase, the impact of auxiliary materials, and the energy use and related emissions which occur during manufacturing have also been added. The data are taken from the LCI of the PEF pilot. Due to lack of other useable data sources the same data have been used for all seven base cases. Table 10 shows an overview of the added manufacturing processes.

Table 8: Data set extra materials: chemistries (modelling all based on GREET2 model)

Chemistries	**LCI data record**	**Amount (/kg product)**	**Unit**
NCM622	NMC622 precursor (see below for LCI)	0.95	kg
	Lithium carbonate {GLO}| production, from concentrated brine | Cut-off, U	0.38	kg
	Electricity, medium voltage {CN}| market group for | Cut-off, U	22.90	MJ
NCM622 precursor	Nickel sulfate {GLO}| market for | Cut-off, U	1.01	kg
	Cobalt {GLO}| market for | Cut-off, U (used as worst proxy for proxy Cobalt Sulfate, like PEF)	0.34	kg
	Manganese sulfate {GLO}| market for | Cut-off, U	0.33	kg
	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	0.88	kg
	Ammonia, liquid {RoW}| market for | Cut-off, U	0.12	kg
	Water, deionised, from tap water, at user {RoW}| market for water, deionised, from tap water, at user | Cut-off, U	0.64	kg
	Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Cut-off, U	0.04	GJ
NCM424	NMC424 precursor (see below for LCI)	0.95	kg
	Lithium carbonate {GLO}| production, from concentrated brine | Cut-off, U	0.38	kg
	Electricity, medium voltage {CN}| market group for | Cut-off, U	22.90	MJ

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[7] https://greet.es.anl.gov/greet.models

[8] http://ec.EURpa.eu/environment/eussd/smgp/pdf/Batteries%20PEFCR%20-%20Life%20Cycle%20Inventory.xlsx

Continuation of Table 8: Data set extra materials: chemistries (modelling all based on GREET2 model)

Chemistries	**LCI data record**	**Amount (/kg product)**	**Unit**
NCM424 precursor	Nickel sulfate {GLO}| market for | Cut-off, U	0.68	kg
	Cobalt {GLO}| market for | Cut-off, U (used as worst proxy for proxy Cobalt Sulfate, like PEF)	0.34	kg
	Manganese sulfate {GLO}| market for | Cut-off, U	0.34	kg
	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	0.90	kg
	Ammonia, liquid {RoW}| market for | Cut-off, U	0.12	kg
	Water, deionised, from tap water, at user {RoW}| market for water, deionised, from tap water, at user | Cut-off, U	0.64	kg
	Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Cut-off, U	0.04	GJ
NCM111	NMC111 precursor (see below for LCI)	0.95	kg
	Lithium carbonate {GLO}| production, from concentrated brine | Cut-off, U	0.38	kg
	Electricity, medium voltage {CN}| market group for | Cut-off, U	22.90	MJ
NCM111 precursor	Nickel sulfate {GLO}| market for | Cut-off, U	0.56	kg
	Cobalt {GLO}| market for | Cut-off, U (used as worst proxy for proxy Cobalt Sulfate, like PEF)	0.56	kg
	Manganese sulfate {GLO}| market for | Cut-off, U	0.55	kg
	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	0.89	kg
	Ammonia, liquid {RoW}| market for | Cut-off, U	0.12	kg
	Water, deionised, from tap water, at user {RoW}| market for water, deionised, from tap water, at user | Cut-off, U	0.64	kg
	Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Cut-off, U	0.04	GJ

Continuation of Table 8: Data set extra materials: chemistries (modelling all based on GREET2 model)

Chemistries	**LCI data record**	**Amount (/kg product)**	**Unit**
NCM532 [9]	NMC532 precursor (see below for LCI)	0.95	kg
	Lithium carbonate {GLO}| production, from concentrated brine | Cut-off, U	0.38	kg
	Electricity, medium voltage {CN}| market group for | Cut-off, U	22.90	MJ
NCM532 precursor [9]	Nickel sulfate {GLO}| market for | Cut-off, U	0.84	kg
	Cobalt {GLO}| market for | Cut-off, U (used as worst proxy for proxy Cobalt Sulfate, like PEF)	0.34	kg
	Manganese sulfate {GLO}| market for | Cut-off, U	0.49	kg
	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	0.89	kg
	Ammonia, liquid {RoW}| market for | Cut-off, U	0.12	kg
	Water, deionised, from tap water, at user {RoW}| market for water, deionised, from tap water, at user | Cut-off, U	0.64	kg
	Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Cut-off, U	0.04	GJ
LMO	Lithium carbonate {GLO}| production, from concentrated brine | Cut-off, U	0.20	kg
	Manganese(III) oxide {GLO}| market for | Cut-off, U	0.87	kg
	Electricity, medium voltage {CN}| market group for | Cut-off, U	0.02	MJ
	Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Cut-off, U	0.01	GJ
NCA [10]	Lithium hydroxide {GLO}| market for | Cut-off, U	0.25	kg
	Oxygen, liquid {RoW}| market for | Cut-off, U	0.04	kg
	NCA (80/15/5) precursor (see below for LCI)	0.95	kg
	Electricity, medium voltage {CN}| market group for | Cut-off, U	26.18	MJ

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[9] NCM532 and its precursor are not such modelled within the GREET2 model. Therefore, the LCI of NCM532 is drafted based upon the modelling of the NCM compositions that are in GREET2 and the chemical equation of NCM532.

[10] In the BOM an amount of NCA (80/15/5) as well as NCA (82/15/3) is included. In the GREET2 model only NCA (80/15/5) is included, therefore the two NCA compositions are assumed as identical and only modelled as NCA (80/15/5).

Continuation of Table 8: Data set extra materials: chemistries (modelling all based on GREET2 model)

Chemistries	**LCI data record**	**Amount (/kg product)**	**Unit**
NCA precursor	Ammonia, liquid {RoW}| market for | Cut-off, U	0.37	kg
	Nickel sulfate {GLO}| market for | Cut-off, U	1.36	kg
	Cobalt {GLO}| market for | Cut-off, U (used as worst proxy for proxy Cobalt Sulfate, like PEF)	0.26	kg
	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	0.88	kg
	Aluminium sulfate, without water, in 4.33% aluminium solution state {GLO}| market for | Cut-off, U	0.09	kg
	Water, deionised, from tap water, at user {RoW}| market for water, deionised, from tap water, at user | Cut-off, U	0.64	kg
	Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Cut-off, U	0.04	GJ
LFP	Lithium hydroxide {GLO}| market for | Cut-off, U	0.27	kg
	Phosphoric acid, industrial grade, without water, in 85% solution state {GLO}| market for | Cut-off, U	0.37	kg
	Iron sulfate {GLO}| market for | Cut-off, U	0.57	kg
	Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Cut-off, U	0.03	GJ

Table 9: Data set extra materials: other

Extra material: other	**LCI data record**	**Based on**
Carbon	Carbon black {GLO}| market for | Cut-off, U	PEF
PVDF	Polyvinylfluoride {GLO}| market for | Alloc Rec, U (adapted to PVDF, no Polyvinylidene fluoride in ecoinvent database available)	-
Graphite	Carbon black {GLO}| market for | Cut-off, U (as proxy)	PEF
CMC	Carboxymethyl cellulose, powder {GLO}| market for | Cut-off, U	-
LiPF6	Lithium hydroxide {GLO}| market for | Cut-off, U (as proxy)	PEF
LiFSI	Lithium hexafluorophosphate {GLO}| market for | Cut-off, U (as proxy)	-
EC (Ethylene carbonate)	Ethylene carbonate {GLO}| market for | Cut-off, U	PEF
DMC (Dimethyl carbonate)	Dimethyl carbonate {GLO}| market for dimethyl carbonate | Cut-off, U	PEF
EMC (Ethyl methyl carbonate)	Dimethyl carbonate {GLO}| market for dimethyl carbonate | Cut-off, U (as proxy)	PEF

Continuation of Table 9: Data set extra materials: other

Extra material: other	LCI data record	Based on
PC (Propylene carbonate)	Polycarbonate {GLO}| market for | Cut-off, U (as proxy)	PEF
Hydrochloric acid	Hydrochloric acid, without water, in 30% solution state {RER}| market for | Cut-off, U	PEF
n-Methylpyrolidone (NMP)	N-methyl-2-pyrrolidone {GLO}| market for | Cut-off, U	PEF

Table 10: LCI data auxiliary materials and the energy use during manufacturing, based on PEF.

Input manufacturing	**Amount (/ kg battery)**	**Unit**
n-Methylpyrolidone (NMP)	0.143	kg
Hydrochloric acid mix (100%)	0.37	kg
Power electrode	40	MJ
Power cell forming	1.2	MJ
Power battery assembly	0.001	MJ

In addition to the data sets presented above, the following assumptions have been made when composing the EcoReports for the seven BCs:

- For the SBR anode binder (position number 17 in the EcoReport) the standard EcoReport material ABS is used as proxy as SBR.
- For the sandwich materials composed of polyethylene and aluminium oxide coating used for cell separators (pos. nr. 31, 32 and 34) the standard EcoReport material 'aluminium sheet/extrusion' is assumed as worst case proxy.
- For the nickel-plated iron case of the cell packaging (pos. nr. 50) cast iron is chosen as proxy based on the assumption that nickel already is included in position number 48.

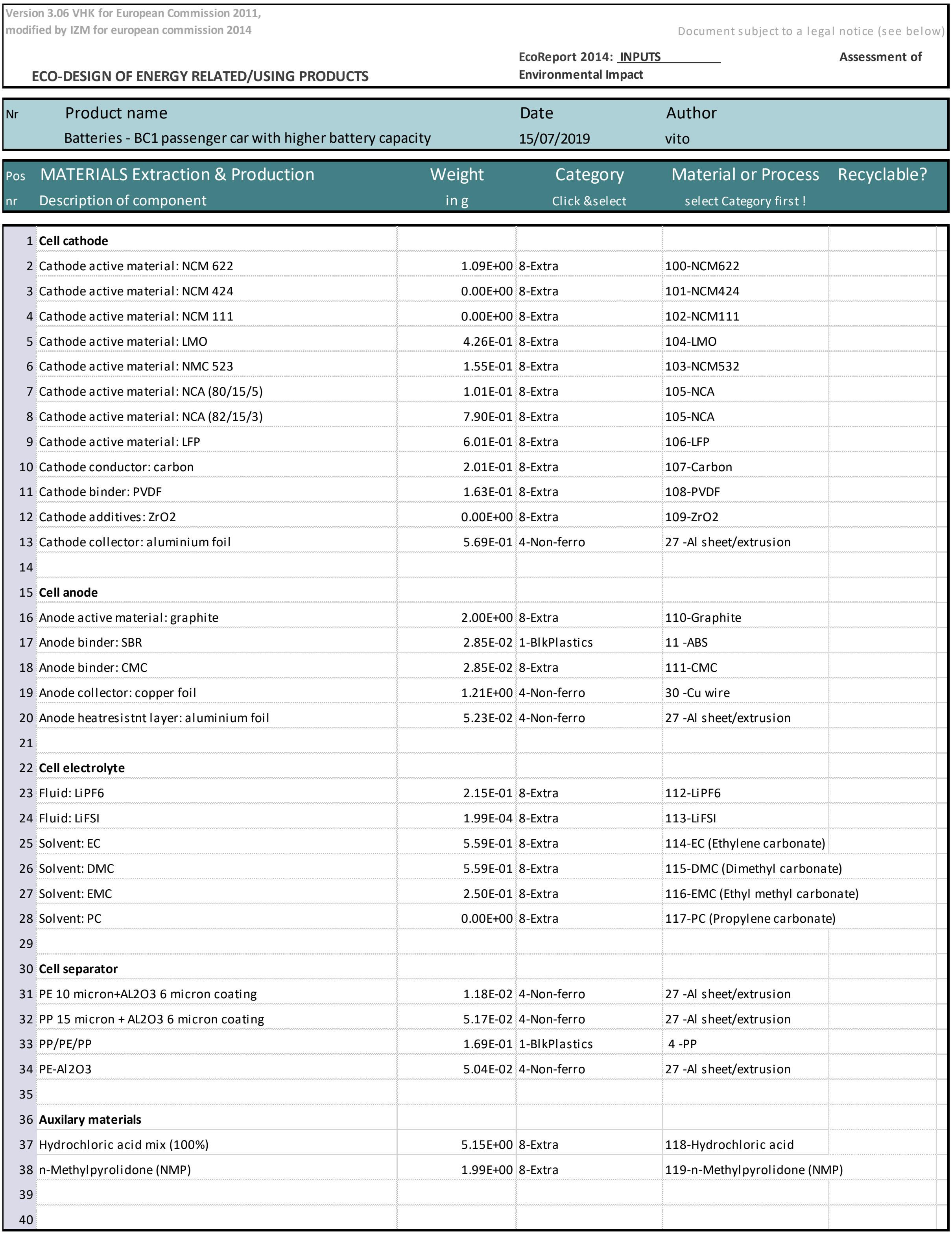
The following subsections provides the Bill-of-Materials (BOM) information per selected BC. The BOM information is provided in the EcoReport format and are based on the data presented in Table 3 and 4 of subtask 4.2 (see section 4.2.1. of Task 4 report).

5.1.3.1.1. BOM BC1 – passenger car BEV with a higher battery capacity

The calculation of the weight of the battery components is based on:

- a nominal battery energy or battery capacity of 80 kWh,
- a total of 43 680 kWh delivered over an economical lifetime of 13 years (functional units),
- 1 battery application system with 1 battery system with a service lifetime of 14.40 years, thus meaning no replacement needed,
- with a battery weight of 609 kg,
- resulting in a conversion to 1 kWh of functional unit of 0.014 kg/kWh.

Table 11: BOM BC1 – passenger car BEV with a higher battery capacity (per FU)



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ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

Nr	Product name	Date	Author
	Batteries - BC1 passenger car with higher battery capacity	15/07/2019	vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**Cell cathode**				
2	Cathode active material: NCM 622	1.09E+00	8-Extra	100-NCM622	
3	Cathode active material: NCM 424	0.00E+00	8-Extra	101-NCM424	
4	Cathode active material: NCM 111	0.00E+00	8-Extra	102-NCM111	
5	Cathode active material: LMO	4.26E-01	8-Extra	104-LMO	
6	Cathode active material: NMC 523	1.55E-01	8-Extra	103-NCM532	
7	Cathode active material: NCA (80/15/5)	1.01E-01	8-Extra	105-NCA	
8	Cathode active material: NCA (82/15/3)	7.90E-01	8-Extra	105-NCA	
9	Cathode active material: LFP	6.01E-01	8-Extra	106-LFP	
10	Cathode conductor: carbon	2.01E-01	8-Extra	107-Carbon	
11	Cathode binder: PVDF	1.63E-01	8-Extra	108-PVDF	
12	Cathode additives: ZrO2	0.00E+00	8-Extra	109-ZrO2	
13	Cathode collector: aluminium foil	5.69E-01	4-Non-ferro	27 -Al sheet/extrusion	
14					
15	**Cell anode**				
16	Anode active material: graphite	2.00E+00	8-Extra	110-Graphite	
17	Anode binder: SBR	2.85E-02	1-BlkPlastics	11 -ABS	
18	Anode binder: CMC	2.85E-02	8-Extra	111-CMC	
19	Anode collector: copper foil	1.21E+00	4-Non-ferro	30 -Cu wire	
20	Anode heatresistnt layer: aluminium foil	5.23E-02	4-Non-ferro	27 -Al sheet/extrusion	
21					
22	**Cell electrolyte**				
23	Fluid: LiPF6	2.15E-01	8-Extra	112-LiPF6	
24	Fluid: LiFSI	1.99E-04	8-Extra	113-LiFSI	
25	Solvent: EC	5.59E-01	8-Extra	114-EC (Ethylene carbonate)	
26	Solvent: DMC	5.59E-01	8-Extra	115-DMC (Dimethyl carbonate)	
27	Solvent: EMC	2.50E-01	8-Extra	116-EMC (Ethyl methyl carbonate)	
28	Solvent: PC	0.00E+00	8-Extra	117-PC (Propylene carbonate)	
29					
30	**Cell separator**				
31	PE 10 micron+AL2O3 6 micron coating	1.18E-02	4-Non-ferro	27 -Al sheet/extrusion	
32	PP 15 micron + AL2O3 6 micron coating	5.17E-02	4-Non-ferro	27 -Al sheet/extrusion	
33	PP/PE/PP	1.69E-01	1-BlkPlastics	4 -PP	
34	PE-Al2O3	5.04E-02	4-Non-ferro	27 -Al sheet/extrusion	
35					
36	**Auxilary materials**				
37	Hydrochloric acid mix (100%)	5.15E+00	8-Extra	118-Hydrochloric acid	
38	n-Methylpyrolidone (NMP)	1.99E+00	8-Extra	119-n-Methylpyrolidone (NMP)	
39					
40					

Continuation of Table 11: BOM BC1 – passenger car BEV with a higher battery capacity (per FU)

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
41	**Cell packaging**				
42	Tab with film: Al Tab	0.00E+00	4-Non-ferro	27 -Al sheet/extrusion	
43	Tab with film: Ni Tab	0.00E+00	5-Coating	41 -Cu/Ni/Cr plating	
44	Exterior covering: PET/Ny/Al/PP/ Laminate	9.97E-03	1-BlkPlastics	10 -PET	
45	Collector parts: Al leads	1.11E-02	4-Non-ferro	27 -Al sheet/extrusion	
46	Collector parts: Cu leads	3.22E-02	4-Non-ferro	30 -Cu wire	
47	Collector parts: Plastic fasteners/cover	2.84E-02	1-BlkPlastics	2 -HDPE	
48	Cover: Aluminum	2.71E-01	4-Non-ferro	27 -Al sheet/extrusion	
49	Case: Aluminium	5.30E-01	4-Non-ferro	27 -Al sheet/extrusion	
50	Case: Ni plated Iron	2.85E-01	3-Ferro	24 -Cast iron	
51					
52	**Module**				
53	Al	3.63E-01	4-Non-ferro	27 -Al sheet/extrusion	
54	PP/PE	1.95E-01	1-BlkPlastics	4 -PP	
55	Steel	1.32E-01	3-Ferro	22 -St sheet galv.	
56	Electronics	6.97E-03	6-Electronics	98 -controller board	
57					
58	**System - BMS**				
59	Steel	2.23E-01	3-Ferro	22 -St sheet galv.	
60	Copper	2.79E-01	4-Non-ferro	30 -Cu wire	
61	Printed circuit board	5.57E-02	6-Electronics	52 -PWB 6 lay 2 kg/m2	
62					
63	**System - thermal management**				
64	Al	5.02E-01	4-Non-ferro	27 -Al sheet/extrusion	
65	Steel	5.57E-02	3-Ferro	22 -St sheet galv.	
66					
67	**System packaging**				
68	Al	1.17E+00	4-Non-ferro	27 -Al sheet/extrusion	
69	PP/PE	8.36E-02	1-BlkPlastics	4 -PP	
70	Steel	3.34E-01	3-Ferro	22 -St sheet galv.	
71	WEEE	8.36E-02	6-Electronics	52 -PWB 6 lay 2 kg/m2	
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5.1.3.1.2. BOM BC2 – passenger car BEV with a lower battery capacity

The calculation of the weight of the battery components is based on:

- a nominal battery energy or battery capacity of 40 kWh,
- a total of 29 568 kWh delivered over an economical lifetime of 14 years (functional units),
- 2 battery application systems with 1 battery systems with a service lifetime of 13.43 years, thus meaning 1 replacement needed[11],
- with a battery weight of 304 kg,
- resulting in a conversion to 1 kWh of functional unit of 0.021 kg/kWh.

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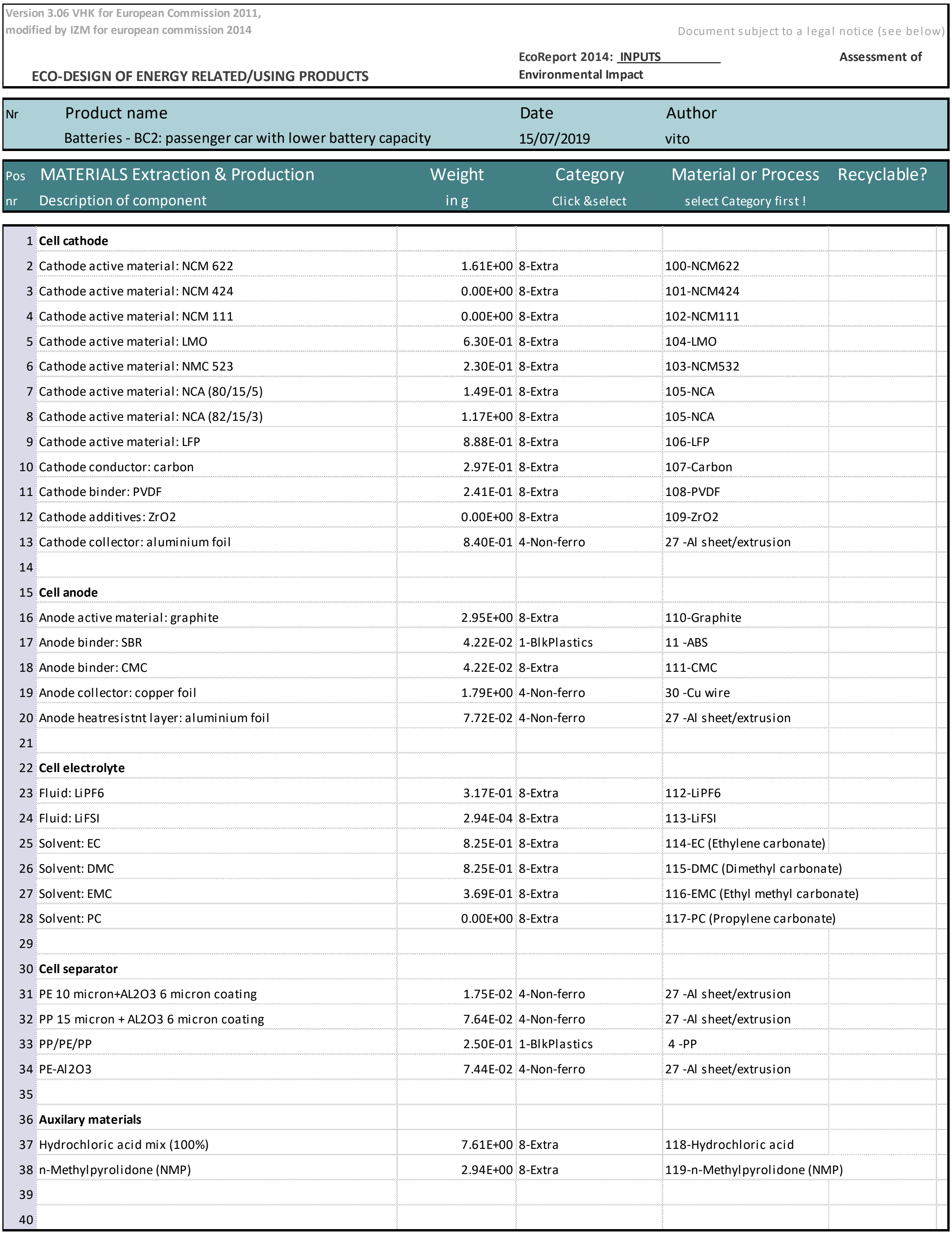
[11] In practice, this replacement will probably not be executed, given the small difference between the service lifetime of the application and the lifetime of the battery system.

Table 12: BOM BC2 – passenger car BEV with a lower battery capacity (per FU)



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ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

Nr	Product name	Date	Author
	Batteries - BC2: passenger car with lower battery capacity	15/07/2019	vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**Cell cathode**				
2	Cathode active material: NCM 622	1.61E+00	8-Extra	100-NCM622	
3	Cathode active material: NCM 424	0.00E+00	8-Extra	101-NCM424	
4	Cathode active material: NCM 111	0.00E+00	8-Extra	102-NCM111	
5	Cathode active material: LMO	6.30E-01	8-Extra	104-LMO	
6	Cathode active material: NMC 523	2.30E-01	8-Extra	103-NCM532	
7	Cathode active material: NCA (80/15/5)	1.49E-01	8-Extra	105-NCA	
8	Cathode active material: NCA (82/15/3)	1.17E+00	8-Extra	105-NCA	
9	Cathode active material: LFP	8.88E-01	8-Extra	106-LFP	
10	Cathode conductor: carbon	2.97E-01	8-Extra	107-Carbon	
11	Cathode binder: PVDF	2.41E-01	8-Extra	108-PVDF	
12	Cathode additives: ZrO2	0.00E+00	8-Extra	109-ZrO2	
13	Cathode collector: aluminium foil	8.40E-01	4-Non-ferro	27 -Al sheet/extrusion	
14					
15	**Cell anode**				
16	Anode active material: graphite	2.95E+00	8-Extra	110-Graphite	
17	Anode binder: SBR	4.22E-02	1-BlkPlastics	11 -ABS	
18	Anode binder: CMC	4.22E-02	8-Extra	111-CMC	
19	Anode collector: copper foil	1.79E+00	4-Non-ferro	30 -Cu wire	
20	Anode heatresistnt layer: aluminium foil	7.72E-02	4-Non-ferro	27 -Al sheet/extrusion	
21					
22	**Cell electrolyte**				
23	Fluid: LiPF6	3.17E-01	8-Extra	112-LiPF6	
24	Fluid: LiFSI	2.94E-04	8-Extra	113-LiFSI	
25	Solvent: EC	8.25E-01	8-Extra	114-EC (Ethylene carbonate)	
26	Solvent: DMC	8.25E-01	8-Extra	115-DMC (Dimethyl carbonate)	
27	Solvent: EMC	3.69E-01	8-Extra	116-EMC (Ethyl methyl carbonate)	
28	Solvent: PC	0.00E+00	8-Extra	117-PC (Propylene carbonate)	
29					
30	**Cell separator**				
31	PE 10 micron+AL2O3 6 micron coating	1.75E-02	4-Non-ferro	27 -Al sheet/extrusion	
32	PP 15 micron + AL2O3 6 micron coating	7.64E-02	4-Non-ferro	27 -Al sheet/extrusion	
33	PP/PE/PP	2.50E-01	1-BlkPlastics	4 -PP	
34	PE-Al2O3	7.44E-02	4-Non-ferro	27 -Al sheet/extrusion	
35					
36	**Auxilary materials**				
37	Hydrochloric acid mix (100%)	7.61E+00	8-Extra	118-Hydrochloric acid	
38	n-Methylpyrolidone (NMP)	2.94E+00	8-Extra	119-n-Methylpyrolidone (NMP)	
39					
40					

Continuation of Table 12: BOM BC2 – passenger car BEV with a lower battery capacity (per FU)

Pos	MATERIALS Extraction & Production	Weight	Category	Material or Process	Recyclable?
nr	Description of component	in g	Click &select	select Category first !	
41	**Cell packaging**				
42	Tab with film: Al Tab	0.00E+00	4-Non-ferro	27 -Al sheet/extrusion	
43	Tab with film: Ni Tab	0.00E+00	5-Coating	41 -Cu/Ni/Cr plating	
44	Exterior covering: PET/Ny/Al/PP/ Laminate	1.47E-02	1-BlkPlastics	10 -PET	
45	Collector parts: Al leads	1.65E-02	4-Non-ferro	27 -Al sheet/extrusion	
46	Collector parts: Cu leads	4.75E-02	4-Non-ferro	30 -Cu wire	
47	Collector parts: Plastic fasteners/cover	4.19E-02	1-BlkPlastics	2 -HDPE	
48	Cover: Aluminum	4.00E-01	4-Non-ferro	27 -Al sheet/extrusion	
49	Case: Aluminium	7.82E-01	4-Non-ferro	27 -Al sheet/extrusion	
50	Case: Ni plated Iron	4.20E-01	3-Ferro	24 -Cast iron	
51					
52	**Module**				
53	Al	5.36E-01	4-Non-ferro	27 -Al sheet/extrusion	
54	PP/PE	2.88E-01	1-BlkPlastics	4 -PP	
55	Steel	1.94E-01	3-Ferro	22 -St sheet galv.	
56	Electronics	1.03E-02	6-Electronics	98 -controller board	
57					
58	**System - BMS**				
59	Steel	3.29E-01	3-Ferro	22 -St sheet galv.	
60	Copper	4.12E-01	4-Non-ferro	30 -Cu wire	
61	Printed circuit board	8.23E-02	6-Electronics	52 -PWB 6 lay 2 kg/m2	
62					
63	**System - thermal management**				
64	Al	7.41E-01	4-Non-ferro	27 -Al sheet/extrusion	
65	Steel	8.23E-02	3-Ferro	22 -St sheet galv.	
66					
67	**System packaging**				
68	Al	1.73E+00	4-Non-ferro	27 -Al sheet/extrusion	
69	PP/PE	1.23E-01	1-BlkPlastics	4 -PP	
70	Steel	4.94E-01	3-Ferro	22 -St sheet galv.	
71	WEEE	1.23E-01	6-Electronics	52 -PWB 6 lay 2 kg/m2	
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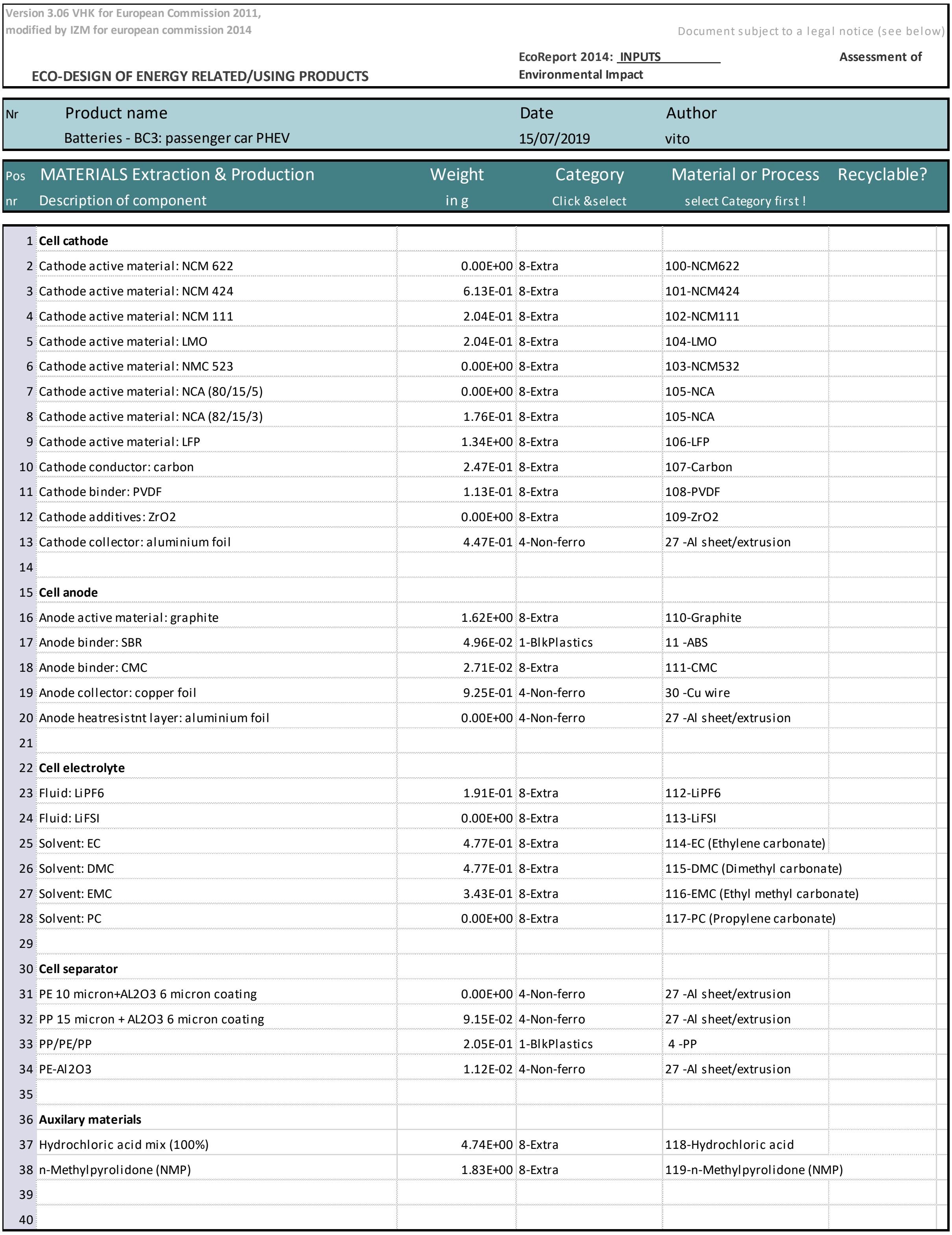
5.1.3.1.3. BOM BC3 – passenger car PHEV

The calculation of the weight of the battery components is based on:

- a nominal battery energy or battery capacity of 12 kWh,
- a total of 19 656 kWh delivered over an economical lifetime of 13 years (functional units),
- 2 battery application system with 1 battery system with a service lifetime of 10.67 years, thus meaning 1 replacement needed,
- with a battery weight of 126 kg,
- resulting in a conversion to 1 kWh of functional unit of 0.013 kg/kWh.

Table 13: BOM BC3 – passenger car PHEV (per FU)



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ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

Nr	Product name	Date	Author
	Batteries - BC3: passenger car PHEV	15/07/2019	vito

Pos	MATERIALS Extraction & Production	Weight	Category	Material or Process	Recyclable?
nr	Description of component	in g	Click &select	select Category first !	
1	**Cell cathode**				
2	Cathode active material: NCM 622	0.00E+00	8-Extra	100-NCM622	
3	Cathode active material: NCM 424	6.13E-01	8-Extra	101-NCM424	
4	Cathode active material: NCM 111	2.04E-01	8-Extra	102-NCM111	
5	Cathode active material: LMO	2.04E-01	8-Extra	104-LMO	
6	Cathode active material: NMC 523	0.00E+00	8-Extra	103-NCM532	
7	Cathode active material: NCA (80/15/5)	0.00E+00	8-Extra	105-NCA	
8	Cathode active material: NCA (82/15/3)	1.76E-01	8-Extra	105-NCA	
9	Cathode active material: LFP	1.34E+00	8-Extra	106-LFP	
10	Cathode conductor: carbon	2.47E-01	8-Extra	107-Carbon	
11	Cathode binder: PVDF	1.13E-01	8-Extra	108-PVDF	
12	Cathode additives: ZrO2	0.00E+00	8-Extra	109-ZrO2	
13	Cathode collector: aluminium foil	4.47E-01	4-Non-ferro	27 -Al sheet/extrusion	
14					
15	**Cell anode**				
16	Anode active material: graphite	1.62E+00	8-Extra	110-Graphite	
17	Anode binder: SBR	4.96E-02	1-BlkPlastics	11 -ABS	
18	Anode binder: CMC	2.71E-02	8-Extra	111-CMC	
19	Anode collector: copper foil	9.25E-01	4-Non-ferro	30 -Cu wire	
20	Anode heatresistnt layer: aluminium foil	0.00E+00	4-Non-ferro	27 -Al sheet/extrusion	
21					
22	**Cell electrolyte**				
23	Fluid: LiPF6	1.91E-01	8-Extra	112-LiPF6	
24	Fluid: LiFSI	0.00E+00	8-Extra	113-LiFSI	
25	Solvent: EC	4.77E-01	8-Extra	114-EC (Ethylene carbonate)	
26	Solvent: DMC	4.77E-01	8-Extra	115-DMC (Dimethyl carbonate)	
27	Solvent: EMC	3.43E-01	8-Extra	116-EMC (Ethyl methyl carbonate)	
28	Solvent: PC	0.00E+00	8-Extra	117-PC (Propylene carbonate)	
29					
30	**Cell separator**				
31	PE 10 micron+AL2O3 6 micron coating	0.00E+00	4-Non-ferro	27 -Al sheet/extrusion	
32	PP 15 micron + AL2O3 6 micron coating	9.15E-02	4-Non-ferro	27 -Al sheet/extrusion	
33	PP/PE/PP	2.05E-01	1-BlkPlastics	4 -PP	
34	PE-Al2O3	1.12E-02	4-Non-ferro	27 -Al sheet/extrusion	
35					
36	**Auxilary materials**				
37	Hydrochloric acid mix (100%)	4.74E+00	8-Extra	118-Hydrochloric acid	
38	n-Methylpyrolidone (NMP)	1.83E+00	8-Extra	119-n-Methylpyrolidone (NMP)	
39					
40					

Continuation of Table 13: BOM BC3 – passenger car PHEV (per FU)

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
41	**Cell packaging**				
42	Tab with film: Al Tab	2.54E-02	4-Non-ferro	27 -Al sheet/extrusion	
43	Tab with film: Ni Tab	8.14E-02	5-Coating	41 -Cu/Ni/Cr plating	
44	Exterior covering: PET/Ny/Al/PP/ Laminate	9.77E-02	1-BlkPlastics	10 -PET	
45	Collector parts: Al leads	1.43E-02	4-Non-ferro	27 -Al sheet/extrusion	
46	Collector parts: Cu leads	4.29E-02	4-Non-ferro	30 -Cu wire	
47	Collector parts: Plastic fasteners/cover	1.91E-02	1-BlkPlastics	2 -HDPE	
48	Cover: Aluminum	1.15E-01	4-Non-ferro	27 -Al sheet/extrusion	
49	Case: Aluminium	7.63E-01	4-Non-ferro	27 -Al sheet/extrusion	
50	Case: Ni plated Iron	6.32E-02	3-Ferro	24 -Cast iron	
51					
52	**Module**				
53	Al	3.88E-01	4-Non-ferro	27 -Al sheet/extrusion	
54	PP/PE	1.20E-01	1-BlkPlastics	4 -PP	
55	Steel	1.26E-01	3-Ferro	22 -St sheet galv.	
56	Electronics	6.41E-03	6-Electronics	98 -controller board	
57					
58	**System - BMS**				
59	Steel	2.56E-01	3-Ferro	22 -St sheet galv.	
60	Copper	3.21E-01	4-Non-ferro	30 -Cu wire	
61	Printed circuit board	6.41E-02	6-Electronics	52 -PWB 6 lay 2 kg/m2	
62					
63	**System - thermal management**				
64	Al	5.77E-01	4-Non-ferro	27 -Al sheet/extrusion	
65	Steel	6.41E-02	3-Ferro	22 -St sheet galv.	
66					
67	**System packaging**				
68	Al	1.35E+00	4-Non-ferro	27 -Al sheet/extrusion	
69	PP/PE	9.62E-02	1-BlkPlastics	4 -PP	
70	Steel	3.85E-01	3-Ferro	22 -St sheet galv.	
71	WEEE	9.62E-02	6-Electronics	52 -PWB 6 lay 2 kg/m2	
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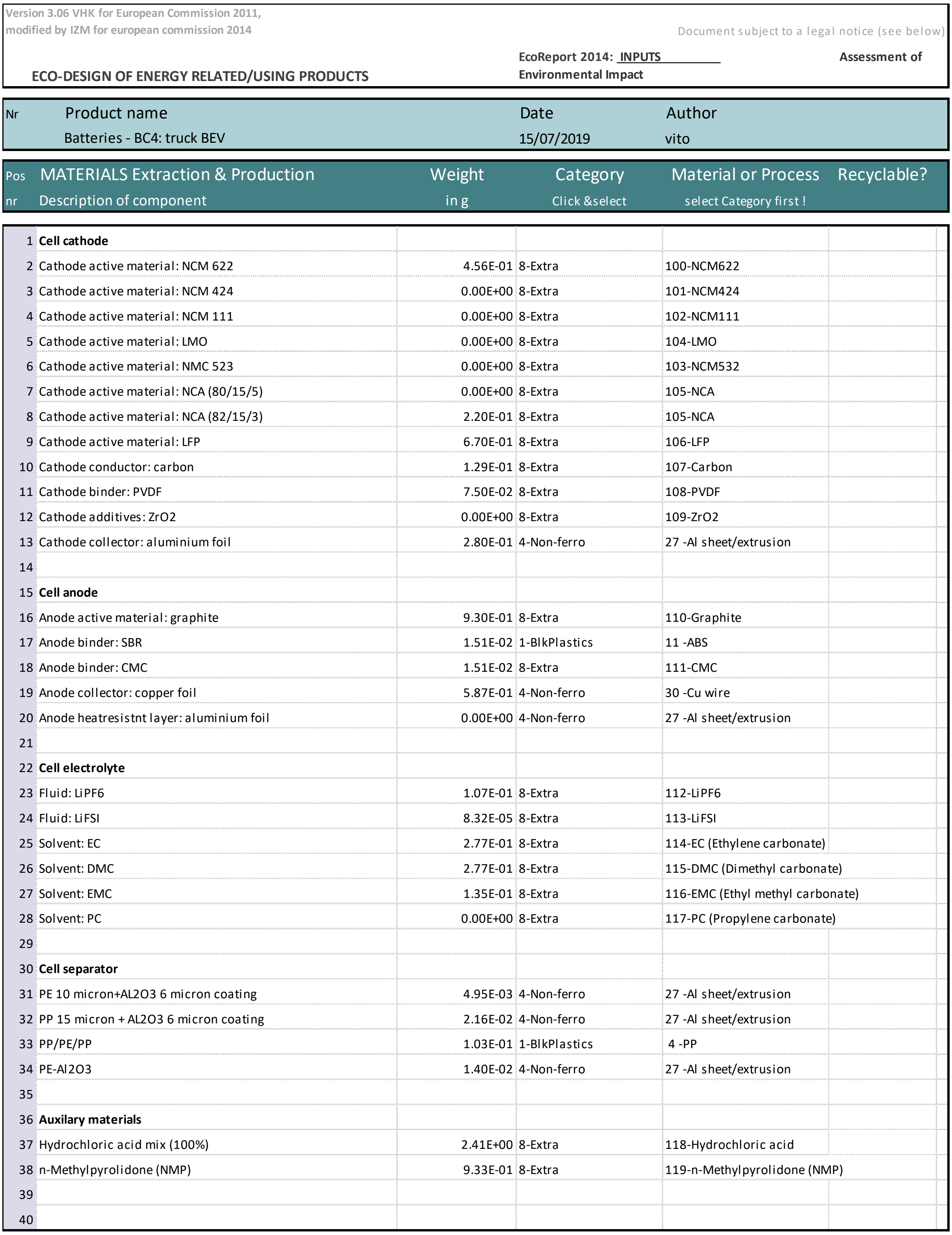
5.1.3.1.4. BOM BC4 – truck BEV

The calculation of the weight of the battery components is based on:

- a nominal battery energy or battery capacity of 30 kWh,
- a total of 940 800 kWh delivered over an economical lifetime of 14 years (functional units),
- 2 battery application system with 12 battery systems with a service lifetime of 8.04 years, thus meaning 1 replacement needed,
- with a battery weight of 256 kg,
- resulting in a conversion to 1 kWh of functional unit of 0.007 kg/kWh.

Table 14: BOM BC4 – truck BEV (per FU)



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Environmental Impact

Assessment of

Nr	Product name	Date	Author
	Batteries - BC4: truck BEV	15/07/2019	vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**Cell cathode**				
2	Cathode active material: NCM 622	4.56E-01	8-Extra	100-NCM622	
3	Cathode active material: NCM 424	0.00E+00	8-Extra	101-NCM424	
4	Cathode active material: NCM 111	0.00E+00	8-Extra	102-NCM111	
5	Cathode active material: LMO	0.00E+00	8-Extra	104-LMO	
6	Cathode active material: NMC 523	0.00E+00	8-Extra	103-NCM532	
7	Cathode active material: NCA (80/15/5)	0.00E+00	8-Extra	105-NCA	
8	Cathode active material: NCA (82/15/3)	2.20E-01	8-Extra	105-NCA	
9	Cathode active material: LFP	6.70E-01	8-Extra	106-LFP	
10	Cathode conductor: carbon	1.29E-01	8-Extra	107-Carbon	
11	Cathode binder: PVDF	7.50E-02	8-Extra	108-PVDF	
12	Cathode additives: ZrO2	0.00E+00	8-Extra	109-ZrO2	
13	Cathode collector: aluminium foil	2.80E-01	4-Non-ferro	27 -Al sheet/extrusion	
14					
15	**Cell anode**				
16	Anode active material: graphite	9.30E-01	8-Extra	110-Graphite	
17	Anode binder: SBR	1.51E-02	1-BlkPlastics	11 -ABS	
18	Anode binder: CMC	1.51E-02	8-Extra	111-CMC	
19	Anode collector: copper foil	5.87E-01	4-Non-ferro	30 -Cu wire	
20	Anode heatresistnt layer: aluminium foil	0.00E+00	4-Non-ferro	27 -Al sheet/extrusion	
21					
22	**Cell electrolyte**				
23	Fluid: LiPF6	1.07E-01	8-Extra	112-LiPF6	
24	Fluid: LiFSI	8.32E-05	8-Extra	113-LiFSI	
25	Solvent: EC	2.77E-01	8-Extra	114-EC (Ethylene carbonate)	
26	Solvent: DMC	2.77E-01	8-Extra	115-DMC (Dimethyl carbonate)	
27	Solvent: EMC	1.35E-01	8-Extra	116-EMC (Ethyl methyl carbonate)	
28	Solvent: PC	0.00E+00	8-Extra	117-PC (Propylene carbonate)	
29					
30	**Cell separator**				
31	PE 10 micron+AL2O3 6 micron coating	4.95E-03	4-Non-ferro	27 -Al sheet/extrusion	
32	PP 15 micron + AL2O3 6 micron coating	2.16E-02	4-Non-ferro	27 -Al sheet/extrusion	
33	PP/PE/PP	1.03E-01	1-BlkPlastics	4 -PP	
34	PE-Al2O3	1.40E-02	4-Non-ferro	27 -Al sheet/extrusion	
35					
36	**Auxilary materials**				
37	Hydrochloric acid mix (100%)	2.41E+00	8-Extra	118-Hydrochloric acid	
38	n-Methylpyrolidone (NMP)	9.33E-01	8-Extra	119-n-Methylpyrolidone (NMP)	
39					
40					

Continuation of *Table 14: BOM BC4 – truck BEV (per FU)*

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
41	**Cell packaging**				
42	Tab with film: Al Tab	0.00E+00	4-Non-ferro	27 -Al sheet/extrusion	
43	Tab with film: Ni Tab	0.00E+00	5-Coating	41 -Cu/Ni/Cr plating	
44	Exterior covering: PET/Ny/Al/PP/ Laminate	4.16E-03	1-BlkPlastics	10 -PET	
45	Collector parts: Al leads	7.17E-03	4-Non-ferro	27 -Al sheet/extrusion	
46	Collector parts: Cu leads	2.15E-02	4-Non-ferro	30 -Cu wire	
47	Collector parts: Plastic fasteners/cover	9.57E-03	1-BlkPlastics	2 -HDPE	
48	Cover: Aluminum	7.27E-02	4-Non-ferro	27 -Al sheet/extrusion	
49	Case: Aluminium	3.83E-01	4-Non-ferro	27 -Al sheet/extrusion	
50	Case: Ni plated Iron	7.93E-02	3-Ferro	24 -Cast iron	
51					
52	**Module**				
53	Al	1.86E-01	4-Non-ferro	27 -Al sheet/extrusion	
54	PP/PE	7.43E-02	1-BlkPlastics	4 -PP	
55	Steel	6.31E-02	3-Ferro	22 -St sheet galv.	
56	Electronics	3.26E-03	6-Electronics	98 -controller board	
57					
58	**System - BMS**				
59	Steel	1.04E-01	3-Ferro	22 -St sheet galv.	
60	Copper	1.30E-01	4-Non-ferro	30 -Cu wire	
61	Printed circuit board	2.61E-02	6-Electronics	52 -PWB 6 lay 2 kg/m2	
62					
63	**System - thermal management**				
64	Al	2.35E-01	4-Non-ferro	27 -Al sheet/extrusion	
65	Steel	2.61E-02	3-Ferro	22 -St sheet galv.	
66					
67	**System packaging**				
68	Al	5.48E-01	4-Non-ferro	27 -Al sheet/extrusion	
69	PP/PE	3.91E-02	1-BlkPlastics	4 -PP	
70	Steel	1.57E-01	3-Ferro	22 -St sheet galv.	
71	WEEE	3.91E-02	6-Electronics	52 -PWB 6 lay 2 kg/m2	
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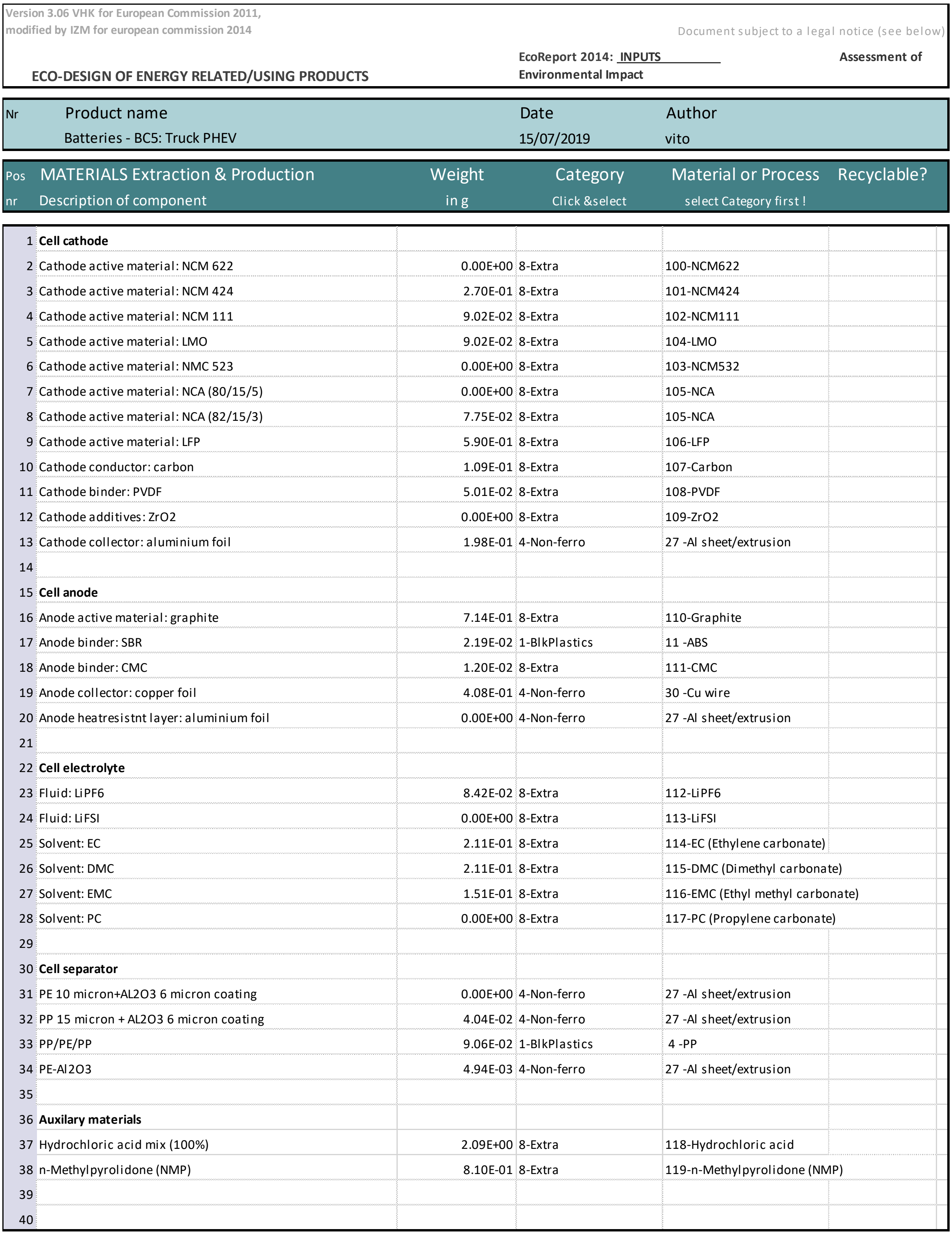
5.1.3.1.5. BOM BC5 – truck PHEV

The calculation of the weight of the battery components is based on:

- a nominal battery energy or battery capacity of 20 kWh,
- a total of 890 400 kWh delivered over an economical lifetime of 12 years (functional units),
- 3 battery application system with 8 battery system with a service lifetime of 5.33 years, thus meaning 2 replacements needed,
- with a battery weight of 210 kg,
- resulting in a conversion to 1 kWh of functional unit of 0.006 kg/kWh.

Table 15: BOM BC5 – truck PHEV (per FU)



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Assessment of

Nr	Product name	Date	Author
	Batteries - BC5: Truck PHEV	15/07/2019	vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**Cell cathode**				
2	Cathode active material: NCM 622	0.00E+00	8-Extra	100-NCM622	
3	Cathode active material: NCM 424	2.70E-01	8-Extra	101-NCM424	
4	Cathode active material: NCM 111	9.02E-02	8-Extra	102-NCM111	
5	Cathode active material: LMO	9.02E-02	8-Extra	104-LMO	
6	Cathode active material: NMC 523	0.00E+00	8-Extra	103-NCM532	
7	Cathode active material: NCA (80/15/5)	0.00E+00	8-Extra	105-NCA	
8	Cathode active material: NCA (82/15/3)	7.75E-02	8-Extra	105-NCA	
9	Cathode active material: LFP	5.90E-01	8-Extra	106-LFP	
10	Cathode conductor: carbon	1.09E-01	8-Extra	107-Carbon	
11	Cathode binder: PVDF	5.01E-02	8-Extra	108-PVDF	
12	Cathode additives: ZrO2	0.00E+00	8-Extra	109-ZrO2	
13	Cathode collector: aluminium foil	1.98E-01	4-Non-ferro	27 -Al sheet/extrusion	
14					
15	**Cell anode**				
16	Anode active material: graphite	7.14E-01	8-Extra	110-Graphite	
17	Anode binder: SBR	2.19E-02	1-BlkPlastics	11 -ABS	
18	Anode binder: CMC	1.20E-02	8-Extra	111-CMC	
19	Anode collector: copper foil	4.08E-01	4-Non-ferro	30 -Cu wire	
20	Anode heatresistnt layer: aluminium foil	0.00E+00	4-Non-ferro	27 -Al sheet/extrusion	
21					
22	**Cell electrolyte**				
23	Fluid: LiPF6	8.42E-02	8-Extra	112-LiPF6	
24	Fluid: LiFSI	0.00E+00	8-Extra	113-LiFSI	
25	Solvent: EC	2.11E-01	8-Extra	114-EC (Ethylene carbonate)	
26	Solvent: DMC	2.11E-01	8-Extra	115-DMC (Dimethyl carbonate)	
27	Solvent: EMC	1.51E-01	8-Extra	116-EMC (Ethyl methyl carbonate)	
28	Solvent: PC	0.00E+00	8-Extra	117-PC (Propylene carbonate)	
29					
30	**Cell separator**				
31	PE 10 micron+AL2O3 6 micron coating	0.00E+00	4-Non-ferro	27 -Al sheet/extrusion	
32	PP 15 micron + AL2O3 6 micron coating	4.04E-02	4-Non-ferro	27 -Al sheet/extrusion	
33	PP/PE/PP	9.06E-02	1-BlkPlastics	4 -PP	
34	PE-Al2O3	4.94E-03	4-Non-ferro	27 -Al sheet/extrusion	
35					
36	**Auxilary materials**				
37	Hydrochloric acid mix (100%)	2.09E+00	8-Extra	118-Hydrochloric acid	
38	n-Methylpyrolidone (NMP)	8.10E-01	8-Extra	119-n-Methylpyrolidone (NMP)	
39					
40					

Continuation of Table 15: BOM BC5 – truck PHEV (per FU)

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
41	**Cell packaging**				
42	Tab with film: Al Tab	1.12E-02	4-Non-ferro	27 -Al sheet/extrusion	
43	Tab with film: Ni Tab	3.59E-02	5-Coating	41 -Cu/Ni/Cr plating	
44	Exterior covering: PET/Ny/Al/PP/ Laminate	4.31E-02	1-BlkPlastics	10 -PET	
45	Collector parts: Al leads	6.32E-03	4-Non-ferro	27 -Al sheet/extrusion	
46	Collector parts: Cu leads	1.90E-02	4-Non-ferro	30 -Cu wire	
47	Collector parts: Plastic fasteners/cover	8.42E-03	1-BlkPlastics	2 -HDPE	
48	Cover: Aluminum	5.09E-02	4-Non-ferro	27 -Al sheet/extrusion	
49	Case: Aluminium	3.37E-01	4-Non-ferro	27 -Al sheet/extrusion	
50	Case: Ni plated Iron	2.79E-02	3-Ferro	24 -Cast iron	
51					
52	**Module**				
53	Al	1.71E-01	4-Non-ferro	27 -Al sheet/extrusion	
54	PP/PE	5.31E-02	1-BlkPlastics	4 -PP	
55	Steel	5.58E-02	3-Ferro	22 -St sheet galv.	
56	Electronics	2.83E-03	6-Electronics	98 -controller board	
57					
58	**System - BMS**				
59	Steel	1.13E-01	3-Ferro	22 -St sheet galv.	
60	Copper	1.42E-01	4-Non-ferro	30 -Cu wire	
61	Printed circuit board	2.83E-02	6-Electronics	52 -PWB 6 lay 2 kg/m2	
62					
63	**System - thermal management**				
64	Al	2.55E-01	4-Non-ferro	27 -Al sheet/extrusion	
65	Steel	2.83E-02	3-Ferro	22 -St sheet galv.	
66					
67	**System packaging**				
68	Al	5.94E-01	4-Non-ferro	27 -Al sheet/extrusion	
69	PP/PE	4.25E-02	1-BlkPlastics	4 -PP	
70	Steel	1.70E-01	3-Ferro	22 -St sheet galv.	
71	WEEE	4.25E-02	6-Electronics	52 -PWB 6 lay 2 kg/m2	
72					
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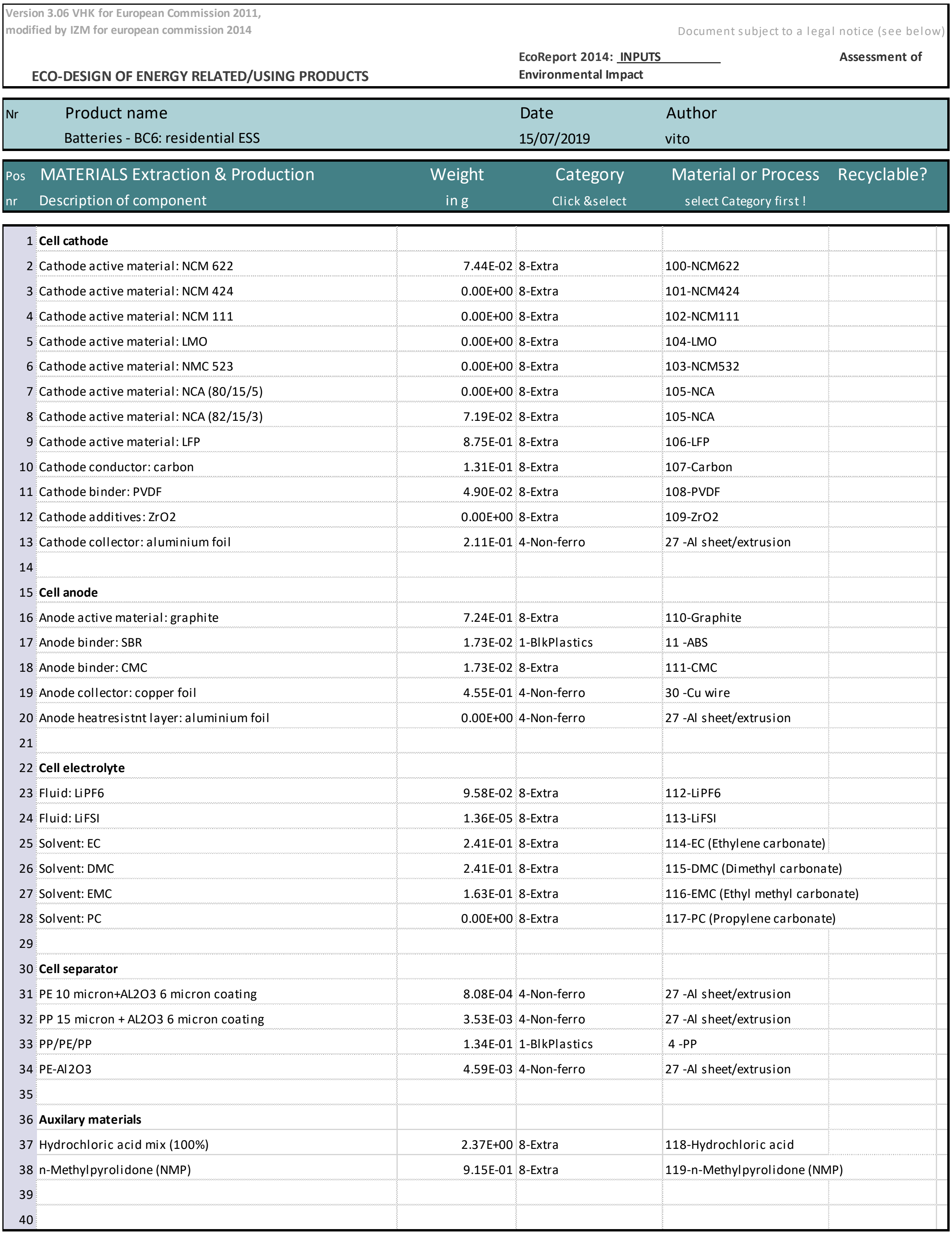
5.1.3.1.6. BOM BC6 – residential ESS

The calculation of the weight of the battery components is based on:

- a nominal battery energy or battery capacity of 10 kWh,
- a total of 40 000 kWh delivered over an economical lifetime of 20 years (functional units),
- 2 battery application system with 1 battery system with a service lifetime of 17.02 years, thus meaning 1 replacement needed,
- with a battery weight of 128 kg,
- resulting in a conversion to 1 kWh of functional unit of 0.006 kg/kWh.

Table 16: BOM BC6 – residential ESS (per FU)



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ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

EcoReport 2014: INPUTS
Environmental Impact

Assessment of

Nr	Product name	Date	Author
	Batteries - BC6: residential ESS	15/07/2019	vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**Cell cathode**				
2	Cathode active material: NCM 622	7.44E-02	8-Extra	100-NCM622	
3	Cathode active material: NCM 424	0.00E+00	8-Extra	101-NCM424	
4	Cathode active material: NCM 111	0.00E+00	8-Extra	102-NCM111	
5	Cathode active material: LMO	0.00E+00	8-Extra	104-LMO	
6	Cathode active material: NMC 523	0.00E+00	8-Extra	103-NCM532	
7	Cathode active material: NCA (80/15/5)	0.00E+00	8-Extra	105-NCA	
8	Cathode active material: NCA (82/15/3)	7.19E-02	8-Extra	105-NCA	
9	Cathode active material: LFP	8.75E-01	8-Extra	106-LFP	
10	Cathode conductor: carbon	1.31E-01	8-Extra	107-Carbon	
11	Cathode binder: PVDF	4.90E-02	8-Extra	108-PVDF	
12	Cathode additives: ZrO2	0.00E+00	8-Extra	109-ZrO2	
13	Cathode collector: aluminium foil	2.11E-01	4-Non-ferro	27 -Al sheet/extrusion	
14					
15	**Cell anode**				
16	Anode active material: graphite	7.24E-01	8-Extra	110-Graphite	
17	Anode binder: SBR	1.73E-02	1-BlkPlastics	11 -ABS	
18	Anode binder: CMC	1.73E-02	8-Extra	111-CMC	
19	Anode collector: copper foil	4.55E-01	4-Non-ferro	30 -Cu wire	
20	Anode heatresistnt layer: aluminium foil	0.00E+00	4-Non-ferro	27 -Al sheet/extrusion	
21					
22	**Cell electrolyte**				
23	Fluid: LiPF6	9.58E-02	8-Extra	112-LiPF6	
24	Fluid: LiFSI	1.36E-05	8-Extra	113-LiFSI	
25	Solvent: EC	2.41E-01	8-Extra	114-EC (Ethylene carbonate)	
26	Solvent: DMC	2.41E-01	8-Extra	115-DMC (Dimethyl carbonate)	
27	Solvent: EMC	1.63E-01	8-Extra	116-EMC (Ethyl methyl carbonate)	
28	Solvent: PC	0.00E+00	8-Extra	117-PC (Propylene carbonate)	
29					
30	**Cell separator**				
31	PE 10 micron+AL2O3 6 micron coating	8.08E-04	4-Non-ferro	27 -Al sheet/extrusion	
32	PP 15 micron + AL2O3 6 micron coating	3.53E-03	4-Non-ferro	27 -Al sheet/extrusion	
33	PP/PE/PP	1.34E-01	1-BlkPlastics	4 -PP	
34	PE-Al2O3	4.59E-03	4-Non-ferro	27 -Al sheet/extrusion	
35					
36	**Auxilary materials**				
37	Hydrochloric acid mix (100%)	2.37E+00	8-Extra	118-Hydrochloric acid	
38	n-Methylpyrolidone (NMP)	9.15E-01	8-Extra	119-n-Methylpyrolidone (NMP)	
39					
40					

Continuation of Table 16: BOM BC6 – residential ESS (per FU)

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
41	**Cell packaging**				
42	Tab with film: Al Tab	0.00E+00	4-Non-ferro	27 -Al sheet/extrusion	
43	Tab with film: Ni Tab	0.00E+00	5-Coating	41 -Cu/Ni/Cr plating	
44	Exterior covering: PET/Ny/Al/PP/ Laminate	6.80E-04	1-BlkPlastics	10 -PET	
45	Collector parts: Al leads	9.38E-03	4-Non-ferro	27 -Al sheet/extrusion	
46	Collector parts: Cu leads	2.81E-02	4-Non-ferro	30 -Cu wire	
47	Collector parts: Plastic fasteners/cover	1.25E-02	1-BlkPlastics	2 -HDPE	
48	Cover: Aluminum	7.06E-02	4-Non-ferro	27 -Al sheet/extrusion	
49	Case: Aluminium	5.00E-01	4-Non-ferro	27 -Al sheet/extrusion	
50	Case: Ni plated Iron	2.59E-02	3-Ferro	24 -Cast iron	
51					
52	**Module**				
53	Al	1.99E-01	4-Non-ferro	27 -Al sheet/extrusion	
54	PP/PE	5.47E-02	1-BlkPlastics	4 -PP	
55	Steel	6.31E-02	3-Ferro	22 -St sheet galv.	
56	Electronics	3.20E-03	6-Electronics	98 -controller board	
57					
58	**System - BMS**				
59	Steel	1.28E-01	3-Ferro	22 -St sheet galv.	
60	Copper	1.60E-01	4-Non-ferro	30 -Cu wire	
61	Printed circuit board	3.20E-02	6-Electronics	52 -PWB 6 lay 2 kg/m2	
62					
63	**System - thermal management**				
64	Al	2.88E-01	4-Non-ferro	27 -Al sheet/extrusion	
65	Steel	3.20E-02	3-Ferro	22 -St sheet galv.	
66					
67	**System packaging**				
68	Al	2.56E-01	4-Non-ferro	27 -Al sheet/extrusion	
69	PP/PE	1.92E-01	1-BlkPlastics	4 -PP	
70	Steel	7.67E-01	3-Ferro	22 -St sheet galv.	
71	WEEE	6.40E-02	6-Electronics	52 -PWB 6 lay 2 kg/m2	
72					
73					
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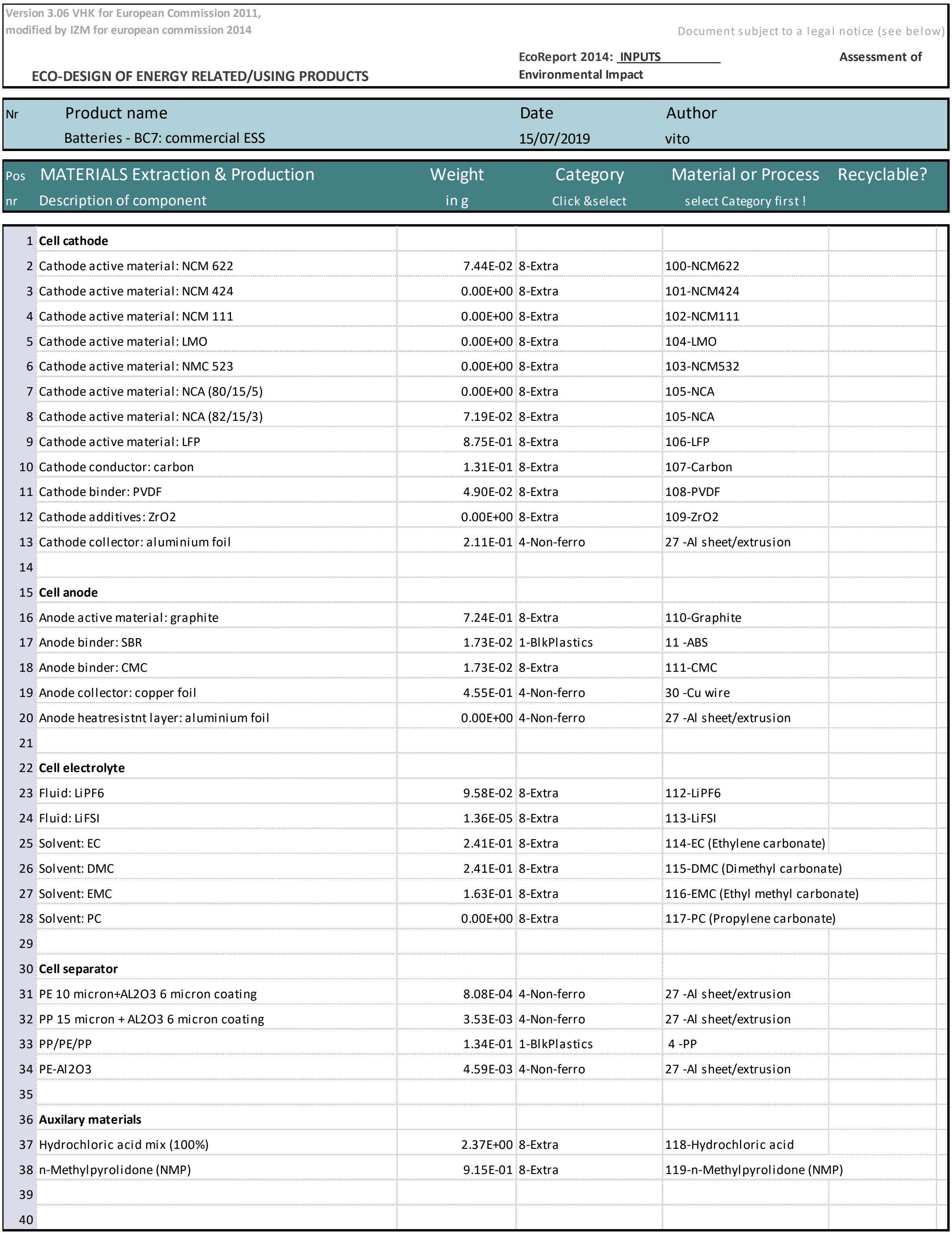
87					

5.1.3.1.7. BOM BC7 – commercial ESS

The calculation of the weight of the battery components is based on:

- a nominal battery energy or battery capacity of 10 kWh,
- a total of 120 000 000 kWh delivered over an economical lifetime of 20 years (functional units),
- 2 battery application system with 3 000 battery system with a service lifetime of 17.02 years, thus meaning 1 replacement needed,
- with a battery weight of 128 kg,
- resulting in a conversion to 1 kWh of functional unit of 0.006 kg/kWh.

Table 17: BOM BC7 – commercial ESS (per FU)



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EcoReport 2014: INPUTS
Environmental Impact

Assessment of

Nr	Product name	Date	Author
	Batteries - BC7: commercial ESS	15/07/2019	vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**Cell cathode**				
2	Cathode active material: NCM 622	7.44E-02	8-Extra	100-NCM622	
3	Cathode active material: NCM 424	0.00E+00	8-Extra	101-NCM424	
4	Cathode active material: NCM 111	0.00E+00	8-Extra	102-NCM111	
5	Cathode active material: LMO	0.00E+00	8-Extra	104-LMO	
6	Cathode active material: NMC 523	0.00E+00	8-Extra	103-NCM532	
7	Cathode active material: NCA (80/15/5)	0.00E+00	8-Extra	105-NCA	
8	Cathode active material: NCA (82/15/3)	7.19E-02	8-Extra	105-NCA	
9	Cathode active material: LFP	8.75E-01	8-Extra	106-LFP	
10	Cathode conductor: carbon	1.31E-01	8-Extra	107-Carbon	
11	Cathode binder: PVDF	4.90E-02	8-Extra	108-PVDF	
12	Cathode additives: ZrO2	0.00E+00	8-Extra	109-ZrO2	
13	Cathode collector: aluminium foil	2.11E-01	4-Non-ferro	27 -Al sheet/extrusion	
14					
15	**Cell anode**				
16	Anode active material: graphite	7.24E-01	8-Extra	110-Graphite	
17	Anode binder: SBR	1.73E-02	1-BlkPlastics	11 -ABS	
18	Anode binder: CMC	1.73E-02	8-Extra	111-CMC	
19	Anode collector: copper foil	4.55E-01	4-Non-ferro	30 -Cu wire	
20	Anode heatresistnt layer: aluminium foil	0.00E+00	4-Non-ferro	27 -Al sheet/extrusion	
21					
22	**Cell electrolyte**				
23	Fluid: LiPF6	9.58E-02	8-Extra	112-LiPF6	
24	Fluid: LiFSI	1.36E-05	8-Extra	113-LiFSI	
25	Solvent: EC	2.41E-01	8-Extra	114-EC (Ethylene carbonate)	
26	Solvent: DMC	2.41E-01	8-Extra	115-DMC (Dimethyl carbonate)	
27	Solvent: EMC	1.63E-01	8-Extra	116-EMC (Ethyl methyl carbonate)	
28	Solvent: PC	0.00E+00	8-Extra	117-PC (Propylene carbonate)	
29					
30	**Cell separator**				
31	PE 10 micron+AL2O3 6 micron coating	8.08E-04	4-Non-ferro	27 -Al sheet/extrusion	
32	PP 15 micron + AL2O3 6 micron coating	3.53E-03	4-Non-ferro	27 -Al sheet/extrusion	
33	PP/PE/PP	1.34E-01	1-BlkPlastics	4 -PP	
34	PE-Al2O3	4.59E-03	4-Non-ferro	27 -Al sheet/extrusion	
35					
36	**Auxilary materials**				
37	Hydrochloric acid mix (100%)	2.37E+00	8-Extra	118-Hydrochloric acid	
38	n-Methylpyrolidone (NMP)	9.15E-01	8-Extra	119-n-Methylpyrolidone (NMP)	
39					
40					

Continuation of Table 17: BOM BC7 – commercial ESS (per FU)

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
41	**Cell packaging**				
42	Tab with film: Al Tab	0.00E+00	4-Non-ferro	27 -Al sheet/extrusion	
43	Tab with film: Ni Tab	0.00E+00	5-Coating	41 -Cu/Ni/Cr plating	
44	Exterior covering: PET/Ny/Al/PP/ Laminate	6.80E-04	1-BlkPlastics	10 -PET	
45	Collector parts: Al leads	9.38E-03	4-Non-ferro	27 -Al sheet/extrusion	
46	Collector parts: Cu leads	2.81E-02	4-Non-ferro	30 -Cu wire	
47	Collector parts: Plastic fasteners/cover	1.25E-02	1-BlkPlastics	2 -HDPE	
48	Cover: Aluminum	7.06E-02	4-Non-ferro	27 -Al sheet/extrusion	
49	Case: Aluminium	5.00E-01	4-Non-ferro	27 -Al sheet/extrusion	
50	Case: Ni plated Iron	2.59E-02	3-Ferro	24 -Cast iron	
51					
52	**Module**				
53	Al	1.99E-01	4-Non-ferro	27 -Al sheet/extrusion	
54	PP/PE	5.47E-02	1-BlkPlastics	4 -PP	
55	Steel	6.31E-02	3-Ferro	22 -St sheet galv.	
56	Electronics	3.20E-03	6-Electronics	98 -controller board	
57					
58	**System - BMS**				
59	Steel	1.28E-01	3-Ferro	22 -St sheet galv.	
60	Copper	1.60E-01	4-Non-ferro	30 -Cu wire	
61	Printed circuit board	3.20E-02	6-Electronics	52 -PWB 6 lay 2 kg/m2	
62					
63	**System - thermal management**				
64	Al	2.88E-01	4-Non-ferro	27 -Al sheet/extrusion	
65	Steel	3.20E-02	3-Ferro	22 -St sheet galv.	
66					
67	**System packaging**				
68	Al	2.56E-01	4-Non-ferro	27 -Al sheet/extrusion	
69	PP/PE	1.92E-01	1-BlkPlastics	4 -PP	
70	Steel	7.67E-01	3-Ferro	22 -St sheet galv.	
71	WEEE	6.40E-02	6-Electronics	52 -PWB 6 lay 2 kg/m2	
72					
73					
74					
75					
76					
77					
78					
79					
80					
81					
82					
83					
84					
85					
86					
87					

5.1.3.1.8. Additional material loss during production phase

The EcoReport tool contains fixed impacts on weight basis for manufacturing of components. These data are used in the study. The only variable that can be edited in this section is the percentage of sheet metal scrap. The default value given by the EcoReport tool is 25 %. This value is reduced to 10 %, which is a recommended value for folded sheets mentioned in the MEErP methodology report.

5.1.3.2. Distribution phase

For the distribution phase the Ecoreport tool requires the volume of the final packaged product to be entered as an input. Based on this volume, the impact of transport of the product to the site of installation is calculated. In the distribution phase the final assembly per m^3 packaged final product is also taken into account in the EcoReport tool. Due to lack of information on the transportation packaging of a battery system, 10 % is added to the battery system volume to model the volume of a packaged battery. The volume of one battery of each BC is shown in the table below. To calculate the volume of a battery system the volume of one battery is multiplied with the total number of batteries needed during Tapp.

Table 18: Overview of the volume assumptions of the Base Cases (based on Task 4)

	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
Volume of one battery [m^3]	0.16	0.08	0.05	0.08	0.08	0.05	0.05
Number of batteries in the application [-]	1	1	1	12	8	1	3 000
Number of battery application systems per Tapp (Ass) [-]	1	2	2	2	3	2	2
Total packed product volume [m^3]	0.18	0.18	0.11	2.02	2.19	0.10	298.93
Total packed product volume [m^3/FU]	4.11×10^{-6}	6.07×10^{-6}	5.60×10^{-6}	2.15×10^{-6}	2.46×10^{-6}	2.49×10^{-6}	2.49×10^{-6}

The distribution phase also includes space heating and lighting of offices, executive travels ([row 62] in the EcoReport calculation sheet) per product. As in this preparatory study the FU is not 1 product but 1 kWh delivered energy by the product, the project team changed the calculations for each BC by dividing the calculated impact for [row 62] by the total amount of kWh delivered energy (AS) and multiplying it with the total number of products/batteries in the application including replacements.

In addition to the packed volume, replies to the EcoReport key questions regarding the product type and installation were given as follows for all BCs:

- ‘Is it an ICT or consumer electronic product less than 15 kg?’ - No.
- ‘Is it an installed appliance?’ - Yes.

5.1.3.3. Use phase

The following aspects are taken into account to model direct and indirect losses during the use phase.

Table 19: Overview of the use phase assumptions of the Base Cases (based on Task 3 and 4)

	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
Application service energy (AS) [kWh/Tapp]	43 680	29 568	19 656	940 800	890 400	40 000	120 x 10^6
Average efficiency of battery system [%]	92	92	92	92	92	92	92
Charger efficiency [%]	85	85	85	92	92	98	98
Brake energy recovery [%]	20	20	20	12	6	n.a.	n.a.
Thermal management efficiency [%]	99	99	99	99	99	99	99
Self-discharge (@STC) [%]	2	2	2	2	2	2	2

The parameters in Table 19 are used as follow to calculate the direct and indirect losses:

- **Direct losses due to average energy efficiency of battery system** = AS / average efficiency of battery system – AS; e.g. for BC1 the direct losses due to the energy efficiency of the battery system = 43 680 kWh / 92 % - 43 680 kWh = 3 798 kWh.
- **Indirect losses due to the battery charger** = (1 – charger efficiency) * (AS / (1 + brake energy recovery)); for example for BC1 these indirect losses = (1 – 85 %) * (43 680 kWh / (1 + 20 %)) = 5 460 kWh.
- **Indirect losses due to thermal management efficiency** = (1 – thermal management efficiency) * AS; in case of BC1, the indirect losses due to thermal management = (1 – 99 %) * 43 680 kWh = 436.8 kWh
- **Indirect losses due to self-discharge (@STC)** = self-discharge * AS; for BC1 the amount indirectly lost due to self-discharge = 2 % * 43 680 = 873.6 kWh.

The next table gives an overview of the calculated losses during the use stage per BC.

Table 20: Overview of the direct and indirect losses during the use phase per Base Case per Tapp and per FU

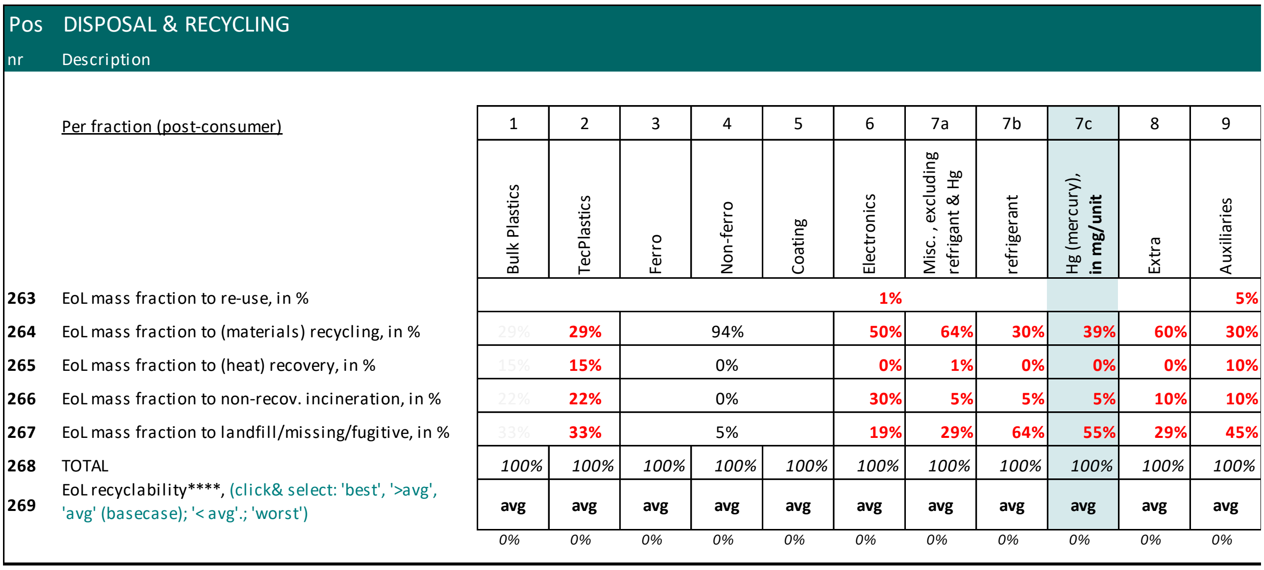
	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
Direct losses due to average efficiency of battery system [kWh/Tapp]	3 798	2 571	1 709	81 809	77 426	3 478	1.04×10^7
Indirect losses due to charger efficiency [kWh/Tapp]	5 460	3 696	2 457	67 200	67 200	800	2.40×10^6
Indirect losses due to thermal management efficiency [kWh/Tapp]	437	296	197	9 408	8 904	400	1.20×10^6
Indirect losses due to self-discharge (@STC) [kWh/Tapp]	874	591	393	18 816	17 808	800	2.40×10^6
Total direct and indirect losses [kWh/Tapp]	10 589	7 154	4 756	177 233	171 338	5 478	1.64×10^7
Direct losses due to average efficiency of battery system [kWh/FU]	0.087	0.087	0.087	0.087	0.087	0.087	0.087
Indirect losses due to charger efficiency [kWh/FU]	0.125	0.125	0.125	0.071	0.075	0.020	0.020
Indirect losses due to thermal management efficiency [kWh/FU]	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Indirect losses due to self-discharge (@STC) [kWh/FU]	0.020	0.020	0.020	0.020	0.020	0.020	0.020
Total direct and indirect losses [kWh/FU]	0.242	0.242	0.242	0.188	0.192	0.137	0.137

The EcoReport tool considers by default the use of spare parts during the use stage, which corresponds with 1 % of the material considered for the production. As it is unlikely that spare parts will be used for this product in the BAU situation, the amount of spare parts in the use stage is set to zero.

5.1.3.4. End-of-Life phase

For the common materials that are available in the EcoReport tool the default EOL values from the MEErP EcoReport tool have been used. They are provided in Table 21. In the EcoReport tool, EOL scenarios are assigned to material categories. It is not possible to assign EOL scenarios to components.

Table 21: Default end-of-life scenarios from the EcoReport tool



Pos nr	DISPOSAL & RECYCLING Description	1	2	3	4	5	6	7a	7b	7c	8	9
	Per fraction (post-consumer)	Bulk Plastics	TecPlastics	Ferro	Non-ferro	Coating	Electronics	Misc., excluding refrigant & Hg	refrigerant	Hg (mercury), **in mg/unit**	Extra	Auxiliaries
263	EoL mass fraction to re-use, in %						**1%**					**5%**
264	EoL mass fraction to (materials) recycling, in %	29%	**29%**	94%			**50%**	**64%**	**30%**	**39%**	**60%**	**30%**
265	EoL mass fraction to (heat) recovery, in %	15%	**15%**	0%			**0%**	**1%**	**0%**	**0%**	**0%**	**10%**
266	EoL mass fraction to non-recov. incineration, in %	22%	**22%**	0%			**30%**	**5%**	**5%**	**5%**	**10%**	**10%**
267	EoL mass fraction to landfill/missing/fugitive, in %	33%	**33%**	5%			**19%**	**29%**	**64%**	**55%**	**29%**	**45%**
268	TOTAL	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*
269	EoL recyclability****, (click& select: 'best', '>avg', 'avg' (basecase); '< avg'.; 'worst')	**avg**	**avg**	**avg**	**avg**	**avg**	**avg**	**avg**	**avg**	**avg**	**avg**	**avg**
		0%	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*

For this product group many materials were not available in the EcoReport tool (as explained in section 5.1.3.1 regarding the modelling of extra materials). The following table gives an overview of the different material fractions in % of the total mass per BC.

Table 22: Overview of the material fractions of the Base Cases [% of the total mass] (calculated by the EcoReport tool)

Material category	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
1 - Bulk Plastics	3.70	3.70	4.60	3.80	4.60	6.40	6.40
2 - Tec Plastics	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3 - Ferro	7.40	7.40	7.00	6.60	7.00	15.90	15.90
4 - Non-ferro	36.60	36.60	39.50	38.20	39.50	34.20	34.20
5 - Coating	0.00	0.00	0.60	0.00	0.60	0.00	0.00
6 - Electronics	1.00	1.00	1.30	1.10	1.30	1.60	1.60
7a - Misc., excl. refrigerant & Hg	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Continuation of Table 22: Overview of the material fractions of the Base Cases [% of the total mass] (calculated by the EcoReport tool)

Material category	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
7b - refrigerant	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8 - Extra	51.20	51.20	47.00	50.40	47.00	42.00	42.00
9 - Auxiliaries	0.00	0.00	0.00	0.00	0.00	0.00	0.00

The extra materials form the biggest fraction of the total mass. Because they form the biggest fraction and the extra materials are very specific for this product group, the EOL scenario for the extra materials have been changed as follows:

- The default recycling rate of 60 % for extra materials has been lowered to an amount that would result in a total mass fraction that goes to recycling of at least 50 %, so it corresponds with the minimum recycling efficiency set in the Batteries Directive 2006/66/EC.
- A minimal recycling rate of 4 % for extra materials was applied, which corresponds with the fraction of cobalt and nickel that is recycled in a BAU situation based on a recycling rate of 16 % for cobalt as well as nickel and a recycling rate of 0 % for manganese, lithium and graphite (see section 4.2.4.3. in Task 4 on recycling); i.e. 4 % = 16 % * amount of Co and Ni / total amount of Co, Ni, Mn, Li and graphite.
- The default assumption that 1 % of the extra materials goes to reuse and 0 % to heat recovery is kept.
- The remaining EOL mass fraction is divided over incineration and landfill in the same ratio as the default MEErP EOL scenario for extra materials, which is 10 % going to incineration and 29 % to landfill. Thus ¼ of the remaining EOL mass fraction goes to incineration and ¾ to landfill.

Based on the above, Table 23 presents the EOL scenarios that has been applied to the extra materials in each base case and the total fraction that is being recycled.

Table 23: Overview of the EOL scenario of the extra materials and the total mass fraction that goes to recycling per base case

EOL mass fraction to	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
Reuse [%]	1	1	1	1	1	1	1
Heat recovery [%]	0	0	0	0	0	0	0
Recycling [%]	14	14	9	13	9	4	4
Incineration [%]	21	21	23	22	23	24	24
Landfill(/missing/fugitive) [%]	64	64	68	65	68	71	71
Total mass fraction that goes to recycling [%]	50.2	50.2	50.5	50.2	50.5	51.4	51.4

The benefits of recycling are in the MEErP EcoReport tool calculated as a percentage of the impacts from production. For the material category ‘Extra’ (and all other categories), MEErP assumes that the benefits of recycling are 40 % of the impacts from the production. In other words, if the impact of the production of the extra materials equals 1 kg CO_2 eq in the impact category global warming, than the benefits attributed to the recycling of the same amount of extra materials in the impact category global warming are: 1*recycling rate*0.4 kg CO_2 eq.

After the extra materials, the second biggest material fraction is the non-ferro metals. For ferro and non-ferro metals the default assumptions are 94 % recycling, 1 % reuse, and 5 % landfilled/missing/fugitive at EOL.

5.2. Subtask 5.2 – Base Case environmental impact assessment

AIM OF SUBTASK 5.2:

The environmental Life Cycle Assessment (LCA) per BC are determined with the EcoReport 2014 tool in MEErP format for the life cycle stages:

- Raw materials use and manufacturing,
- Distribution,
- Use phase,
- End-of-Life (EOL).

The following subsections give the LCA results per BC. The last subsection of this subtask presents the Critical Raw Material (CRM) indicators for the BCs.

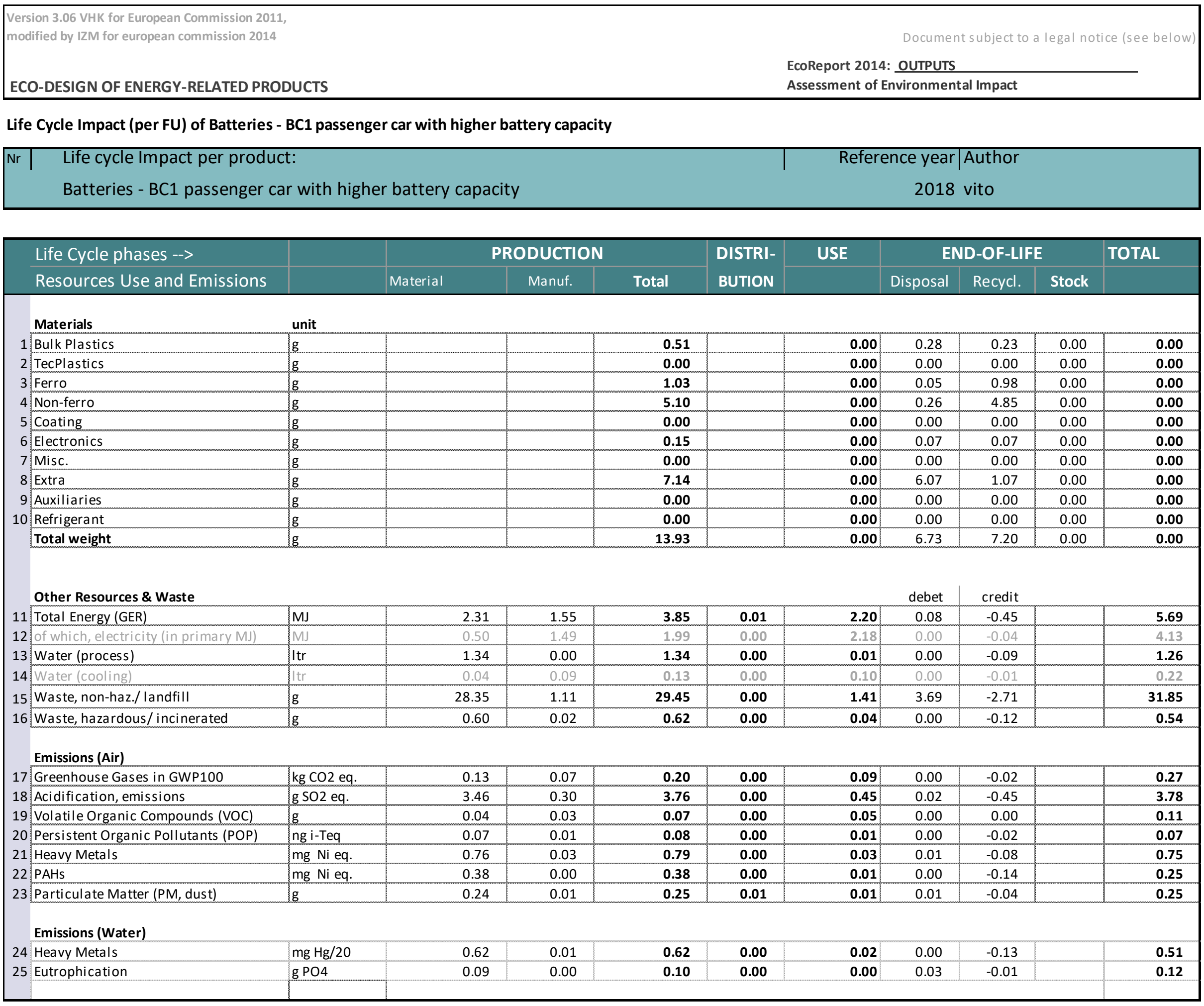
Based on the LCA results of all BCs, one can conclude that **the production phase has the biggest contribution** on the total life cycle impact in all impact categories. When looking into the production phase in more detail for the xEV BCs, the following points are notable:

- The cathode active material gives the biggest contribution across the different impact categories considered in the MEErP. This is more perceptible for the BEV BCs (1, 2 and 4) than the PHEV and ESS BCs.
- The contribution of the auxiliary materials in the impact categories water (process and cooling) and eutrophication is high, which caused by the use of n-Methylpyrolidone (NMP).
- The battery application system packaging gives a high contribution in hazardous waste due to the amount of Waste Electrical and Electronic Equipment (WEEE).

5.2.1. EcoReport LCA results BC1 – passenger car BEV with a higher battery capacity

Table 24 provides the environmental impact results in absolute values for 1 kWh delivered by a battery system in a battery electric vehicle passenger car with a higher battery capacity. Figure 1 is a graphical presentation of the LCA results of BC1.

Table 24: EcoReport LCA results per FU of for BC1 PC BEV HIGH



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EcoReport 2014: OUTPUTS
Assessment of Environmental Impact

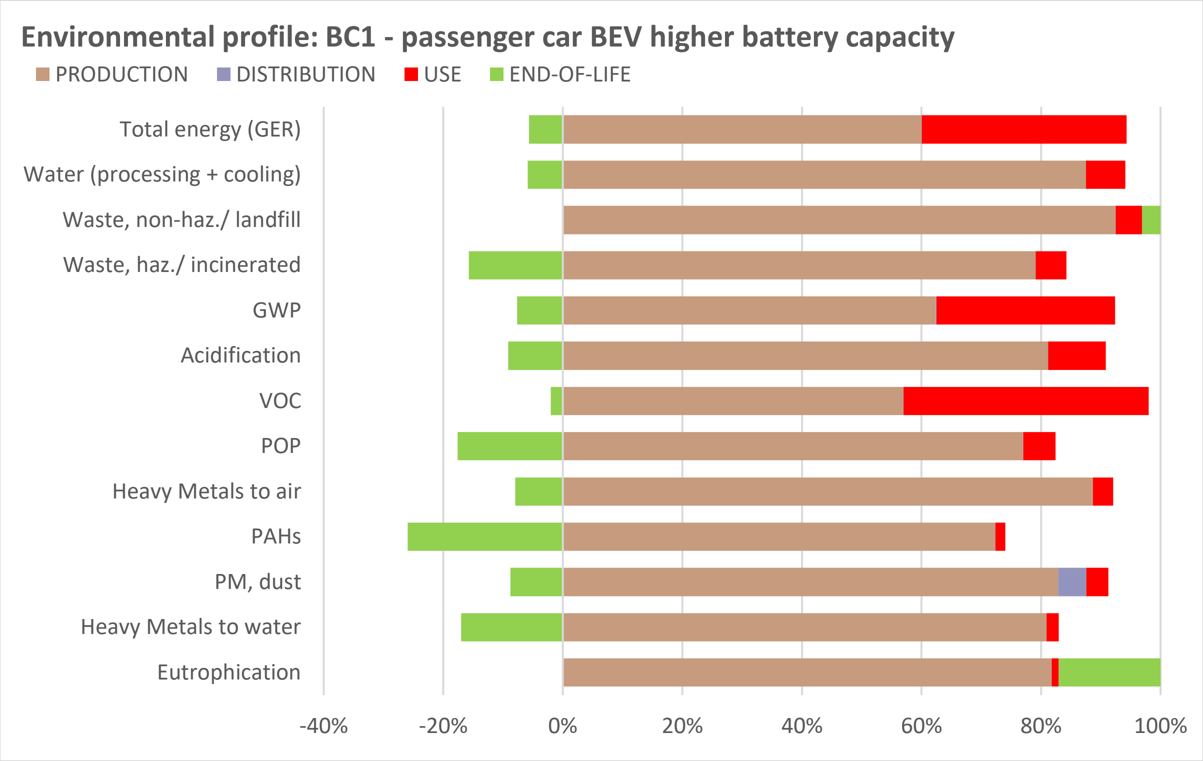
ECO-DESIGN OF ENERGY-RELATED PRODUCTS

Life Cycle Impact (per FU) of Batteries - BC1 passenger car with higher battery capacity

Nr	Life cycle Impact per product:	Reference year	Author
	Batteries - BC1 passenger car with higher battery capacity	2018	vito

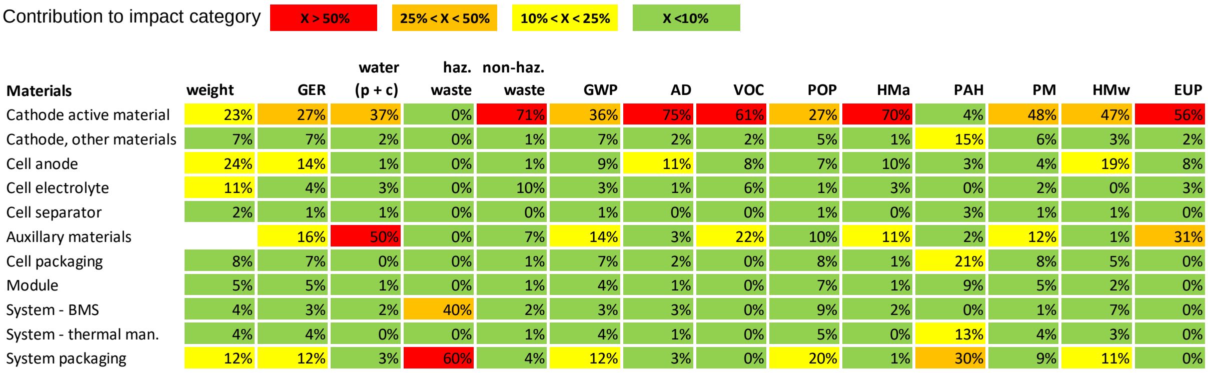
	Life Cycle phases --> Resources Use and Emissions		PRODUCTION Material	 Manuf.	 **Total**	**DISTRI- BUTION**	**USE**	**END-OF-LIFE** Disposal	 Recycl.	 **Stock**	**TOTAL**
	Materials	**unit**									
1	Bulk Plastics	g			**0.51**		**0.00**	0.28	0.23	0.00	**0.00**
2	TecPlastics	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
3	Ferro	g			**1.03**		**0.00**	0.05	0.98	0.00	**0.00**
4	Non-ferro	g			**5.10**		**0.00**	0.26	4.85	0.00	**0.00**
5	Coating	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
6	Electronics	g			**0.15**		**0.00**	0.07	0.07	0.00	**0.00**
7	Misc.	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
8	Extra	g			**7.14**		**0.00**	6.07	1.07	0.00	**0.00**
9	Auxiliaries	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
10	Refrigerant	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
	Total weight	g			**13.93**		**0.00**	6.73	7.20	0.00	**0.00**
	Other Resources & Waste							debet	credit		
11	Total Energy (GER)	MJ	2.31	1.55	**3.85**	**0.01**	**2.20**	0.08	-0.45		**5.69**
12	of which, electricity (in primary MJ)	MJ	0.50	1.49	**1.99**	**0.00**	**2.18**	0.00	-0.04		**4.13**
13	Water (process)	ltr	1.34	0.00	**1.34**	**0.00**	**0.01**	0.00	-0.09		**1.26**
14	Water (cooling)	ltr	0.04	0.09	**0.13**	**0.00**	**0.10**	0.00	-0.01		**0.22**
15	Waste, non-haz./ landfill	g	28.35	1.11	**29.45**	**0.00**	**1.41**	3.69	-2.71		**31.85**
16	Waste, hazardous/ incinerated	g	0.60	0.02	**0.62**	**0.00**	**0.04**	0.00	-0.12		**0.54**
	Emissions (Air)										
17	Greenhouse Gases in GWP100	kg CO2 eq.	0.13	0.07	**0.20**	**0.00**	**0.09**	0.00	-0.02		**0.27**
18	Acidification, emissions	g SO2 eq.	3.46	0.30	**3.76**	**0.00**	**0.45**	0.02	-0.45		**3.78**
19	Volatile Organic Compounds (VOC)	g	0.04	0.03	**0.07**	**0.00**	**0.05**	0.00	0.00		**0.11**
20	Persistent Organic Pollutants (POP)	ng i-Teq	0.07	0.01	**0.08**	**0.00**	**0.01**	0.00	-0.02		**0.07**
21	Heavy Metals	mg Ni eq.	0.76	0.03	**0.79**	**0.00**	**0.03**	0.01	-0.08		**0.75**
22	PAHs	mg Ni eq.	0.38	0.00	**0.38**	**0.00**	**0.01**	0.00	-0.14		**0.25**
23	Particulate Matter (PM, dust)	g	0.24	0.01	**0.25**	**0.01**	**0.01**	0.01	-0.04		**0.25**
	Emissions (Water)										
24	Heavy Metals	mg Hg/20	0.62	0.01	**0.62**	**0.00**	**0.02**	0.00	-0.13		**0.51**
25	Eutrophication	g PO4	0.09	0.00	**0.10**	**0.00**	**0.00**	0.03	-0.01		**0.12**

Figure 1: Relative contribution of the life cycle stages per FU of BC1 PC BEV HIGH based on the EcoReport LCA results



The table below shows the relative contribution to the impact caused by the raw materials of the different battery system components in BC1 per impact category.

Table 25: Results for raw materials used in the production phase per FU of BC1 PC BEV HIGH based on the EcoReport LCA results



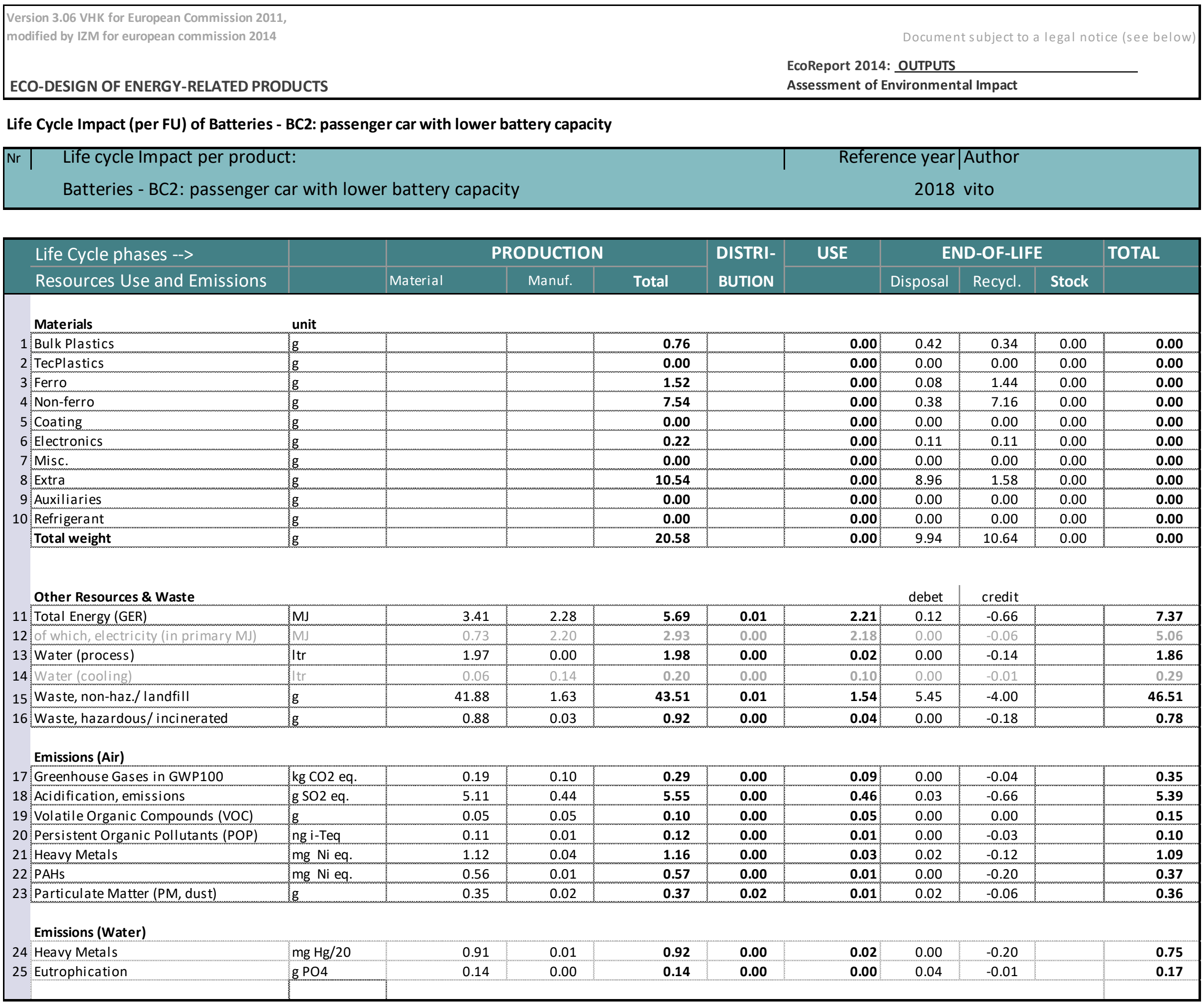
Contribution to impact category 🟥 X > 50% 🟧 25% < X < 50% 🟨 10% < X < 25% 🟩 X <10%

Materials	weight	GER	water (p + c)	haz. waste	non-haz. waste	GWP	AD	VOC	POP	HMa	PAH	PM	HMw	EUP
Cathode active material	23%	27%	37%	0%	71%	36%	75%	61%	27%	70%	4%	48%	47%	56%
Cathode, other materials	7%	7%	2%	0%	1%	7%	2%	2%	5%	1%	15%	6%	3%	2%
Cell anode	24%	14%	1%	0%	1%	9%	11%	8%	7%	10%	3%	4%	19%	8%
Cell electrolyte	11%	4%	3%	0%	10%	3%	1%	6%	1%	3%	0%	2%	0%	3%
Cell separator	2%	1%	1%	0%	0%	1%	0%	0%	1%	0%	3%	1%	1%	0%
Auxillary materials		16%	50%	0%	7%	14%	3%	22%	10%	11%	2%	12%	1%	31%
Cell packaging	8%	7%	0%	0%	1%	7%	2%	0%	8%	1%	21%	8%	5%	0%
Module	5%	5%	1%	0%	1%	4%	1%	0%	7%	1%	9%	5%	2%	0%
System - BMS	4%	3%	2%	40%	2%	3%	3%	0%	9%	2%	0%	1%	7%	0%
System - thermal man.	4%	4%	0%	0%	1%	4%	1%	0%	5%	0%	13%	4%	3%	0%
System packaging	12%	12%	3%	60%	4%	12%	3%	0%	20%	1%	30%	9%	11%	0%

5.2.2. EcoReport LCA results BC2 – passenger car BEV with a lower battery capacity

Table 26 provides the environmental impact results in absolute values for 1 kWh delivered by a battery system in a battery electric vehicle passenger car with a lower battery capacity. Figure 2 is a graphical presentation of the LCA results of BC2.

Table 26: EcoReport LCA results per FU of for BC2 PC BEV LOW



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ECO-DESIGN OF ENERGY-RELATED PRODUCTS

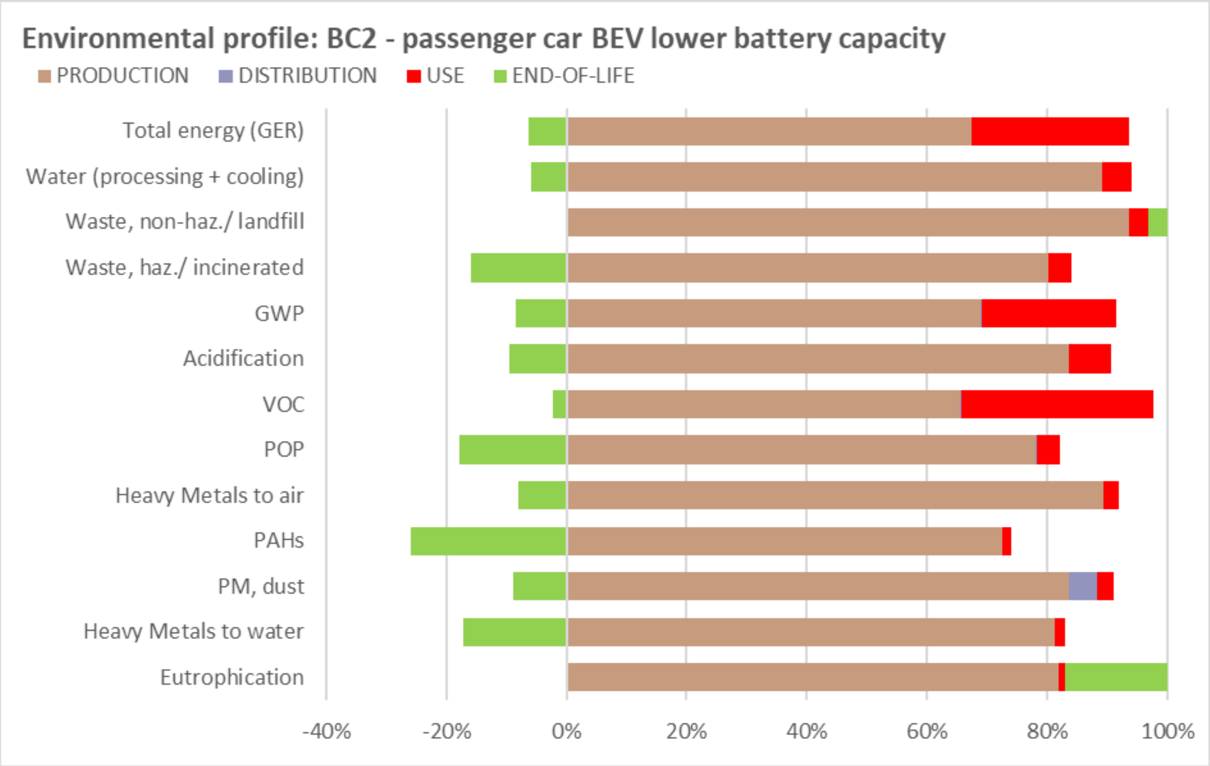
EcoReport 2014: OUTPUTS
Assessment of Environmental Impact

Life Cycle Impact (per FU) of Batteries - BC2: passenger car with lower battery capacity

Nr	Life cycle Impact per product:	Reference year	Author
	Batteries - BC2: passenger car with lower battery capacity	2018	vito

	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	END-OF-LIFE			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total	BUTION		Disposal	Recycl.	Stock	
	Materials	**unit**									
1	Bulk Plastics	g			**0.76**		**0.00**	0.42	0.34	0.00	**0.00**
2	TecPlastics	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
3	Ferro	g			**1.52**		**0.00**	0.08	1.44	0.00	**0.00**
4	Non-ferro	g			**7.54**		**0.00**	0.38	7.16	0.00	**0.00**
5	Coating	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
6	Electronics	g			**0.22**		**0.00**	0.11	0.11	0.00	**0.00**
7	Misc.	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
8	Extra	g			**10.54**		**0.00**	8.96	1.58	0.00	**0.00**
9	Auxiliaries	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
10	Refrigerant	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
	Total weight	g			**20.58**		**0.00**	9.94	10.64	0.00	**0.00**
	Other Resources & Waste							debet	credit		
11	Total Energy (GER)	MJ	3.41	2.28	**5.69**	**0.01**	**2.21**	0.12	-0.66		**7.37**
12	of which, electricity (in primary MJ)	MJ	0.73	2.20	**2.93**	**0.00**	**2.18**	0.00	-0.06		**5.06**
13	Water (process)	ltr	1.97	0.00	**1.98**	**0.00**	**0.02**	0.00	-0.14		**1.86**
14	Water (cooling)	ltr	0.06	0.14	**0.20**	**0.00**	**0.10**	0.00	-0.01		**0.29**
15	Waste, non-haz./ landfill	g	41.88	1.63	**43.51**	**0.01**	**1.54**	5.45	-4.00		**46.51**
16	Waste, hazardous/ incinerated	g	0.88	0.03	**0.92**	**0.00**	**0.04**	0.00	-0.18		**0.78**
	Emissions (Air)										
17	Greenhouse Gases in GWP100	kg CO2 eq.	0.19	0.10	**0.29**	**0.00**	**0.09**	0.00	-0.04		**0.35**
18	Acidification, emissions	g SO2 eq.	5.11	0.44	**5.55**	**0.00**	**0.46**	0.03	-0.66		**5.39**
19	Volatile Organic Compounds (VOC)	g	0.05	0.05	**0.10**	**0.00**	**0.05**	0.00	0.00		**0.15**
20	Persistent Organic Pollutants (POP)	ng i-Teq	0.11	0.01	**0.12**	**0.00**	**0.01**	0.00	-0.03		**0.10**
21	Heavy Metals	mg Ni eq.	1.12	0.04	**1.16**	**0.00**	**0.03**	0.02	-0.12		**1.09**
22	PAHs	mg Ni eq.	0.56	0.01	**0.57**	**0.00**	**0.01**	0.00	-0.20		**0.37**
23	Particulate Matter (PM, dust)	g	0.35	0.02	**0.37**	**0.02**	**0.01**	0.02	-0.06		**0.36**
	Emissions (Water)										
24	Heavy Metals	mg Hg/20	0.91	0.01	**0.92**	**0.00**	**0.02**	0.00	-0.20		**0.75**
25	Eutrophication	g PO4	0.14	0.00	**0.14**	**0.00**	**0.00**	0.04	-0.01		**0.17**

Figure 2: Relative contribution of the life cycle stages per FU of BC2 PC BEV HIGH based on the EcoReport LCA results



The table below shows the relative contribution to the impact caused by the raw materials of the different battery system components in BC2 per impact category.

Table 27: Results for raw materials used in the production phase per FU of BC2 PC BEV LOW based on the EcoReport LCA results

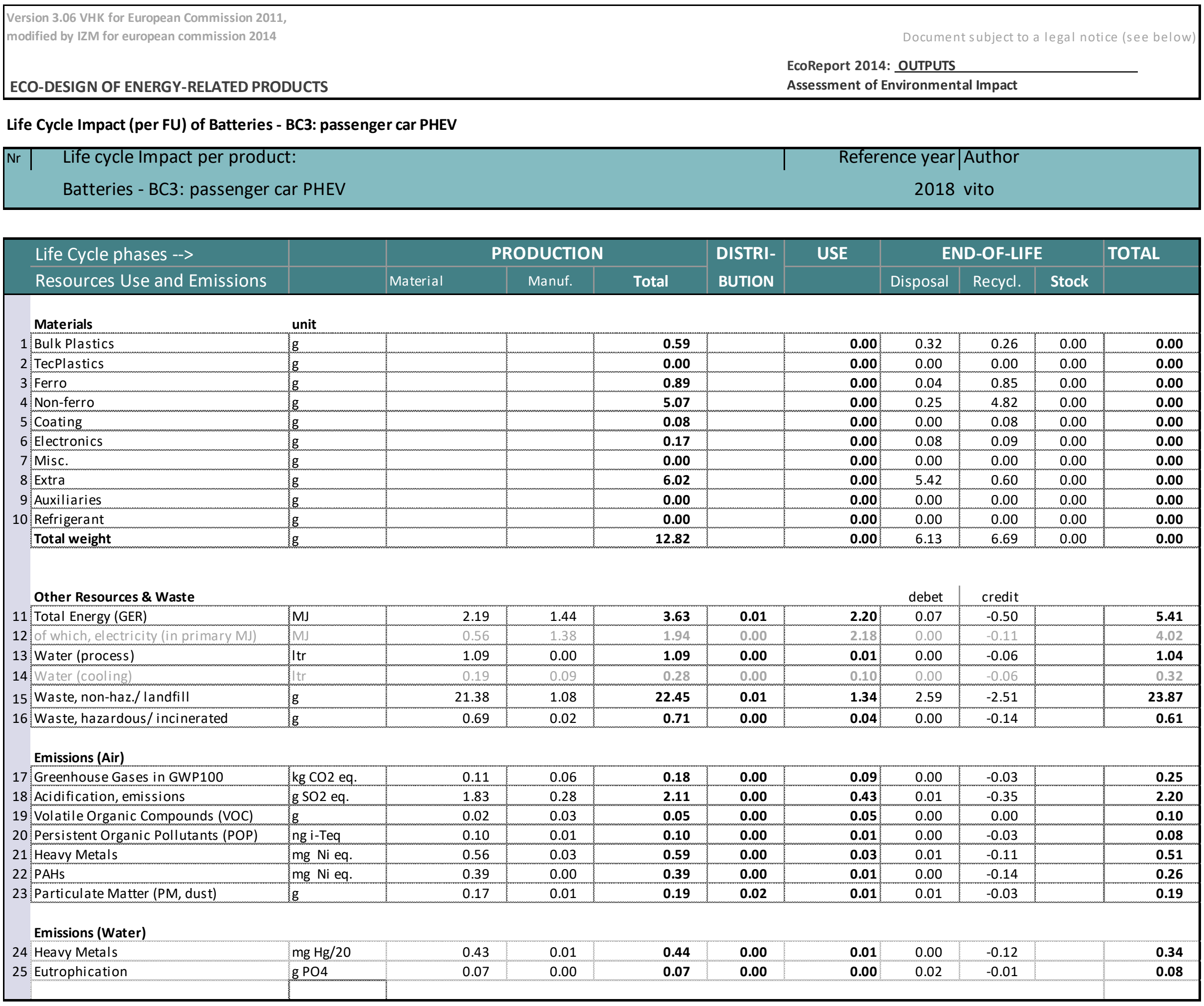
Contribution to impact category 🟥 X > 50% 🟧 25% < X < 50% 🟨 10% < X < 25% 🟩 X <10%

Materials	weight	GER	water (p + c)	haz. waste	non-haz. waste	GWP	AD	VOC	POP	HMa	PAH	PM	HMw	EUP
Cathode active material	23%	27%	37%	0%	71%	36%	75%	61%	27%	70%	4%	48%	47%	56%
Cathode, other materials	7%	7%	2%	0%	1%	7%	2%	2%	5%	1%	15%	6%	3%	2%
Cell anode	24%	14%	1%	0%	1%	9%	11%	8%	7%	10%	3%	4%	19%	8%
Cell electrolyte	11%	4%	3%	0%	10%	3%	1%	6%	1%	3%	0%	2%	0%	3%
Cell seperator	2%	1%	1%	0%	0%	1%	0%	0%	1%	0%	3%	1%	1%	0%
Auxillary materials		16%	50%	0%	7%	14%	3%	22%	10%	11%	2%	12%	1%	31%
Cell packaging	8%	7%	0%	0%	1%	7%	2%	0%	8%	1%	21%	8%	5%	0%
Module	5%	5%	1%	0%	1%	4%	1%	0%	7%	1%	9%	5%	2%	0%
System - BMS	4%	3%	2%	40%	2%	3%	3%	0%	9%	2%	0%	1%	7%	0%
System - thermal man.	4%	4%	0%	0%	1%	4%	1%	0%	5%	0%	13%	4%	3%	0%
System packaging	12%	12%	3%	60%	4%	12%	3%	0%	20%	1%	30%	9%	11%	0%

5.2.3. EcoReport LCA results BC3 – passenger car PHEV

Table 28 provides the environmental impact results in absolute values for 1 kWh delivered by a battery system in a plug-in hybrid vehicle passenger car. Figure 1 is a graphical presentation of the LCA results of BC3.

Table 28: EcoReport LCA results per FU of for BC3 PC PHEV



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ECO-DESIGN OF ENERGY-RELATED PRODUCTS

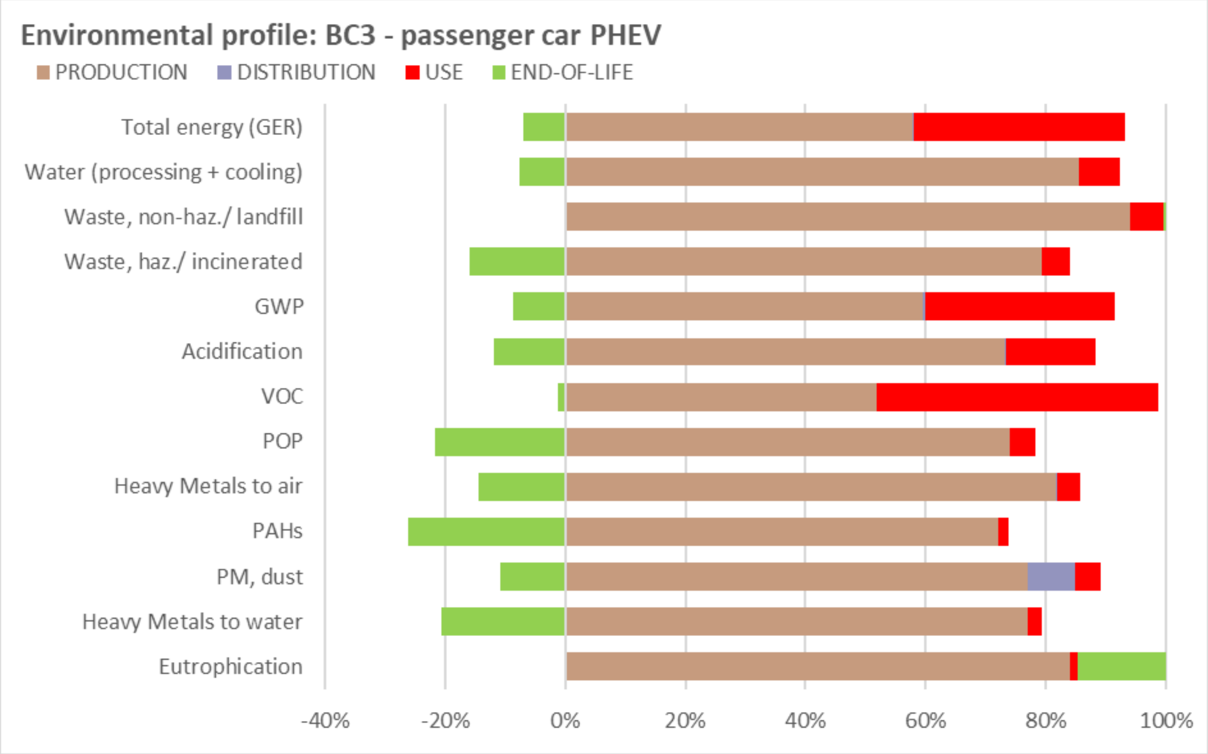
EcoReport 2014: OUTPUTS
Assessment of Environmental Impact

Life Cycle Impact (per FU) of Batteries - BC3: passenger car PHEV

Nr	Life cycle Impact per product:	Reference year	Author
	Batteries - BC3: passenger car PHEV	2018	vito

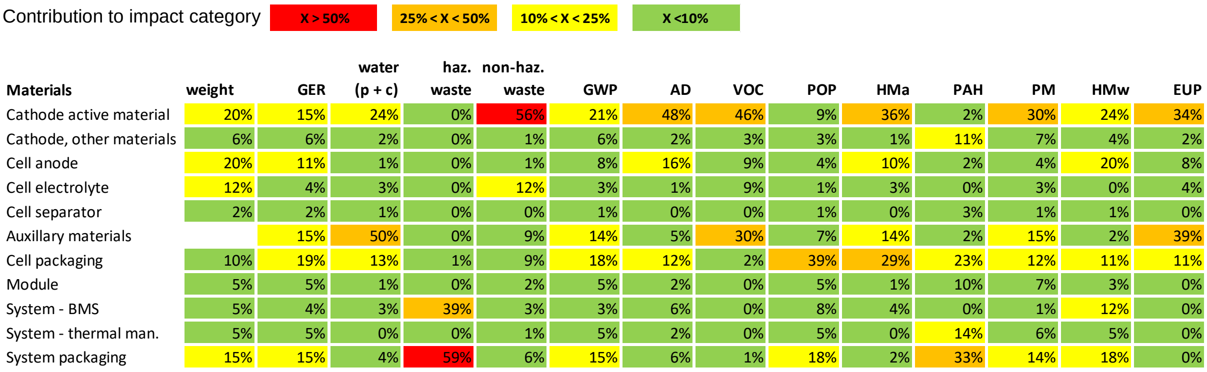
	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	END-OF-LIFE			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total	BUTION		Disposal	Recycl.	Stock	
	Materials	**unit**									
1	Bulk Plastics	g			**0.59**		**0.00**	0.32	0.26	0.00	**0.00**
2	TecPlastics	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
3	Ferro	g			**0.89**		**0.00**	0.04	0.85	0.00	**0.00**
4	Non-ferro	g			**5.07**		**0.00**	0.25	4.82	0.00	**0.00**
5	Coating	g			**0.08**		**0.00**	0.00	0.08	0.00	**0.00**
6	Electronics	g			**0.17**		**0.00**	0.08	0.09	0.00	**0.00**
7	Misc.	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
8	Extra	g			**6.02**		**0.00**	5.42	0.60	0.00	**0.00**
9	Auxiliaries	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
10	Refrigerant	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
	Total weight	g			**12.82**		**0.00**	6.13	6.69	0.00	**0.00**
	Other Resources & Waste							debet	credit		
11	Total Energy (GER)	MJ	2.19	1.44	**3.63**	**0.01**	**2.20**	0.07	-0.50		**5.41**
12	of which, electricity (in primary MJ)	MJ	0.56	1.38	**1.94**	**0.00**	**2.18**	0.00	-0.11		**4.02**
13	Water (process)	ltr	1.09	0.00	**1.09**	**0.00**	**0.01**	0.00	-0.06		**1.04**
14	Water (cooling)	ltr	0.19	0.09	**0.28**	**0.00**	**0.10**	0.00	-0.06		**0.32**
15	Waste, non-haz./ landfill	g	21.38	1.08	**22.45**	**0.01**	**1.34**	2.59	-2.51		**23.87**
16	Waste, hazardous/ incinerated	g	0.69	0.02	**0.71**	**0.00**	**0.04**	0.00	-0.14		**0.61**
	Emissions (Air)										
17	Greenhouse Gases in GWP100	kg CO2 eq.	0.11	0.06	**0.18**	**0.00**	**0.09**	0.00	-0.03		**0.25**
18	Acidification, emissions	g SO2 eq.	1.83	0.28	**2.11**	**0.00**	**0.43**	0.01	-0.35		**2.20**
19	Volatile Organic Compounds (VOC)	g	0.02	0.03	**0.05**	**0.00**	**0.05**	0.00	0.00		**0.10**
20	Persistent Organic Pollutants (POP)	ng i-Teq	0.10	0.01	**0.10**	**0.00**	**0.01**	0.00	-0.03		**0.08**
21	Heavy Metals	mg Ni eq.	0.56	0.03	**0.59**	**0.00**	**0.03**	0.01	-0.11		**0.51**
22	PAHs	mg Ni eq.	0.39	0.00	**0.39**	**0.00**	**0.01**	0.00	-0.14		**0.26**
23	Particulate Matter (PM, dust)	g	0.17	0.01	**0.19**	**0.02**	**0.01**	0.01	-0.03		**0.19**
	Emissions (Water)										
24	Heavy Metals	mg Hg/20	0.43	0.01	**0.44**	**0.00**	**0.01**	0.00	-0.12		**0.34**
25	Eutrophication	g PO4	0.07	0.00	**0.07**	**0.00**	**0.00**	0.02	-0.01		**0.08**

Figure 3: Relative contribution of the life cycle stages per FU of BC3 PC PHEV based on the EcoReport LCA results



The table below shows the relative contribution to the impact caused by the raw materials of the different battery system components in BC3 per impact category.

Table 29: Results for raw materials used in the production phase per FU of BC3 PC PHEV based on the EcoReport LCA results



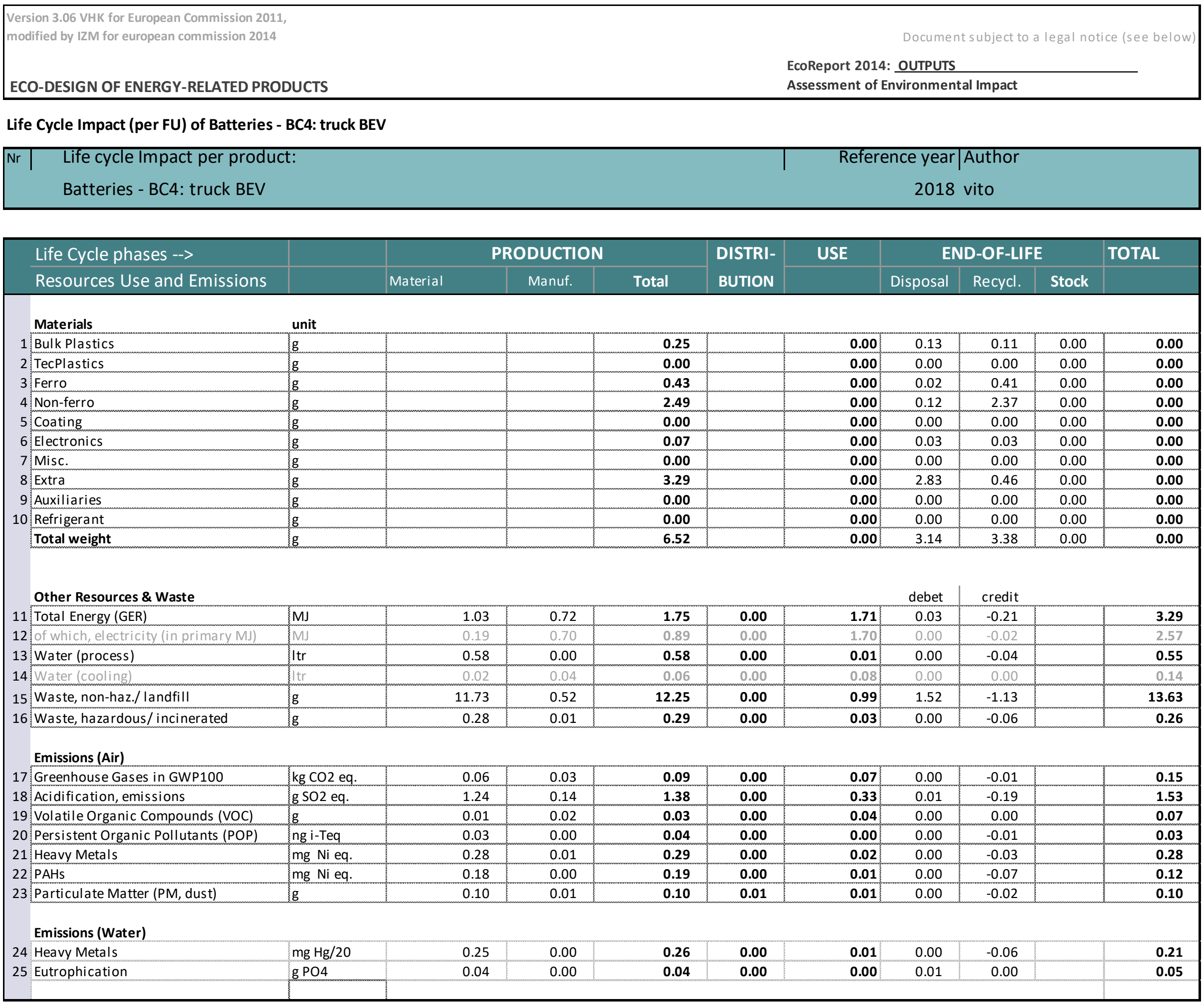
Contribution to impact category 🟥 X > 50% 🟧 25% < X < 50% 🟨 10% < X < 25% 🟩 X <10%

Materials	weight	GER	water (p + c)	haz. waste	non-haz. waste	GWP	AD	VOC	POP	HMa	PAH	PM	HMw	EUP
Cathode active material	20%	15%	24%	0%	56%	21%	48%	46%	9%	36%	2%	30%	24%	34%
Cathode, other materials	6%	6%	2%	0%	1%	6%	2%	3%	3%	1%	11%	7%	4%	2%
Cell anode	20%	11%	1%	0%	1%	8%	16%	9%	4%	10%	2%	4%	20%	8%
Cell electrolyte	12%	4%	3%	0%	12%	3%	1%	9%	1%	3%	0%	3%	0%	4%
Cell separator	2%	2%	1%	0%	0%	1%	0%	0%	1%	0%	3%	1%	1%	0%
Auxillary materials		15%	50%	0%	9%	14%	5%	30%	7%	14%	2%	15%	2%	39%
Cell packaging	10%	19%	13%	1%	9%	18%	12%	2%	39%	29%	23%	12%	11%	11%
Module	5%	5%	1%	0%	2%	5%	2%	0%	5%	1%	10%	7%	3%	0%
System - BMS	5%	4%	3%	39%	3%	3%	6%	0%	8%	4%	0%	1%	12%	0%
System - thermal man.	5%	5%	0%	0%	1%	5%	2%	0%	5%	0%	14%	6%	5%	0%
System packaging	15%	15%	4%	59%	6%	15%	6%	1%	18%	2%	33%	14%	18%	0%

5.2.4. EcoReport LCA results BC4 – truck BEV

Table 30 provides the environmental impact results in absolute values for 1 kWh delivered by a battery system in a battery electric vehicle truck. Figure 4 is a graphical presentation of the LCA results of BC4.

Table 30: EcoReport LCA results per FU of for BC4 Truck BEV



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EcoReport 2014: OUTPUTS
Assessment of Environmental Impact

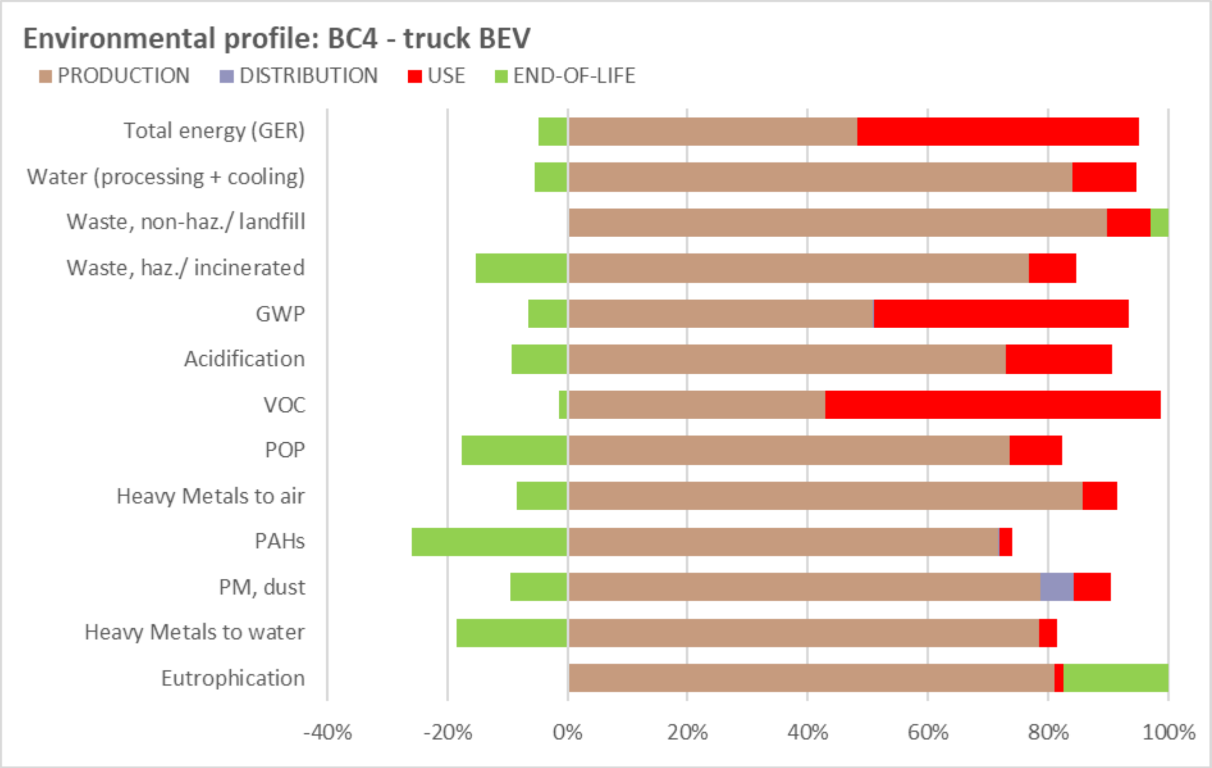
ECO-DESIGN OF ENERGY-RELATED PRODUCTS

Life Cycle Impact (per FU) of Batteries - BC4: truck BEV

Nr	Life cycle Impact per product:	Reference year	Author
	Batteries - BC4: truck BEV	2018	vito

	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	END-OF-LIFE			TOTAL
	Resources Use and Emissions		Material	Manuf.	**Total**	**BUTION**		Disposal	Recycl.	**Stock**	
	Materials	**unit**									
1	Bulk Plastics	g			**0.25**		**0.00**	0.13	0.11	0.00	**0.00**
2	TecPlastics	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
3	Ferro	g			**0.43**		**0.00**	0.02	0.41	0.00	**0.00**
4	Non-ferro	g			**2.49**		**0.00**	0.12	2.37	0.00	**0.00**
5	Coating	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
6	Electronics	g			**0.07**		**0.00**	0.03	0.03	0.00	**0.00**
7	Misc.	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
8	Extra	g			**3.29**		**0.00**	2.83	0.46	0.00	**0.00**
9	Auxiliaries	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
10	Refrigerant	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
	Total weight	g			**6.52**		**0.00**	3.14	3.38	0.00	**0.00**
	Other Resources & Waste							debet	credit		
11	Total Energy (GER)	MJ	1.03	0.72	**1.75**	**0.00**	**1.71**	0.03	-0.21		**3.29**
12	of which, electricity (in primary MJ)	MJ	0.19	0.70	**0.89**	**0.00**	**1.70**	0.00	-0.02		**2.57**
13	Water (process)	ltr	0.58	0.00	**0.58**	**0.00**	**0.01**	0.00	-0.04		**0.55**
14	Water (cooling)	ltr	0.02	0.04	**0.06**	**0.00**	**0.08**	0.00	0.00		**0.14**
15	Waste, non-haz./ landfill	g	11.73	0.52	**12.25**	**0.00**	**0.99**	1.52	-1.13		**13.63**
16	Waste, hazardous/ incinerated	g	0.28	0.01	**0.29**	**0.00**	**0.03**	0.00	-0.06		**0.26**
	Emissions (Air)										
17	Greenhouse Gases in GWP100	kg CO2 eq.	0.06	0.03	**0.09**	**0.00**	**0.07**	0.00	-0.01		**0.15**
18	Acidification, emissions	g SO2 eq.	1.24	0.14	**1.38**	**0.00**	**0.33**	0.01	-0.19		**1.53**
19	Volatile Organic Compounds (VOC)	g	0.01	0.02	**0.03**	**0.00**	**0.04**	0.00	0.00		**0.07**
20	Persistent Organic Pollutants (POP)	ng i-Teq	0.03	0.00	**0.04**	**0.00**	**0.00**	0.00	-0.01		**0.03**
21	Heavy Metals	mg Ni eq.	0.28	0.01	**0.29**	**0.00**	**0.02**	0.00	-0.03		**0.28**
22	PAHs	mg Ni eq.	0.18	0.00	**0.19**	**0.00**	**0.01**	0.00	-0.07		**0.12**
23	Particulate Matter (PM, dust)	g	0.10	0.01	**0.10**	**0.01**	**0.01**	0.00	-0.02		**0.10**
	Emissions (Water)										
24	Heavy Metals	mg Hg/20	0.25	0.00	**0.26**	**0.00**	**0.01**	0.00	-0.06		**0.21**
25	Eutrophication	g PO4	0.04	0.00	**0.04**	**0.00**	**0.00**	0.01	0.00		**0.05**

Figure 4: Relative contribution of the life cycle stages per FU of BC4 Truck BEV based on the EcoReport LCA results



The table below shows the relative contribution to the impact caused by the raw materials of the different battery system components in BC4 per impact category.

Table 31: Results for raw materials used in the production phase per FU of BC4 Truck BEV based on the EcoReport LCA results

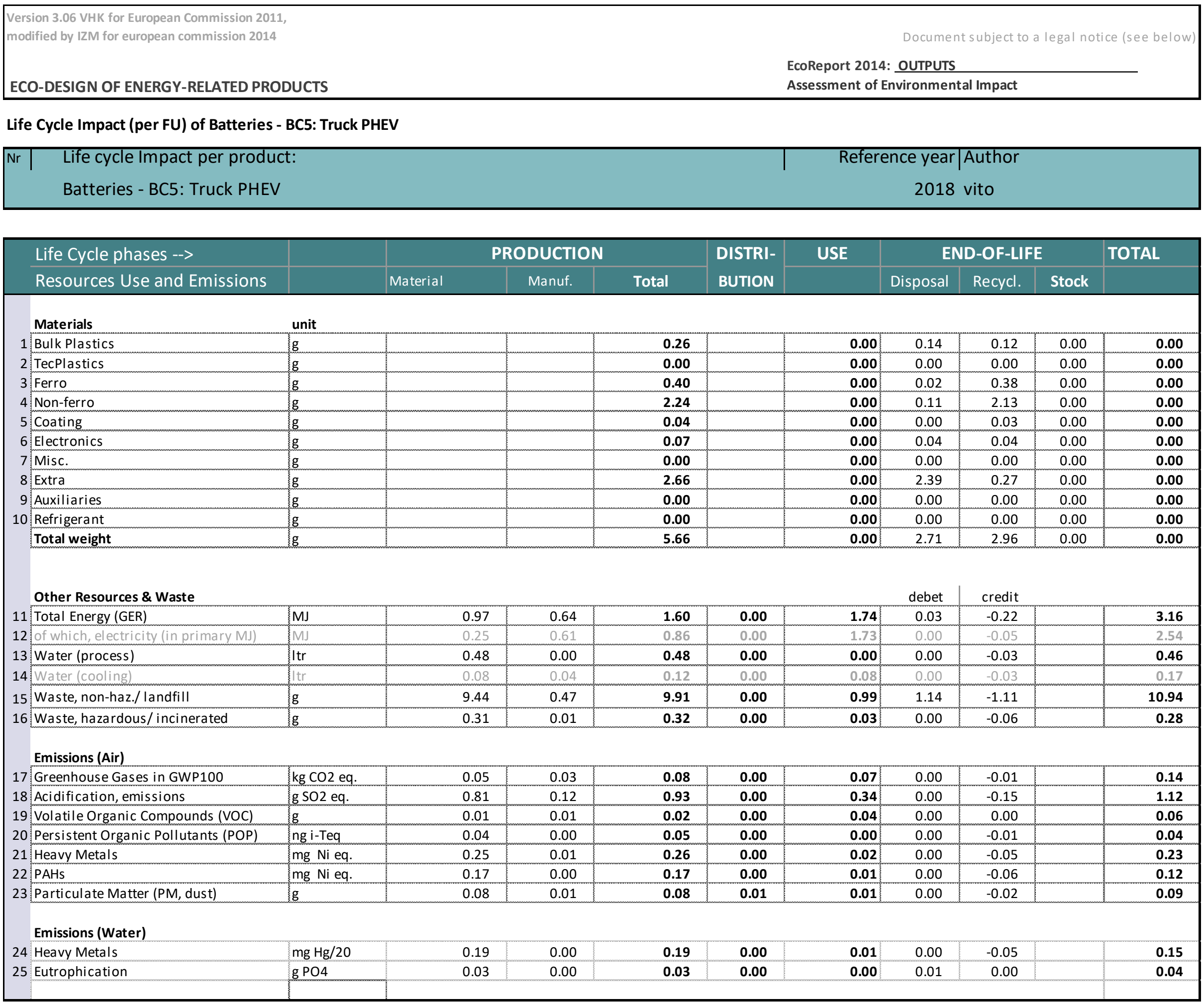
Contribution to impact category **X > 50%** **25% < X < 50%** **10% < X < 25%** **X <10%**

Materials	**weight**	**GER**	**water (p + c)**	**haz. waste**	**haz. waste**	**GWP**	**AD**	**VOC**	**POP**	**HMa**	**PAH**	**PM**	**HMw**	**EUP**
Cathode active material	21%	21%	32%	0%	66%	29%	66%	53%	21%	62%	3%	39%	37%	48%
Cathode, other materials	7%	8%	2%	0%	2%	8%	2%	3%	5%	2%	15%	8%	4%	3%
Cell anode	24%	14%	1%	0%	1%	10%	15%	9%	7%	13%	2%	5%	22%	9%
Cell electrolyte	12%	4%	4%	0%	12%	4%	1%	8%	2%	4%	0%	3%	0%	4%
Cell seperator	2%	1%	1%	0%	0%	1%	0%	0%	1%	0%	2%	1%	1%	0%
Auxillary materials		16%	54%	0%	8%	15%	4%	26%	10%	14%	2%	14%	1%	36%
Cell packaging	9%	9%	0%	0%	2%	9%	3%	0%	9%	1%	24%	9%	7%	0%
Module	5%	5%	1%	0%	2%	5%	1%	0%	8%	1%	10%	6%	3%	0%
System - BMS	4%	3%	2%	40%	2%	3%	4%	0%	10%	3%	0%	1%	8%	0%
System - thermal man.	4%	4%	0%	0%	1%	4%	1%	0%	6%	0%	12%	4%	3%	0%
System packaging	12%	13%	4%	60%	5%	13%	4%	0%	21%	1%	29%	10%	13%	0%

5.2.5. EcoReport LCA results BC5 – truck PHEV

Table 32 provides the environmental impact results in absolute values for 1 kWh delivered by a battery system in a plug-in hybrid vehicle truck. Figure 5 is a graphical presentation of the LCA results of BC5.

Table 32: EcoReport LCA results per FU of for BC5 Truck PHEV



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EcoReport 2014: OUTPUTS
Assessment of Environmental Impact

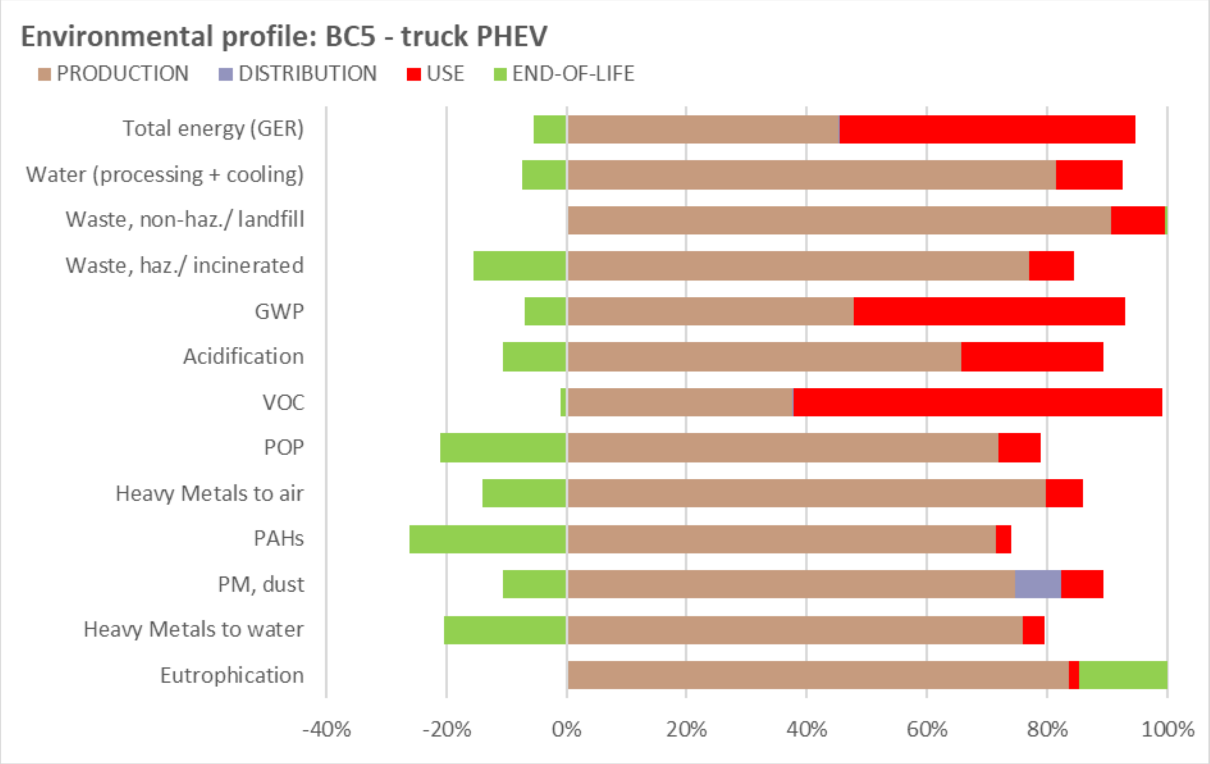
ECO-DESIGN OF ENERGY-RELATED PRODUCTS

Life Cycle Impact (per FU) of Batteries - BC5: Truck PHEV

Nr	Life cycle Impact per product:	Reference year	Author
	Batteries - BC5: Truck PHEV	2018	vito

Nr	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	END-OF-LIFE			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total	BUTION		Disposal	Recycl.	Stock	
	Materials	**unit**									
1	Bulk Plastics	g			**0.26**		**0.00**	0.14	0.12	0.00	**0.00**
2	TecPlastics	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
3	Ferro	g			**0.40**		**0.00**	0.02	0.38	0.00	**0.00**
4	Non-ferro	g			**2.24**		**0.00**	0.11	2.13	0.00	**0.00**
5	Coating	g			**0.04**		**0.00**	0.00	0.03	0.00	**0.00**
6	Electronics	g			**0.07**		**0.00**	0.04	0.04	0.00	**0.00**
7	Misc.	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
8	Extra	g			**2.66**		**0.00**	2.39	0.27	0.00	**0.00**
9	Auxiliaries	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
10	Refrigerant	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
	Total weight	g			**5.66**		**0.00**	2.71	2.96	0.00	**0.00**
	Other Resources & Waste							debet	credit		
11	Total Energy (GER)	MJ	0.97	0.64	**1.60**	**0.00**	**1.74**	0.03	-0.22		**3.16**
12	of which, electricity (in primary MJ)	MJ	0.25	0.61	**0.86**	**0.00**	**1.73**	0.00	-0.05		**2.54**
13	Water (process)	ltr	0.48	0.00	**0.48**	**0.00**	**0.00**	0.00	-0.03		**0.46**
14	Water (cooling)	ltr	0.08	0.04	**0.12**	**0.00**	**0.08**	0.00	-0.03		**0.17**
15	Waste, non-haz./ landfill	g	9.44	0.47	**9.91**	**0.00**	**0.99**	1.14	-1.11		**10.94**
16	Waste, hazardous/ incinerated	g	0.31	0.01	**0.32**	**0.00**	**0.03**	0.00	-0.06		**0.28**
	Emissions (Air)										
17	Greenhouse Gases in GWP100	kg CO2 eq.	0.05	0.03	**0.08**	**0.00**	**0.07**	0.00	-0.01		**0.14**
18	Acidification, emissions	g SO2 eq.	0.81	0.12	**0.93**	**0.00**	**0.34**	0.00	-0.15		**1.12**
19	Volatile Organic Compounds (VOC)	g	0.01	0.01	**0.02**	**0.00**	**0.04**	0.00	0.00		**0.06**
20	Persistent Organic Pollutants (POP)	ng i-Teq	0.04	0.00	**0.05**	**0.00**	**0.00**	0.00	-0.01		**0.04**
21	Heavy Metals	mg Ni eq.	0.25	0.01	**0.26**	**0.00**	**0.02**	0.00	-0.05		**0.23**
22	PAHs	mg Ni eq.	0.17	0.00	**0.17**	**0.00**	**0.01**	0.00	-0.06		**0.12**
23	Particulate Matter (PM, dust)	g	0.08	0.01	**0.08**	**0.01**	**0.01**	0.00	-0.02		**0.09**
	Emissions (Water)										
24	Heavy Metals	mg Hg/20	0.19	0.00	**0.19**	**0.00**	**0.01**	0.00	-0.05		**0.15**
25	Eutrophication	g PO4	0.03	0.00	**0.03**	**0.00**	**0.00**	0.01	0.00		**0.04**

Figure 5: Relative contribution of the life cycle stages per FU of BC5 Truck PHEV based on the EcoReport LCA results



The table below shows the relative contribution to the impact caused by the raw materials of the different battery system components in BC5 per impact category.

Table 33: Results for raw materials used in the production phase per FU of BC5 Truck PHEV based on the EcoReport LCA results

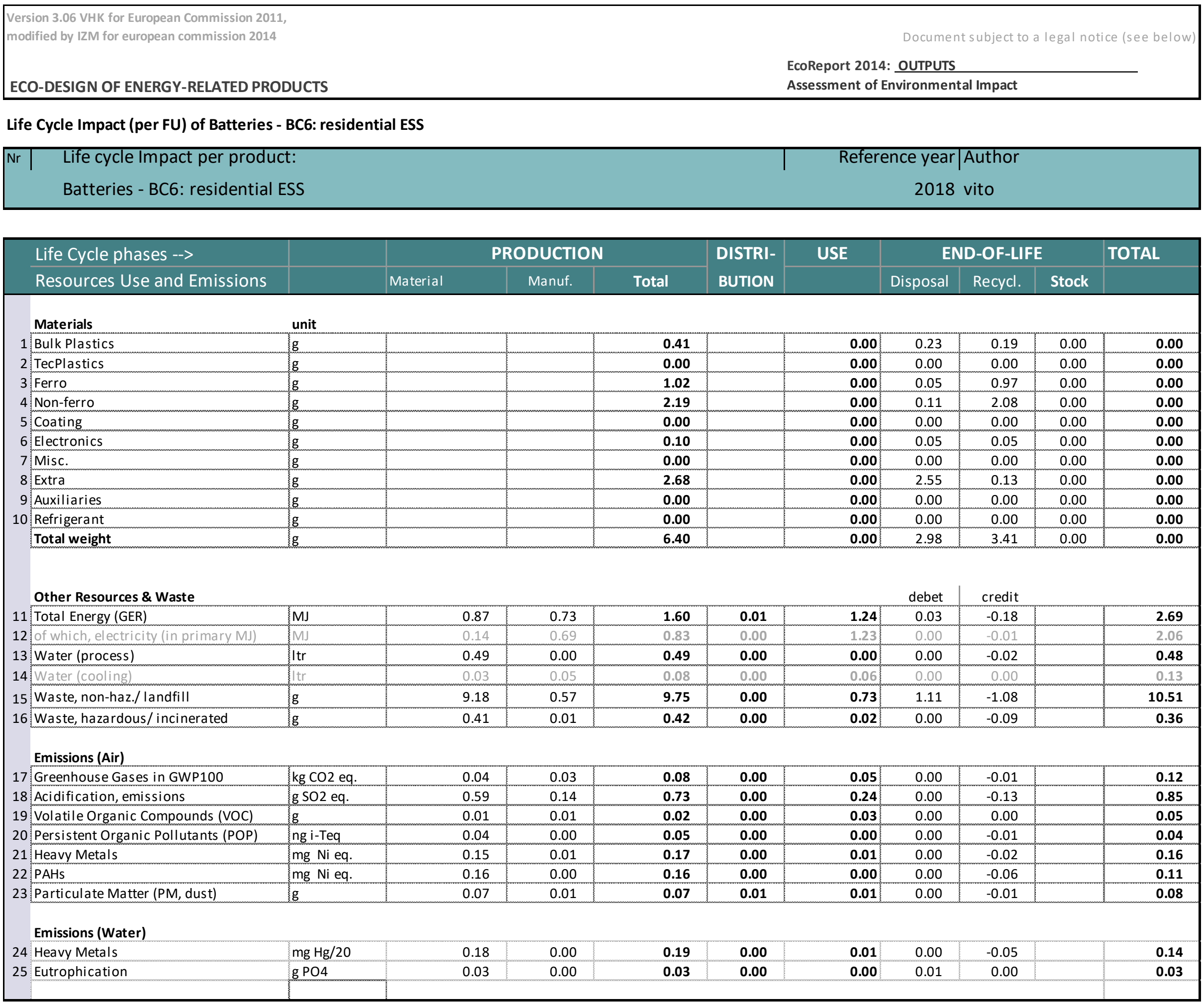
Contribution to impact category 🟥 X > 50% 🟧 25% < X < 50% 🟨 10% < X < 25% 🟩 X <10%

Materials	**weight**	**GER**	**water (p + c)**	**haz. waste**	**haz. waste**	**GWP**	**AD**	**VOC**	**POP**	**HMa**	**PAH**	**PM**	**HMw**	**EUP**
Cathode active material	20%	15%	24%	0%	56%	21%	48%	46%	9%	36%	2%	30%	24%	34%
Cathode, other materials	6%	6%	2%	0%	1%	6%	2%	3%	3%	1%	11%	7%	4%	2%
Cell anode	20%	11%	1%	0%	1%	8%	16%	9%	4%	10%	2%	4%	20%	8%
Cell electrolyte	12%	4%	3%	0%	12%	3%	1%	9%	1%	3%	0%	3%	0%	4%
Cell seperator	2%	2%	1%	0%	0%	1%	0%	0%	1%	0%	3%	1%	1%	0%
Auxillary materials		15%	50%	0%	9%	14%	5%	30%	7%	14%	2%	15%	2%	39%
Cell packaging	10%	19%	13%	1%	9%	18%	12%	2%	39%	29%	23%	12%	11%	11%
Module	5%	5%	1%	0%	2%	5%	2%	0%	5%	1%	10%	7%	3%	0%
System - BMS	5%	4%	3%	39%	3%	3%	6%	0%	8%	4%	0%	1%	12%	0%
System - thermal man.	5%	5%	0%	0%	1%	5%	2%	0%	5%	0%	14%	6%	5%	0%
System packaging	15%	15%	4%	59%	6%	15%	6%	1%	18%	2%	33%	14%	18%	0%

5.2.6. EcoReport LCA results BC6 – residential ESS

Table 34 provides the environmental impact results in absolute values for 1 kWh delivered by a battery system in a residential energy storage system. Figure 6 is a graphical presentation of the LCA results of BC6.

Table 34: EcoReport LCA results per FU of for BC6 residential ESS



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EcoReport 2014: OUTPUTS
Assessment of Environmental Impact

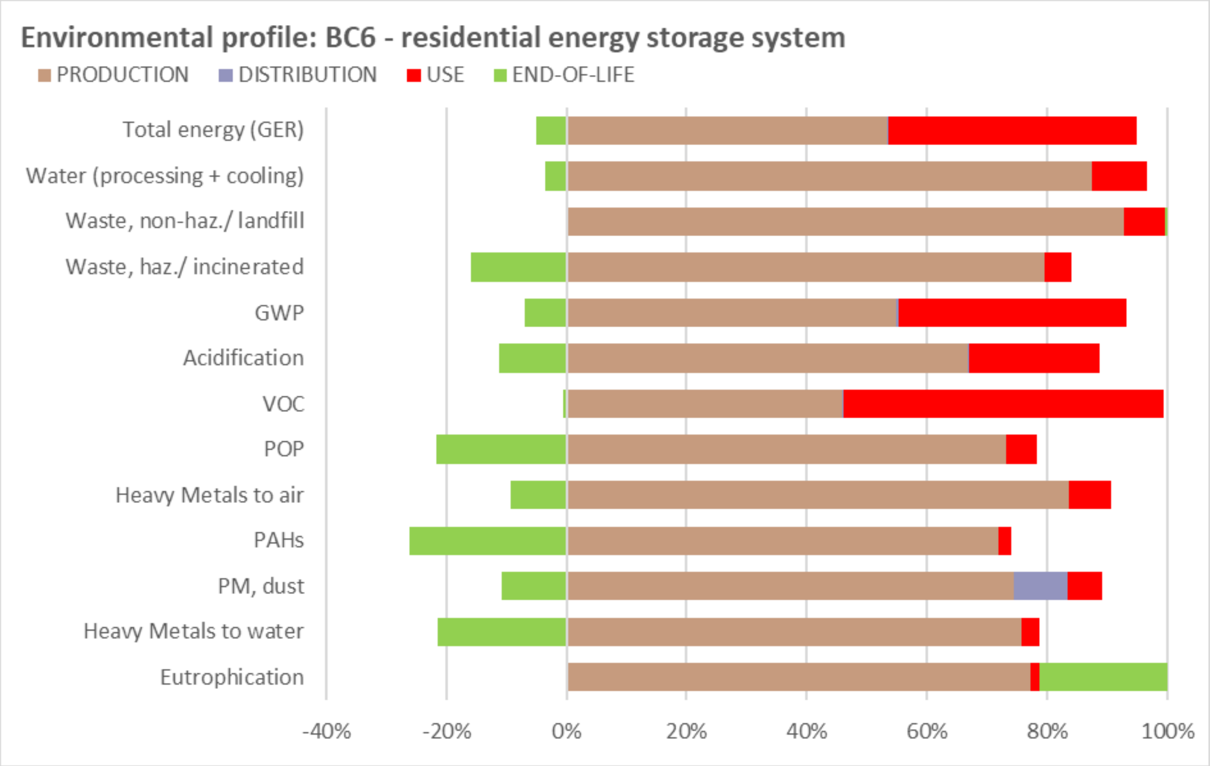
ECO-DESIGN OF ENERGY-RELATED PRODUCTS

Life Cycle Impact (per FU) of Batteries - BC6: residential ESS

Nr	Life cycle Impact per product:	Reference year	Author
	Batteries - BC6: residential ESS	2018	vito

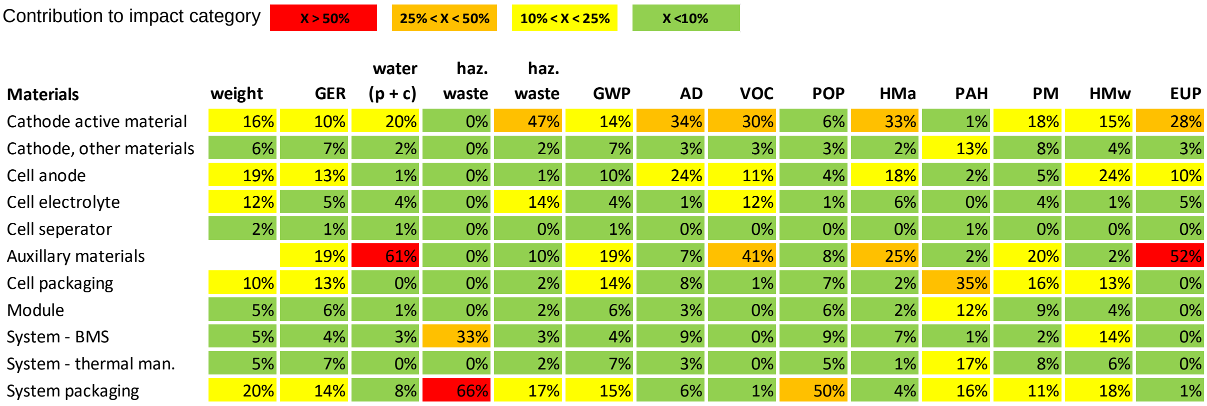
	Life Cycle phases --> Resources Use and Emissions		PRODUCTION Material	 Manuf.	 **Total**	**DISTRI- BUTION**	**USE**	**END-OF-LIFE** Disposal	 Recycl.	 **Stock**	**TOTAL**
	Materials	**unit**									
1	Bulk Plastics	g			**0.41**		**0.00**	0.23	0.19	0.00	**0.00**
2	TecPlastics	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
3	Ferro	g			**1.02**		**0.00**	0.05	0.97	0.00	**0.00**
4	Non-ferro	g			**2.19**		**0.00**	0.11	2.08	0.00	**0.00**
5	Coating	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
6	Electronics	g			**0.10**		**0.00**	0.05	0.05	0.00	**0.00**
7	Misc.	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
8	Extra	g			**2.68**		**0.00**	2.55	0.13	0.00	**0.00**
9	Auxiliaries	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
10	Refrigerant	g			**0.00**		**0.00**	0.00	0.00	0.00	**0.00**
	Total weight	g			**6.40**		**0.00**	2.98	3.41	0.00	**0.00**
	Other Resources & Waste							debet	credit		
11	Total Energy (GER)	MJ	0.87	0.73	**1.60**	**0.01**	**1.24**	0.03	-0.18		**2.69**
12	of which, electricity (in primary MJ)	MJ	0.14	0.69	**0.83**	**0.00**	**1.23**	0.00	-0.01		**2.06**
13	Water (process)	ltr	0.49	0.00	**0.49**	**0.00**	**0.00**	0.00	-0.02		**0.48**
14	Water (cooling)	ltr	0.03	0.05	**0.08**	**0.00**	**0.06**	0.00	0.00		**0.13**
15	Waste, non-haz./ landfill	g	9.18	0.57	**9.75**	**0.00**	**0.73**	1.11	-1.08		**10.51**
16	Waste, hazardous/ incinerated	g	0.41	0.01	**0.42**	**0.00**	**0.02**	0.00	-0.09		**0.36**
	Emissions (Air)										
17	Greenhouse Gases in GWP100	kg CO2 eq.	0.04	0.03	**0.08**	**0.00**	**0.05**	0.00	-0.01		**0.12**
18	Acidification, emissions	g SO2 eq.	0.59	0.14	**0.73**	**0.00**	**0.24**	0.00	-0.13		**0.85**
19	Volatile Organic Compounds (VOC)	g	0.01	0.01	**0.02**	**0.00**	**0.03**	0.00	0.00		**0.05**
20	Persistent Organic Pollutants (POP)	ng i-Teq	0.04	0.00	**0.05**	**0.00**	**0.00**	0.00	-0.01		**0.04**
21	Heavy Metals	mg Ni eq.	0.15	0.01	**0.17**	**0.00**	**0.01**	0.00	-0.02		**0.16**
22	PAHs	mg Ni eq.	0.16	0.00	**0.16**	**0.00**	**0.00**	0.00	-0.06		**0.11**
23	Particulate Matter (PM, dust)	g	0.07	0.01	**0.07**	**0.01**	**0.01**	0.00	-0.01		**0.08**
	Emissions (Water)										
24	Heavy Metals	mg Hg/20	0.18	0.00	**0.19**	**0.00**	**0.01**	0.00	-0.05		**0.14**
25	Eutrophication	g PO4	0.03	0.00	**0.03**	**0.00**	**0.00**	0.01	0.00		**0.03**

Figure 6: Relative contribution of the life cycle stages per FU of BC6 residential ESS based on the EcoReport LCA results



The table below shows the relative contribution to the impact caused by the raw materials of the different battery system components in BC6 per impact category.

Table 35: Results for raw materials used in the production phase per FU of BC6 residential ESS based on the EcoReport LCA results



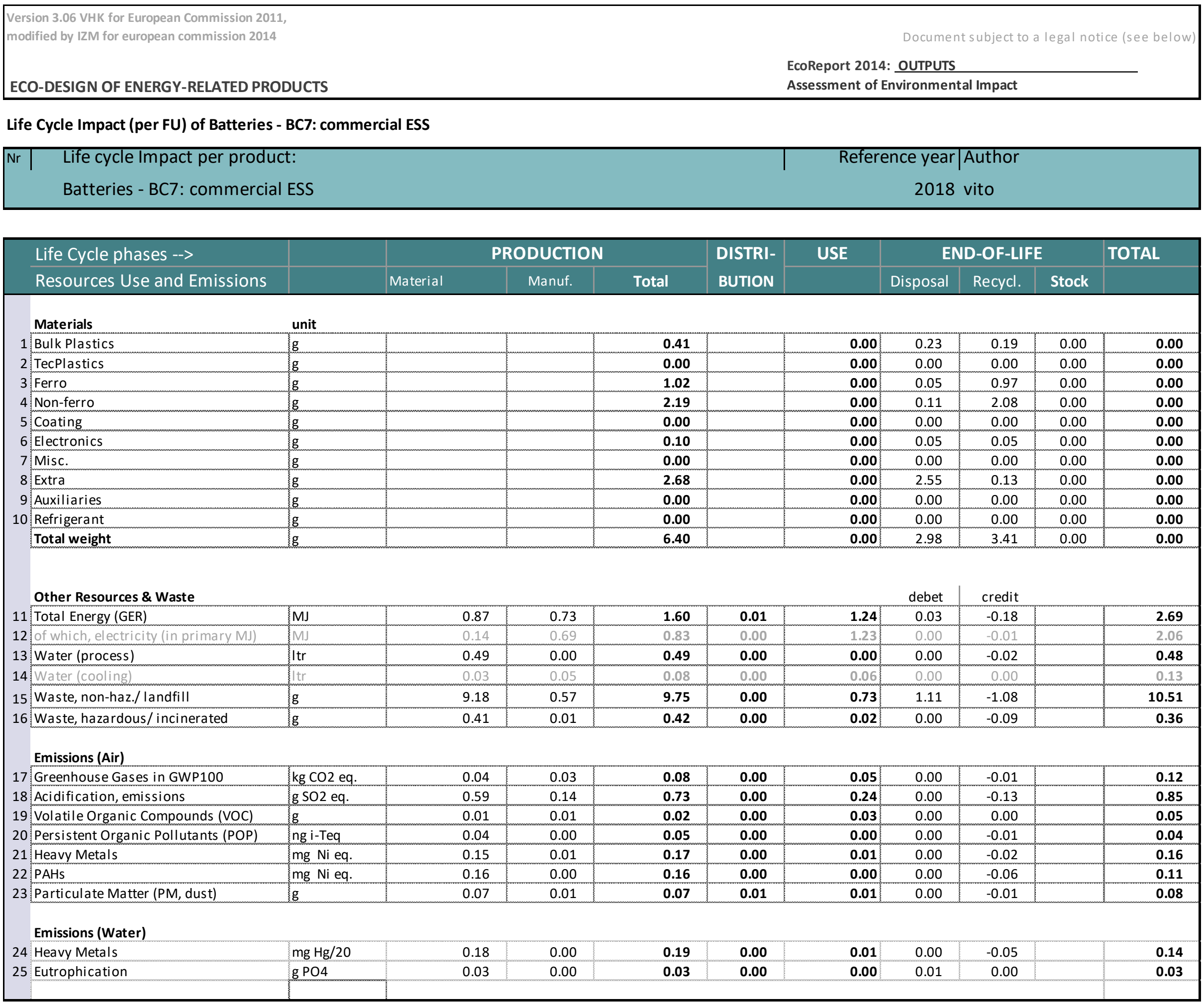
Contribution to impact category 🟥 X > 50% 🟧 25% < X < 50% 🟨 10% < X < 25% 🟩 X <10%

Materials	weight	GER	water (p + c)	haz. waste	haz. waste	GWP	AD	VOC	POP	HMa	PAH	PM	HMw	EUP
Cathode active material	16%	10%	20%	0%	47%	14%	34%	30%	6%	33%	1%	18%	15%	28%
Cathode, other materials	6%	7%	2%	0%	2%	7%	3%	3%	3%	2%	13%	8%	4%	3%
Cell anode	19%	13%	1%	0%	1%	10%	24%	11%	4%	18%	2%	5%	24%	10%
Cell electrolyte	12%	5%	4%	0%	14%	4%	1%	12%	1%	6%	0%	4%	1%	5%
Cell seperator	2%	1%	1%	0%	0%	1%	0%	0%	0%	0%	1%	0%	0%	0%
Auxillary materials		19%	61%	0%	10%	19%	7%	41%	8%	25%	2%	20%	2%	52%
Cell packaging	10%	13%	0%	0%	2%	14%	8%	1%	7%	2%	35%	16%	13%	0%
Module	5%	6%	1%	0%	2%	6%	3%	0%	6%	2%	12%	9%	4%	0%
System - BMS	5%	4%	3%	33%	3%	4%	9%	0%	9%	7%	1%	2%	14%	0%
System - thermal man.	5%	7%	0%	0%	2%	7%	3%	0%	5%	1%	17%	8%	6%	0%
System packaging	20%	14%	8%	66%	17%	15%	6%	1%	50%	4%	16%	11%	18%	1%

5.2.7. EcoReport LCA results BC7 – commercial ESS

Table 36 provides the environmental impact results in absolute values for 1 kWh delivered by a battery system in a residential energy storage system. Figure 7 is a graphical presentation of the LCA results of BC7.

Table 36: EcoReport LCA results per FU of for BC7 commercial ESS



Version 3.06 VHK for European Commission 2011,
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Document subject to a legal notice (see below)

EcoReport 2014: OUTPUTS
Assessment of Environmental Impact

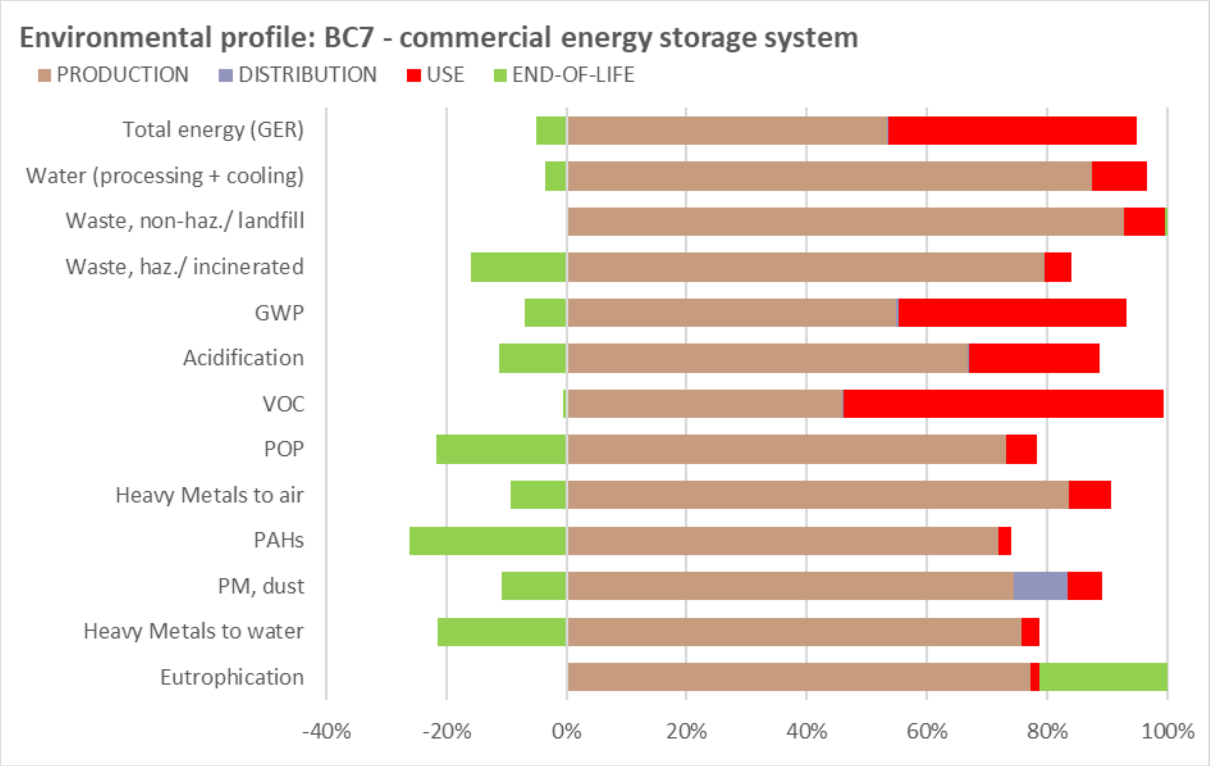
ECO-DESIGN OF ENERGY-RELATED PRODUCTS

Life Cycle Impact (per FU) of Batteries - BC7: commercial ESS

Nr	Life cycle Impact per product:	Reference year	Author
	Batteries - BC7: commercial ESS	2018	vito

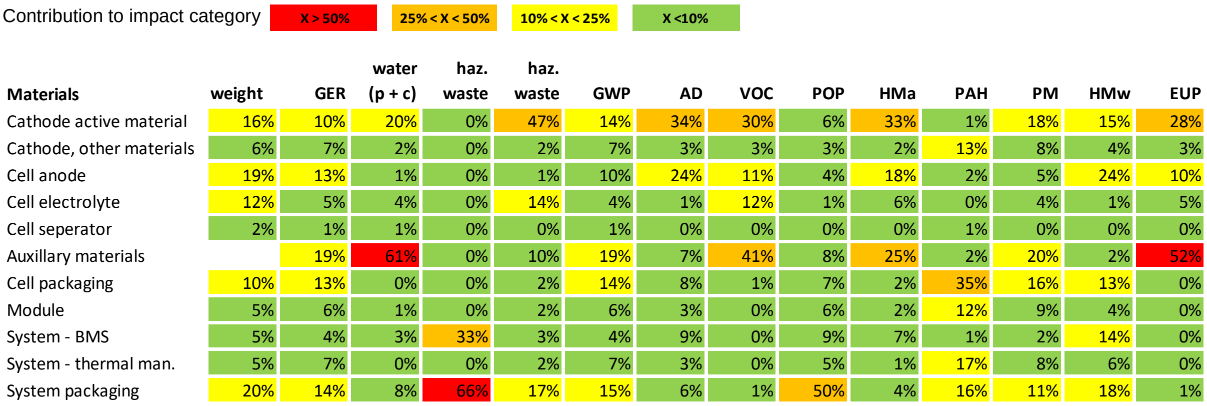
	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	END-OF-LIFE			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total	BUTION		Disposal	Recycl.	Stock	
	Materials	**unit**									
1	Bulk Plastics	g			0.41		0.00	0.23	0.19	0.00	0.00
2	TecPlastics	g			0.00		0.00	0.00	0.00	0.00	0.00
3	Ferro	g			1.02		0.00	0.05	0.97	0.00	0.00
4	Non-ferro	g			2.19		0.00	0.11	2.08	0.00	0.00
5	Coating	g			0.00		0.00	0.00	0.00	0.00	0.00
6	Electronics	g			0.10		0.00	0.05	0.05	0.00	0.00
7	Misc.	g			0.00		0.00	0.00	0.00	0.00	0.00
8	Extra	g			2.68		0.00	2.55	0.13	0.00	0.00
9	Auxiliaries	g			0.00		0.00	0.00	0.00	0.00	0.00
10	Refrigerant	g			0.00		0.00	0.00	0.00	0.00	0.00
	Total weight	g			6.40		0.00	2.98	3.41	0.00	0.00
	Other Resources & Waste							debet	credit		
11	Total Energy (GER)	MJ	0.87	0.73	1.60	0.01	1.24	0.03	-0.18		2.69
12	of which, electricity (in primary MJ)	MJ	0.14	0.69	0.83	0.00	1.23	0.00	-0.01		2.06
13	Water (process)	ltr	0.49	0.00	0.49	0.00	0.00	0.00	-0.02		0.48
14	Water (cooling)	ltr	0.03	0.05	0.08	0.00	0.06	0.00	0.00		0.13
15	Waste, non-haz./ landfill	g	9.18	0.57	9.75	0.00	0.73	1.11	-1.08		10.51
16	Waste, hazardous/ incinerated	g	0.41	0.01	0.42	0.00	0.02	0.00	-0.09		0.36
	Emissions (Air)										
17	Greenhouse Gases in GWP100	kg CO2 eq.	0.04	0.03	0.08	0.00	0.05	0.00	-0.01		0.12
18	Acidification, emissions	g SO2 eq.	0.59	0.14	0.73	0.00	0.24	0.00	-0.13		0.85
19	Volatile Organic Compounds (VOC)	g	0.01	0.01	0.02	0.00	0.03	0.00	0.00		0.05
20	Persistent Organic Pollutants (POP)	ng i-Teq	0.04	0.00	0.05	0.00	0.00	0.00	-0.01		0.04
21	Heavy Metals	mg Ni eq.	0.15	0.01	0.17	0.00	0.01	0.00	-0.02		0.16
22	PAHs	mg Ni eq.	0.16	0.00	0.16	0.00	0.00	0.00	-0.06		0.11
23	Particulate Matter (PM, dust)	g	0.07	0.01	0.07	0.01	0.01	0.00	-0.01		0.08
	Emissions (Water)										
24	Heavy Metals	mg Hg/20	0.18	0.00	0.19	0.00	0.01	0.00	-0.05		0.14
25	Eutrophication	g PO4	0.03	0.00	0.03	0.00	0.00	0.01	0.00		0.03

Figure 7: Relative contribution of the life cycle stages per FU of BC7 commercial ESS based on the EcoReport LCA results



The table below shows the relative contribution to the impact caused by the raw materials of the different battery system components in BC7 per impact category.

Table 37: Results for raw materials used in the production phase per FU of BC7 commercial ESS based on the EcoReport LCA results



Contribution to impact category X > 50% 25% < X < 50% 10% < X < 25% X <10%

Materials	weight	GER	water (p + c)	haz. waste	haz. waste	GWP	AD	VOC	POP	HMa	PAH	PM	HMw	EUP
Cathode active material	16%	10%	20%	0%	47%	14%	34%	30%	6%	33%	1%	18%	15%	28%
Cathode, other materials	6%	7%	2%	0%	2%	7%	3%	3%	3%	2%	13%	8%	4%	3%
Cell anode	19%	13%	1%	0%	1%	10%	24%	11%	4%	18%	2%	5%	24%	10%
Cell electrolyte	12%	5%	4%	0%	14%	4%	1%	12%	1%	6%	0%	4%	1%	5%
Cell seperator	2%	1%	1%	0%	0%	1%	0%	0%	0%	0%	1%	0%	0%	0%
Auxillary materials		19%	61%	0%	10%	19%	7%	41%	8%	25%	2%	20%	2%	52%
Cell packaging	10%	13%	0%	0%	2%	14%	8%	1%	7%	2%	35%	16%	13%	0%
Module	5%	6%	1%	0%	2%	6%	3%	0%	6%	2%	12%	9%	4%	0%
System - BMS	5%	4%	3%	33%	3%	4%	9%	0%	9%	7%	1%	2%	14%	0%
System - thermal man.	5%	7%	0%	0%	2%	7%	3%	0%	5%	1%	17%	8%	6%	0%
System packaging	20%	14%	8%	66%	17%	15%	6%	1%	50%	4%	16%	11%	18%	1%

5.2.8. Critical Raw Materials

The Critical Raw Material (CRM) indicator in this preparatory study is calculated according to MEErP 2011. There are 14 CRMs listed in the MEErP methodology, however the number of CRMs for the EU has increased to 27 in 2017[12]. There are two raw materials within battery systems that are seen as CRMs: i.e. cobalt and natural graphite. Lithium, manganese, and nickel are also used in battery systems, but are still assessed as non-critical raw materials (non-CRMs) by the EC[13]. Although the latter three materials are not yet seen as critical, the three are included in this assessment as the criticality threshold can be passed when the demand for the three materials increases.

The CRM indicator in the EcoReport tool is calculated by multiplying the weight of a CRM (in kg) with a material specific characterisation factor (CF) with the unit kg antimony (Sb) equivalent per kg CRM. The CFs are calculated with the following formula provided in the MEErP methodology report part 2:

- CF [kg Sb eq./kg CRM] = 451 / (A * B * C * (1 – D))

In which: A = the EU consumption [ton/yr]
B = the import dependency rate [%]
C = the substitutability supply risk [%]
D = the recycling rate [%]

The number 451 is the result of (A * B * C1 * (1 – D)) of the reference material antimony. However, this value is based on figures dating from 2006-2007 and the EU consumption, substitutability supply risk and recycling rate of antimony have changed much. When using data from the 2017 CRM Factsheets of the EC (Deloitte, et al. 2017) for A, B and C, and additional sources for the recycling rate D, the multiplication for antimony will result in 13 392. Because of the big difference between 451 and 13 392, the study team of this preparatory study decided to use the updated figure to determine the CRM indicator of all the other (non-)CRMs within this study. Thus changing the formula into:

- CF [kg Sb eq./kg CRM] = 13 392 / (A * B * C * (1 – D))

The data used to calculate the updated and additional CFs (European Commision 2017, Deloitte, et al. 2017, and see also footnote 14) and the resulting CFs are given in the table below.

---

[12] http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

[13] https://publications.europa.eu/en/publication-detail/-/publication/6f1e28a7-98fb-11e7-b92d-01aa75ed71a1/language-en

Table 38: Input values for and result of the calculation of the updated and additional CRM characterisation factors

	EU consumption (A) [ton/yr]	Import dependency rate (B) [%]	Substitutability supply risk (C) [%]	Recycling rate (D) [%] [14]	A*B*C*(1 – D)	Characteri-sation factor (kg Sb eq./kg)
Antimony (CRM)	18 000	100	93	20	13 392.0	1.00
Cobalt (CRM)	30 000	32	100	68	3072.0	4.36
Lithium (non-CRM)	4 200	86	91	0	3 286.9	4.07
Manganese (non-CRM)	1 400 000	89	100	53	585 620.0	0.02
Natural graphite (CRM)	91 000	99	97	3	84 765.7	0.16
Nickel (non-CRM)	300 000	59	96	58	71 366.4	0.19

Table 39 gives the overview of the CRM indicators for all BCs, calculated with the CFs in Table 38. The share of the CRM indictor of each material in the CRM indicator of the total battery system are also included in Table 39. In addition, the weight of the total battery system and of the (non-)CRM are also given per FU in absolute figures and relative numbers for the individual materials, based on the total numbers of batteries needed in application and including replacements.

---

[14] In the (non-)CRM factsheets of the EC not all recycling rates are included (though the recycling input rate (EOL-RIR) are presented for each material, also known as the recycled content). The recycling rates presented here are general rates i.e. not specific for EV batteries as CRM characterisation factors need to be applicable for every type of product group not only for EV batteries. To determine the recycling rates the following sources were used:

- Antimony (UNEP 2011, Dupont, et al. 2016)
- Cobalt (UNEP 2011, Deloitte, et al. 2017)
- Lithium (UNEP 2011)
- Manganese (UNEP 2011)
- Natural graphite (Deloitte, et al. 2017)
- Nickel (Ellingsen and Hung 2018, UNEP 2011)

Table 39: Overview of the critical raw materials per FU per BC

		BC1	BC2	BC3	BC4	BC5	BC6	BC7
		PC BEV HIGH	PC BEV LOW	PC PHEV	Truck BEV	Truck PHEV	Resid. ESS	Comm. ESS
Total battery appl. system(s)	Weight [g/FU]	13.93	20.58	12.82	6.52	5.66	6.40	6.40
	CRM indicator	$2.82\cdot10^{-3}$	$4.17\cdot10^{-3}$	$1.74\cdot10^{-3}$	$1.01\cdot10^{-3}$	$7.67\cdot10^{-4}$	$4.44\cdot10^{-4}$	$4.44\cdot10^{-4}$
Cobalt	Weight [g/FU]	0.22	0.32	0.13	0.07	0.06	0.01	0.01
	[%]	1.57	1.57	0.99	1.08	0.99	0.23	0.23
	CRM indicator	$9.54\cdot10^{-4}$	$1.41\cdot10^{-3}$	$5.56\cdot10^{-4}$	$3.08\cdot10^{-4}$	$2.46\cdot10^{-4}$	$6.37\cdot10^{-5}$	$6.37\cdot10^{-5}$
	[%]	33.82	33.82	32.00	30.38	32.00	14.35	14.35
Lithium	Weight [g/FU]	0.34	0.50	0.21	0.12	0.09	0.06	0.06
	[%]	2.44	2.44	1.67	1.91	1.67	0.98	0.98
	CRM indicator	$1.39\cdot10^{-3}$	$2.05\cdot10^{-3}$	$8.70\cdot10^{-4}$	$5.09\cdot10^{-4}$	$3.84\cdot10^{-4}$	$2.55\cdot10^{-4}$	$2.55\cdot10^{-4}$
	[%]	49.19	49.19	50.08	50.27	50.08	57.38	57.38
Manganese	Weight [g/FU]	0.39	0.58	0.26	0.05	0.12	0.01	0.01
	[%]	2.81	2.81	2.05	0.74	2.05	0.12	0.12
	CRM indicator	$8.96\cdot10^{-6}$	$1.32\cdot10^{-5}$	$6.02\cdot10^{-6}$	$1.10\cdot10^{-6}$	$2.66\cdot10^{-6}$	$1.80\cdot10^{-7}$	$1.80\cdot10^{-7}$
	[%]	0.32	0.32	0.35	0.11	0.35	0.04	0.04
Natural graphite	Weight [g/FU]	2.00	2.95	1.62	0.93	0.72	0.72	0.72
	[%]	14.34	14.34	12.61	14.25	12.61	11.32	11.32
	CRM indicator	$3.16\cdot10^{-4}$	$4.66\cdot10^{-4}$	$2.56\cdot10^{-4}$	$1.47\cdot10^{-4}$	$1.13\cdot10^{-4}$	$1.14\cdot10^{-4}$	$1.14\cdot10^{-4}$
	[%]	11.20	11.20	14.70	14.51	12.61	25.78	25.78
Nickel	Weight [g/FU]	0.82	1.21	0.27	0.25	0.12	0.06	0.06
	[%]	5.90	5.90	2.07	3.91	2.07	0.91	0.91
	CRM indicator	$1.54\cdot10^{-4}$	$2.28\cdot10^{-4}$	$4.99\cdot10^{-5}$	$4.78\cdot10^{-5}$	$2.20\cdot10^{-5}$	$1.09\cdot10^{-6}$	$1.09\cdot10^{-6}$
	[%]	5.47	5.47	2.87	4.72	2.87	2.45	2.45

Based on Table 39 it can be concluded that for the CRM in EV batteries lithium and cobalt are the biggest contributors to the CRM indicator for the EV base cases (BC1 to 5) and for the ESS base cases (BC 6 and 7) lithium and natural graphite. This is because cobalt and lithium have high CRM characterisation factors compared to the other materials. The high CF of cobalt is caused by the import dependency and for lithium because it is not being recycled. The amount of cobalt (and manganese) is much lower in the ESS base cases compared to the EV base cases, which causes the shift from cobalt to natural graphite of becoming the second biggest contributor to the CRM indicator for BC 6 and 7.

5.3. Subtask 5.3 – Base Case Life Cycle Costs

AIM OF SUBTASK 5.3:

The Life Cycle Costs (LCC) and Levelized Cost Of Energy (LCOE) for the consumer are calculated per BC, for more background information on LCC and LCOE see section 5.1.2.1. Given the complexity of the LCC and LCOE calculation, a separate calculation spreadsheet was created instead of using the EcoReport tool. But for the calculation of the societal LCC the EcoReport is used, as the societal LCC are linked to the emissions to air calculated with the EcoReport. Section 5.3.1 presents the LCC and LCOE results of all base cases and section 5.3.2 the LCC for society.

5.3.1. LCC and LCOE results of all Base Cases

An overview of all the assumptions made to calculate the LCC and LCOE is given Table 40. Data has been sourced from previous sections. The LCC and LCOE results of all BCs are summarised in Table 41. The calculation details per year are given in the next sub-sections per BC.

Table 40: Overview of the assumed parameters for the LCC and LCOE of the Base Cases

	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
Economic lifetime of application (Tapp) [yr]	13	14	13	14	12	20	20
Application service energy (AS) [kWh/Tapp]	43 680	29 568	19 656	940 800	890 400	40 000	120 x 10^6
Service life of battery (Tbat) [y]	14.40	13.43	10.67	8.04	5.33	17.02	17.02
Nominal battery system capacity [kWh]	80	40	12	30	20	10	10
Number of batteries in the application [-]	1	1	1	12	8	1	3 000
Number of battery application systems per Tapp (Ass) [-]	1	2	2	2	3	2	2
Average efficiency of battery system [%]	92	92	92	92	92	92	92
Charger efficiency [%]	85	85	85	92	92	98	98
Brake energy recovery [%]	20	20	20	12	6	n.a.	n.a.

Continuation of Table 40: Overview of the assumed parameters for the LCC and LCOE of the Base Cases

	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
Thermal management efficiency [%]	99	99	99	99	99	99	99
Self-discharge (@STC) [%]	2	2	2	2	2	2	2
Electricity cost (incl. VAT) [EUR/kWh][15]	0.213	0.213	0.213	0.101	0.101	0.213	0.101
Discount rate [%]	4	4	4	4	4	4	4
Discount rate electricity [%]	0	0	0	0	0	0	0
CAPEX battery system cost per declared initial capacity [EUR/kWh]	206	206	254	220	212	683	683
OPEX battery system replacement [EUR/service]	700	700	700	400	400	100	100
CAPEX decommissioning battery system at EOL [EUR]	1 200	600	180	450	300	150	150

Table 41: Overview of the life cycle costing results of the Base Cases

	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
LCOE or LCC per FU [EUR/kWh]	0.461	0.547	0.377	0.177	0.125	0.293	0.278
LCC total for all batteries in application per Tapp [EUR/appl.]	20 152	16 179	7 401	166 397	111 511	11 723	33 328 317

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[15] For the commercial sector, costs are typically without VAT.

5.3.1.1. Detailed LCC results BC1 – passenger car BEV with a higher battery capacity

Table 42: Details of the Life Cycle Cost calculation per year for BC1 – PC BEV HIGH

Event	Year	Other PWF ratio	Elec. PWF ratio	CAPEX [euro]	Other OPEX [euro]	Electricity OPEX [euro]	NPV OPEX+CAPEX [euro/yr]	Direct losses elec. per year [kWh]	Indirect losses elec. per year [kWh]
purchase EV	1	1.000	1.000	16 480 €	700 €	173.16 €	17 353.16 €	292.2	520.8
	2	0.925	1.000			173.16 €	173.16 €	292.2	520.8
	3	0.889	1.000			173.16 €	173.16 €	292.2	520.8
	4	0.855	1.000			173.16 €	173.16 €	292.2	520.8
	5	0.822	1.000			173.16 €	173.16 €	292.2	520.8
	6	0.790	1.000			173.16 €	173.16 €	292.2	520.8
	7	0.760	1.000			173.16 €	173.16 €	292.2	520.8
	8	0.731	1.000			173.16 €	173.16 €	292.2	520.8
	9	0.703	1.000			173.16 €	173.16 €	292.2	520.8
	10	0.676	1.000			173.16 €	173.16 €	292.2	520.8
	11	0.650	1.000			173.16 €	173.16 €	292.2	520.8
	12	0.625	1.000			173.16 €	173.16 €	292.2	520.8
EOL	13	0.601	1.000	1 200 €		173.16 €	893.85 €	292.2	520.8
Total				17 680 €	700 €	2 251.12 €	20 151.81 €	3 798.3	6 770.4

5.3.1.2. Detailed LCC results BC2 – passenger car BEV with a lower battery capacity

Table 43: Details of the Life Cycle Cost calculation per year for BC2 – PC BEV LOW

Event	Year	Other PWF ratio	Elec. PWF ratio	CAPEX [euro]	Other OPEX [euro]	Electricity OPEX [euro]	NPV OPEX+CAPEX [euro/yr]	Direct losses elec. per year [kWh]	Indirect losses elec. per year [kWh]
purchase EV	1	1.000	1.000	8 240 €	700 €	108.85 €	9 048.85 €	183.7	327.4
	2	0.925	1.000			108.85 €	108.85 €	183.7	327.4
	3	0.889	1.000			108.85 €	108.85 €	183.7	327.4
	4	0.855	1.000			108.85 €	108.85 €	183.7	327.4
	5	0.822	1.000			108.85 €	108.85 €	183.7	327.4
	6	0.790	1.000			108.85 €	108.85 €	183.7	327.4
	7	0.760	1.000			108.85 €	108.85 €	183.7	327.4
	8	0.731	1.000			108.85 €	108.85 €	183.7	327.4
	9	0.703	1.000			108.85 €	108.85 €	183.7	327.4
	10	0.676	1.000			108.85 €	108.85 €	183.7	327.4
	11	0.650	1.000			108.85 €	108.85 €	183.7	327.4
	12	0.625	1.000			108.85 €	108.85 €	183.7	327.4
O&M	13	0.601	1.000	8 240 €	700 €	108.85 €	5 477.98 €	183.7	327.4
EOL	14	0.577	1.000	600 €		108.85 €	455.33 €	183.7	327.4
Total				17 080 €	1 400 €	1 523.84 €	16 179.46 €	2 571.1	4 583.0

5.3.1.3. Detailed LCC results BC3 – passenger car PHEV

Table 44: Details of the Life Cycle Cost calculation per year for BC3 – PC PHEV

Event	Year	Other PWF ratio	Elec. PWF ratio	CAPEX [euro]	Other OPEX [euro]	Electricity OPEX [euro]	NPV OPEX+CAPEX [euro/yr]	Direct losses elec. per year [kWh]	Indirect losses elec. per year [kWh]
purchase EV	1	1.000	1.000	3 048 €	700 €	77.92 €	3 825.92 €	131.5	234.4
	2	0.925	1.000			77.92 €	77.92 €	131.5	234.4
	3	0.889	1.000			77.92 €	77.92 €	131.5	234.4
	4	0.855	1.000			77.92 €	77.92 €	131.5	234.4
	5	0.822	1.000			77.92 €	77.92 €	131.5	234.4
	6	0.790	1.000			77.92 €	77.92 €	131.5	234.4
	7	0.760	1.000			77.92 €	77.92 €	131.5	234.4
	8	0.731	1.000			77.92 €	77.92 €	131.5	234.4
	9	0.703	1.000			77.92 €	77.92 €	131.5	234.4
O&M	10	0.676	1.000	3 048 €	700 €	77.92 €	2 609.94 €	131.5	234.4
	11	0.650	1.000			77.92 €	77.92 €	131.5	234.4
	12	0.625	1.000			77.92 €	77.92 €	131.5	234.4
EOL	13	0.601	1.000	180 €		77.92 €	186.03 €	131.5	234.4
Total				6 276 €	1 400 €	1 013.01 €	7 401.12 €	1709.2	3 046.7

5.3.1.4. Detailed LCC results BC4 – truck BEV

Table 45: Details of the Life Cycle Cost calculation per year for BC4 – Truck BEV

Event	Year	Other PWF ratio	Elec. PWF ratio	CAPEX [euro]	Other OPEX [euro]	Electricity OPEX [euro]	NPV OPEX+CAPEX [euro/yr]	Direct losses elec. per year [kWh]	Indirect losses elec. per year [kWh]
purchase EV	1	1.000	1.000	79 200 €	4 800 €	1 278.61 €	85 278.61 €	5 843.5	6 816.0
	2	0.925	1.000			1 278.61 €	1 278.61 €	5 843.5	6 816.0
	3	0.889	1.000			1 278.61 €	1 278.61 €	5 843.5	6 816.0
	4	0.855	1.000			1 278.61 €	1 278.61 €	5 843.5	6 816.0
	5	0.822	1.000			1 278.61 €	1 278.61 €	5 843.5	6 816.0
	6	0.790	1.000			1 278.61 €	1 278.61 €	5 843.5	6 816.0
	7	0.760	1.000			1 278.61 €	1 278.61 €	5 843.5	6 816.0
O&M	8	0.731	1.000	79 200 €	4 800 €	1 278.61 €	62 656.58 €	5 843.5	6 816.0
	9	0.703	1.000			1 278.61 €	1 278.61 €	5 843.5	6 816.0
	10	0.676	1.000			1 278.61 €	1 278.61 €	5 843.5	6 816.0
	11	0.650	1.000			1 278.61 €	1 278.61 €	5 843.5	6 816.0
	12	0.625	1.000			1 278.61 €	1 278.61 €	5 843.5	6 816.0
	13	0.601	1.000			1 278.61 €	1 278.61 €	5 843.5	6 816.0
EOL	14	0.577	1.000	5 400 €		1 278.61 €	4 396.97 €	5 843.5	6 816.0
Total				163 800 €	9 600 €	17 900.50 €	166 396.84 €	81 808.7	95 424.0

5.3.1.5. Detailed LCC results BC5 – truck PHEV

Table 46: Details of the Life Cycle Cost calculation per year for BC5 – Truck PHEV

Event	Year	Other PWF ratio	Elec. PWF ratio	CAPEX [euro]	Other OPEX [euro]	Electricity OPEX [euro]	NPV OPEX+CAPEX [euro/yr]	Direct losses elec. per year [kWh]	Indirect losses elec. per year [kWh]
purchase EV	1	1.000	1.000	33 920 €	3 200 €	1 442.10 €	38 562.10 €	6 452.2	7 826.0
	2	0.925	1.000			1 442.10 €	1 442.10 €	6 452.2	7 826.0
	3	0.889	1.000			1 442.10 €	1 442.10 €	6 452.2	7 826.0
	4	0.855	1.000			1 442.10 €	1 442.10 €	6 452.2	7 826.0
O&M	5	0.822	1.000	33 920 €	3 200 €	1 442.10 €	31 952.03 €	6 452.2	7 826.0
	6	0.790	1.000			1 442.10 €	1 442.10 €	6 452.2	7 826.0
	7	0.760	1.000			1 442.10 €	1 442.10 €	6 452.2	7 826.0
	8	0.731	1.000			1 442.10 €	1 442.10 €	6 452.2	7 826.0
	9	0.703	1.000			1 442.10 €	1 442.10 €	6 452.2	7 826.0
O&M	10	0.676	1.000	33 920 €	3 200 €	1 442.10 €	26 519.04 €	6 452.2	7 826.0
	11	0.650	1.000			1 442.10 €	1 442.10 €	6 452.2	7 826.0
EOL	12	0.625	1.000	2 400 €		1 442.10 €	2 941.13 €	6 452.2	7 826.0
Total				104 160 €	9 600 €	17 305.15 €	111 511.06 €	77 426.1	93 912.0

5.3.1.6. Detailed LCC results BC6 – residential ESS

Table 47: Details of the Life Cycle Cost calculation per year for BC6 – residential ESS

Event	Year	Other PWF ratio	Elec. PWF ratio	CAPEX [euro]	Other OPEX [euro]	Electricity OPEX [euro]	NPV OPEX+CAPEX [euro/yr]	Direct losses elec. per year [kWh]	Indirect losses elec. per year [kWh]
purchase EV	1	1.000	1.000	6 830 €	100 €	58.34 €	6 988.34 €	173.9	100.0
	2	0.925	1.000			58.34 €	58.34 €	173.9	100.0
	3	0.889	1.000			58.34 €	58.34 €	173.9	100.0
	4	0.855	1.000			58.34 €	58.34 €	173.9	100.0
	5	0.822	1.000			58.34 €	58.34 €	173.9	100.0
	6	0.790	1.000			58.34 €	58.34 €	173.9	100.0
	7	0.760	1.000			58.34 €	58.34 €	173.9	100.0
	8	0.731	1.000			58.34 €	58.34 €	173.9	100.0
	9	0.703	1.000			58.34 €	58.34 €	173.9	100.0
	10	0.676	1.000			58.34 €	58.34 €	173.9	100.0
	11	0.650	1.000			58.34 €	58.34 €	173.9	100.0
	12	0.625	1.000			58.34 €	58.34 €	173.9	100.0
	13	0.601	1.000			58.34 €	58.34 €	173.9	100.0
	14	0.577	1.000			58.34 €	58.34 €	173.9	100.0
	15	0.555	1.000			58.34 €	58.34 €	173.9	100.0
	16	0.534	1.000			58.34 €	58.34 €	173.9	100.0
O&M	17	0.513	1.000	6 830 €	100 €	58.34 €	3 616.02 €	173.9	100.0
	18	0.494	1.000			58.34 €	58.34 €	173.9	100.0
	19	0.475	1.000			58.34 €	58.34 €	173.9	100.0
EOL	20	0.456	1.000	150 €		58.34 €	126.80 €	173.9	100.0
Total				13 810 €	200 €	1 167 €	11 723 €	3478.3	2000.0

5.3.1.7. Detailed LCC results BC7 – commercial ESS

Table 48: Details of the Life Cycle Cost calculation per year for BC7 – commercial ESS

Event	Year	Other PWF ratio	Elec. PWF ratio	CAPEX [euro]	Other OPEX [euro]	Electricity OPEX [euro]	NPV OPEX+CAPEX [euro/yr]	Direct losses elec. per year [kWh]	Indirect losses elec. per year [kWh]
purchase EV	1	1.000	1.000	20 490 000 €	300 000 €	82 996 €	20 872 996 €	521 739	300 000
	2	0.925	1.000			82 996 €	82 996 €	521 739	300 000
	3	0.889	1.000			82 996 €	82 996 €	521 739	300 000
	4	0.855	1.000			82 996 €	82 996 €	521 739	300 000
	5	0.822	1.000			82 996 €	82 996 €	521 739	300 000
	6	0.790	1.000			82 996 €	82 996 €	521 739	300 000
	7	0.760	1.000			82 996 €	82 996 €	521 739	300 000
	8	0.731	1.000			82 996 €	82 996 €	521 739	300 000
	9	0.703	1.000			82 996 €	82 996 €	521 739	300 000
	10	0.676	1.000			82 996 €	82 996 €	521 739	300 000
	11	0.650	1.000			82 996 €	82 996 €	521 739	300 000
	12	0.625	1.000			82 996 €	82 996 €	521 739	300 000
	13	0.601	1.000			82 996 €	82 996 €	521 739	300 000
	14	0.577	1.000			82 996 €	82 996 €	521 739	300 000
	15	0.555	1.000			82 996 €	82 996 €	521 739	300 000
	16	0.534	1.000			82 996 €	82 996 €	521 739	300 000
O&M	17	0.513	1.000	20 490 000 €	300 000 €	82 996 €	10 756 025 €	521 739	300 000
	18	0.494	1.000			82 996 €	82 996 €	521 739	300 000
	19	0.475	1.000			82 996 €	82 996 €	521 739	300 000
EOL	20	0.456	1.000	450 000 €		82 996 €	288 370 €	521 739	300 000
Total				41 430 000 €	600 000 €	1 659 913 €	33 328 317 €	10 434 783	6 000 000

5.3.2. Life Cycle Costs for society of all Base Cases

Societal LCC are costs for marginal external damages. Within the EcoReport, these costs are only calculated for the emissions to air by multiplying the emissions mass calculated in the EcoReport with fixed rates of external marginal costs to society (see Table 49).

Table 49: External marginal costs to society rates within EcoReport 2014 (main sources mentioned in the MEErP 2011 Methodology part 1: CO2 ETS trading price 1.1.2011, EEA 2011)

Emissions to air	Unit	EUR/unit
Greenhouse gases in GWP100 (GHG)	kg CO2 eq.	0.014
Acidification potential (AP)	g SO2 eq.	0.0085
Volatile organic compounds (VOC)	g	0.00076
Persistent Organic Pollutants (POP)	ng i-Teq	0.000027
Heavy metals: other (HM1)	mg Ni eq.	0.000175
Heavy metals: stainless steel, CRT, bitumen (HM2)	mg Ni eq.	0.00004
Heavy metals: electricity, copper (HM3)	mg Ni eq.	0.0003
Polycyclic aromatic hydrocarbons (PAH)	mg Ni eq.	0.001279
Particulate matter (PM)	g	0.01546

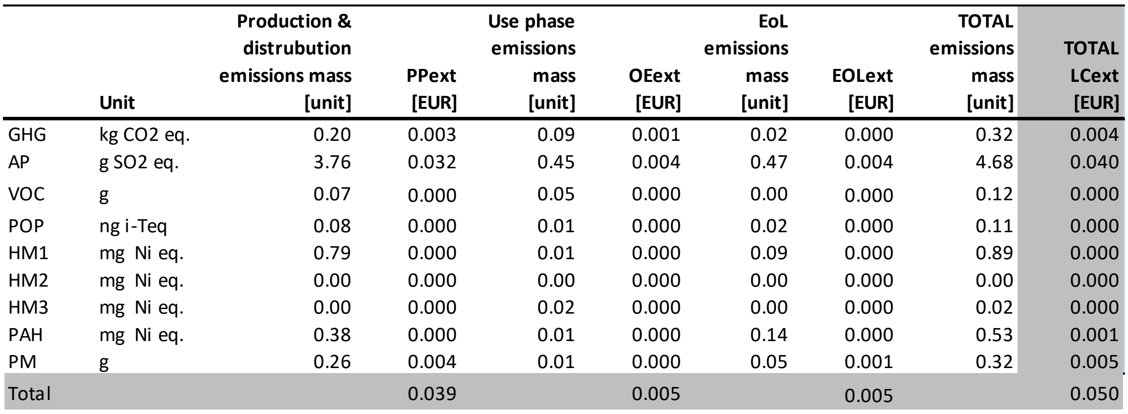
The societal LCC results of all BCs are summarised in Table 50. The calculation details per life cycle phase and impact categories are given in the next sub-sections per BC.

Table 50: Overview of the societal life cycle costing results (marginal external damages) of the Base Cases

	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
Societal LCC per FU [EUR/kWh]	0.050	0.072	0.034	0.021	0.017	0.013	0.013
Societal LCC total for all batteries in application per Tapp [EUR/appl.]	2 189	2 119	663	19 924	14 830	531	1 582 515

5.3.2.1. Detailed societal LCC results BC1 – passenger car BEV with a higher battery capacity

Table 51: Details of the societal Life Cycle Cost (marginal external damages) calculation per FU for BC1 – PC BEV HIGH



	Unit	Production & distrubution emissions mass [unit]	PPext [EUR]	Use phase emissions mass [unit]	OEext [EUR]	EoL emissions mass [unit]	EOLext [EUR]	TOTAL emissions mass [unit]	TOTAL LCext [EUR]
GHG	kg CO2 eq.	0.20	0.003	0.09	0.001	0.02	0.000	0.32	0.004
AP	g SO2 eq.	3.76	0.032	0.45	0.004	0.47	0.004	4.68	0.040
VOC	g	0.07	0.000	0.05	0.000	0.00	0.000	0.12	0.000
POP	ng i-Teq	0.08	0.000	0.01	0.000	0.02	0.000	0.11	0.000
HM1	mg Ni eq.	0.79	0.000	0.01	0.000	0.09	0.000	0.89	0.000
HM2	mg Ni eq.	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000
HM3	mg Ni eq.	0.00	0.000	0.02	0.000	0.00	0.000	0.02	0.000
PAH	mg Ni eq.	0.38	0.000	0.01	0.000	0.14	0.000	0.53	0.001
PM	g	0.26	0.004	0.01	0.000	0.05	0.001	0.32	0.005
Total			0.039		0.005		0.005		0.050

5.3.2.2. Detailed societal LCC results BC2 – passenger car BEV with a lower battery capacity

Table 52: Details of the societal Life Cycle Cost (marginal external damages) per FU for BC2 – PC BEV LOW

	Unit	Production & distrubution emissions mass [unit]	PPext [EUR]	Use phase emissions mass [unit]	OEext [EUR]	EoL emissions mass [unit]	EOLext [EUR]	TOTAL emissions mass [unit]	TOTAL LCext [EUR]
GHG	kg CO2 eq.	0.29	0.004	0.09	0.001	0.04	0.001	0.42	0.006
AP	g SO2 eq.	5.56	0.047	0.46	0.004	0.69	0.006	6.71	0.057
VOC	g	0.10	0.000	0.05	0.000	0.00	0.000	0.15	0.000
POP	ng i-Teq	0.12	0.000	0.01	0.000	0.03	0.000	0.16	0.000
HM1	mg Ni eq.	1.16	0.000	0.01	0.000	0.14	0.000	1.31	0.000
HM2	mg Ni eq.	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000
HM3	mg Ni eq.	0.00	0.000	0.02	0.000	0.00	0.000	0.02	0.000
PAH	mg Ni eq.	0.57	0.001	0.01	0.000	0.20	0.000	0.78	0.001
PM	g	0.39	0.006	0.01	0.000	0.08	0.001	0.47	0.007
Total			0.058		0.006		0.008		0.072

5.3.2.3. Detailed societal LCC results BC3 – passenger car PHEV

Table 53: Details of the societal Life Cycle Cost (marginal external damages) per FU for BC3 – PC PHEV

	Unit	Production & distrubution emissions mass [unit]	PPext [EUR]	Use phase emissions mass [unit]	OEext [EUR]	EoL emissions mass [unit]	EOLext [EUR]	TOTAL emissions mass [unit]	TOTAL LCext [EUR]
GHG	kg CO2 eq.	0.18	0.003	0.09	0.001	0.03	0.000	0.30	0.004
AP	g SO2 eq.	2.11	0.018	0.43	0.004	0.36	0.003	2.90	0.025
VOC	g	0.05	0.000	0.05	0.000	0.00	0.000	0.10	0.000
POP	ng i-Teq	0.10	0.000	0.01	0.000	0.03	0.000	0.14	0.000
HM1	mg Ni eq.	0.59	0.000	0.01	0.000	0.11	0.000	0.71	0.000
HM2	mg Ni eq.	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000
HM3	mg Ni eq.	0.00	0.000	0.02	0.000	0.00	0.000	0.02	0.000
PAH	mg Ni eq.	0.39	0.001	0.01	0.000	0.14	0.000	0.55	0.001
PM	g	0.20	0.003	0.01	0.000	0.04	0.001	0.26	0.004
Total			0.024		0.005		0.004		0.034

5.3.2.4. Detailed societal LCC results BC4 – truck BEV

Table 54: Details of the societal Life Cycle Cost (marginal external damages) per FU for BC4 – Truck BEV

	Unit	Production & distrubution emissions mass [unit]	PPext [EUR]	Use phase emissions mass [unit]	OEext [EUR]	EoL emissions mass [unit]	EOLext [EUR]	TOTAL emissions mass [unit]	TOTAL LCext [EUR]
GHG	kg CO2 eq.	0.09	0.001	0.07	0.001	0.01	0.000	0.17	0.002
AP	g SO2 eq.	1.38	0.012	0.33	0.003	0.19	0.002	1.90	0.016
VOC	g	0.03	0.000	0.04	0.000	0.00	0.000	0.07	0.000
POP	ng i-Teq	0.04	0.000	0.00	0.000	0.01	0.000	0.05	0.000
HM1	mg Ni eq.	0.29	0.000	0.00	0.000	0.04	0.000	0.33	0.000
HM2	mg Ni eq.	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000
HM3	mg Ni eq.	0.00	0.000	0.02	0.000	0.00	0.000	0.02	0.000
PAH	mg Ni eq.	0.19	0.000	0.01	0.000	0.07	0.000	0.26	0.000
PM	g	0.11	0.002	0.01	0.000	0.02	0.000	0.14	0.002
Total			0.015		0.004		0.002		0.021

5.3.2.5. Detailed societal LCC results BC5 – truck PHEV

Table 55: Details of the societal Life Cycle Cost (marginal external damages) per FU for BC5 – Truck PHEV

	Unit	Production & distrubution emissions mass [unit]	PPext [EUR]	Use phase emissions mass [unit]	OEext [EUR]	EoL emissions mass [unit]	EOLext [EUR]	TOTAL emissions mass [unit]	TOTAL LCext [EUR]
GHG	kg CO2 eq.	0.08	0.001	0.07	0.001	0.01	0.000	0.16	0.002
AP	g SO2 eq.	0.93	0.008	0.34	0.003	0.16	0.001	1.43	0.012
VOC	g	0.02	0.000	0.04	0.000	0.00	0.000	0.06	0.000
POP	ng i-Teq	0.05	0.000	0.00	0.000	0.01	0.000	0.06	0.000
HM1	mg Ni eq.	0.26	0.000	0.00	0.000	0.05	0.000	0.31	0.000
HM2	mg Ni eq.	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000
HM3	mg Ni eq.	0.00	0.000	0.02	0.000	0.00	0.000	0.02	0.000
PAH	mg Ni eq.	0.17	0.000	0.01	0.000	0.06	0.000	0.24	0.000
PM	g	0.09	0.001	0.01	0.000	0.02	0.000	0.12	0.002
Total			0.011		0.004		0.002		0.017

5.3.2.6. Detailed societal LCC results BC6 – residential ESS

Table 56: Details of the societal Life Cycle Cost (marginal external damages) per FU for BC6 – residential ESS

	Unit	Production & distrubution emissions mass [unit]	PPext [EUR]	Use phase emissions mass [unit]	OEext [EUR]	EoL emissions mass [unit]	EOLext [EUR]	TOTAL emissions mass [unit]	TOTAL LCext [EUR]
GHG	kg CO2 eq.	0.08	0.001	0.05	0.001	0.01	0.000	0.14	0.002
AP	g SO2 eq.	0.73	0.006	0.24	0.002	0.13	0.001	1.10	0.009
VOC	g	0.02	0.000	0.03	0.000	0.00	0.000	0.05	0.000
POP	ng i-Teq	0.05	0.000	0.00	0.000	0.01	0.000	0.06	0.000
HM1	mg Ni eq.	0.17	0.000	0.00	0.000	0.02	0.000	0.19	0.000
HM2	mg Ni eq.	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000
HM3	mg Ni eq.	0.00	0.000	0.01	0.000	0.00	0.000	0.01	0.000
PAH	mg Ni eq.	0.16	0.000	0.00	0.000	0.06	0.000	0.23	0.000
PM	g	0.08	0.001	0.01	0.000	0.02	0.000	0.10	0.002
Total			0.009		0.003		0.002		0.013

5.3.2.7. Detailed societal LCC results BC7 – commercial ESS

Table 57: Details of the societal Life Cycle Cost (marginal external damages) per FU for BC7 – commercial ESS

	Unit	Production & distrubution emissions mass [unit]	PPext [EUR]	Use phase emissions mass [unit]	OEext [EUR]	EoL emissions mass [unit]	EOLext [EUR]	TOTAL emissions mass [unit]	TOTAL LCext [EUR]
GHG	kg CO2 eq.	0.08	0.001	0.05	0.001	0.01	0.000	0.14	0.002
AP	g SO2 eq.	0.73	0.006	0.24	0.002	0.13	0.001	1.10	0.009
VOC	g	0.02	0.000	0.03	0.000	0.00	0.000	0.05	0.000
POP	ng i-Teq	0.05	0.000	0.00	0.000	0.01	0.000	0.06	0.000
HM1	mg Ni eq.	0.17	0.000	0.00	0.000	0.02	0.000	0.19	0.000
HM2	mg Ni eq.	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000
HM3	mg Ni eq.	0.00	0.000	0.01	0.000	0.00	0.000	0.01	0.000
PAH	mg Ni eq.	0.16	0.000	0.00	0.000	0.06	0.000	0.23	0.000
PM	g	0.08	0.001	0.01	0.000	0.02	0.000	0.10	0.002
Total			0.009		0.003		0.002		0.013

5.4. Subtask 5.4 – EU totals

The stock and market data from section 5.1.2.3 are used to aggregate the data from subtask 5.2 (LCA) and 5.3 (LCC) to EU-28 level.

The total energy use due to direct and indirect losses is calculated per BC with the following formula:

- EU total energy use per year = stock [application units] * energy use per application [kWh/year]

  In which: the number of application units in stock was determined by dividing the installed capacity by the typical capacity of the application.

Table 58 shows the total energy use due to losses in the use stage per BC and all BCs calculated for the EU for the reference year 2018. The assessed battery systems in **EU-28 consumed in 2018 0.89 TWh**.

Table 58: EU total of the total energy use during use stage of the assessed battery application systems (reference year 2018)

	Installed capacity [GWh]	Nominal battery system capacity [kWh]	Stock [battery units]	Typical application capacity [kWh]	Stock [application units]	Energy use per application [kWh/year]	Total energy use for EU [TWh/yr]
BC1 – PC BEV HIGH	6.79	80	84 877	80	84 877	813	0.07
BC2 – PC BEV LOW	18.89	40	472 348	40	472 348	511	0.24
BC3 – PC PHEV	10.04	12	836 283	12	836 283	366	0.31
BC4 – Truck BEV	0.20	30	6 600	360	550	12 659	0.01
BC5 – Truck PHEV	0.16	20	8 000	160	1 000	14 278	0.01
BC6 – Resid. ESS	6.83	10	682 811	10	682 811	274	0.19
BC7 – Com. ESS	2.27	10	226 510	30 000	76	821 739	0.06
Total	45.17		2 317 428				0.89

The total Net Present Value of the annual LCC over the economic lifetime of the sold applications in 2018 is calculated per BC with the following formula:

- EU total NPV [EUR/yr] = sales [applications units] * LCC [EUR/appl.] / Tapp [yr]

  In which: the number of sold application units was determined by dividing the sold capacity by the typical capacity of the application.

The results of calculating the EU total NPV based on reference year 2018 are presented in Table 59 showing that the assessed battery systems in **EU-28 sums up to an NPV of the annual total LCC of the applications sold in 2018 of about 435 MEUR**.

Table 59: EU total of the total NPV of the annual life cycle costs of the assessed battery application systems over their economic lifetime (reference year 2018)

	Sold capacity [GWh]	Typical application capacity [kWh]	Sales [application units]	LCC [EUR/appl,]	Economic lifetime of application (Tapp) [yr]	Total NPV for EU [MEUR/yr]
BC1 – PC BEV HIGH	2.76	80	34 552	20 152	13	53.56
BC2 – PC BEV LOW	5.99	40	149 694	16 179	14	172.99
BC3 – PC PHEV	2.58	12	214 974	7 401	13	122.39
BC4 – Truck BEV	0.02	360	69	166 397	14	0.82
BC5 – Truck PHEV	0.03	160	200	111 511	12	1.86
BC6 – Resid. ESS	0.95	10	95 105	11 723	20	55.75
BC7 – Comm. ESS	0.50	30 000	17	33 328 317	20	27.75
Total	12.84					435.12

5.5. Comparison with the Product Environmental Footprint pilot

This section compares the results of the environmental LCA executed within this preparatory study with the EcoReport 2014 tool according to the MEErP format with the results of the Product Environmental Footprint (PEF) pilot on rechargeable batteries. The PEF method was developed by the Institute for Environment and Sustainability (IES) of the Joint Research Centre (JRC), a Directorate General of the EC upon mandate of the EC Directorate General Environment (DG ENV). The PEF is a harmonised methodology for the calculation of the environmental performance of products (i.e. goods and/or services) from a life cycle perspective.

Annex B contains a comparison of the MEErP environmental impact categories with PEF environmental impact categories. Both methodologies apply different principles (e.g. regarding end-of-life). **The comparison included in this preparatory study is just to verify whether the order of magnitude of the results is in the same range.**

In the rechargeable batteries PEF pilot, the following four batteries were assessed: Li-ion in cordless power tools, Li-ion in ICT, NiMH in ICT, and Li-ion in e-mobility. Only the latter is comparable with two of the seven BCs within this preparatory study, i.e. BC1 and BC2 the BEV passenger car. The only impact category that is directly comparable (same environmental impact and expressed in a similar unit) is the impact category ‘global warming’ (see Annex B). **Only the impact caused in the production phase are compared, as the scenarios for the distribution, use phase, and EOL within the MEErP methodology are very different to the one in the PEF pilot.**

Table 60 gives an overview of the comparison. Although BC1 and BC2 have a higher battery weight than the PEF battery, the results per FU are lower for the two BCs in comparison with the PEF battery due to the higher amount of total energy delivered over the lifetime. But when looking at the distribution of the GWP impact in the production phase between the raw material acquisition and the manufacturing and the GWP impact per kg battery, the figures are comparable:

- The share between the raw materials and the manufacturing for the PEF is 63/37 % and for the BCs it is 66/34 %.
- The GWP results per kg battery is for the PEF pilot 13.7 kg CO_2 eq./kg and for the two BCs 14.14 kg CO_2 eq./kg.

Table 60: Overview of the comparison between the e-mobility Li-ion battery of the PEF pilot and BC1 – passenger car BEV.

	PEF	BC1	BC2
	e-mobility Li-ion	PC BEV HIGH	PC BEV LOW
Specifications			
Battery weight [kg]	225	609	304
Number of battery application systems per Tapp (Ass) [-]	1	1	2
Total energy delivered over the lifetime [kWh]	8 000	43 680	29 568
Conversion to unit analysis [kg/kWh]	0.028	0.014	0.021
GWP results production phase [kg CO_2 eq./FU[16]]	[17]		
Raw material acquisition	0.244 (63.4%)	0.129 (65.6%)	0.191 (65.6%)
Manufacturing of the product	0.141 (36.6%)	0.068 (34.3%)	0.100 (34.4%)
Total production phase	0.385	0.197	0.290
GWP results per kg battery application system [kg CO_2 eq./kg]	[18]		
Raw material acquisition	8.66	9.28	9.28
Manufacturing of the product	5.05	4.86	4.86
Total production phase	13.70	14.14	14.14

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[16] Functional unit is defined in Task 1 as '1 kWh (kilowatt-hour) of the total output energy delivered over the service life by the battery system (measured in kWh)'

[17] The amounts of the PEF pilot are calculated based on the figures provided within the LCI excel PEF batteries; G version - April 2017 (received on 18/02/2018 by the project team from Recharge). By taking the shares of the life cycle stages, i.e. 45.1 % and 26.3 % (sheet 'Most relevant LCS'), and multiplying them with the total life cycle impact, i.e. 0.543 (sheet 'Benchmark').

[18] The amounts of the PEF pilot are calculated based on the calculated GWP results per FU (see footnote 17) and multiplying them with 8 000/225.

5.6. Comparison with other literature sources

A similar comparison to check whether the order of magnitude of the results is in the same range can be done with other literature. Based on Peters et al. paper review, the average GHG emissions for battery production across all chemistries are **110 kg CO_2 eq. per kWh of storage capacity**. The results for the different battery chemistries are presented in Figure 8 (Peters, et al. 2017). An overview of the GWP impact per kWh storage capacity and per kg battery of all BCs are given in Table 61, please bear in mind that the BCs are a conscious abstraction of the reality of complete battery application systems compiled of a mix of battery chemistries.

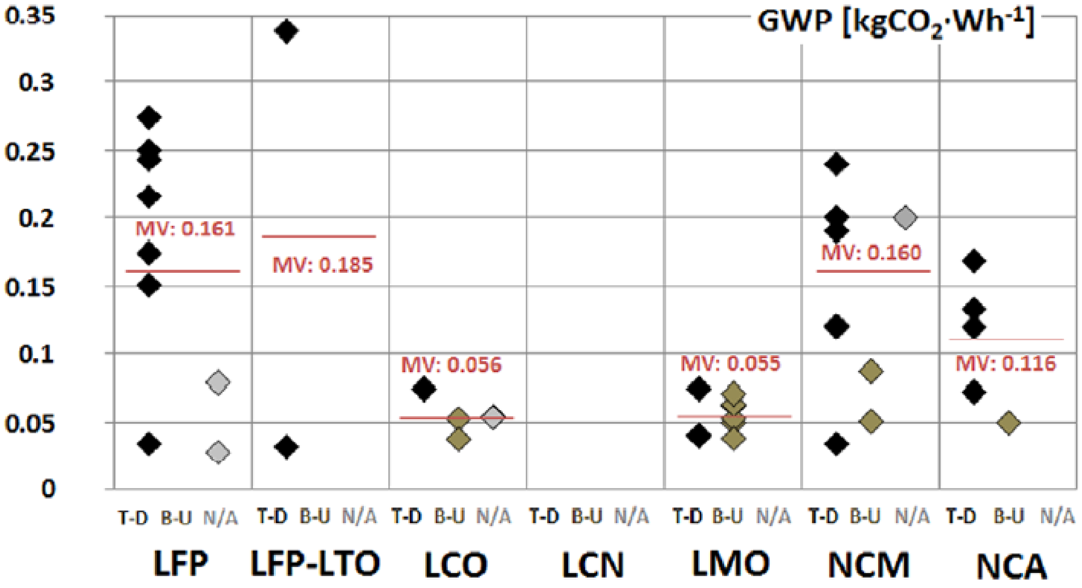

Figure 8: GWP results obtained for different battery chemistries. T-D: Top-Down modelling; B-U: Bottom-up; N/A: not given. MV: mean value (Peters, et al. 2017)

Table 61: Overview of the GWP impact [kg CO_2 eq.] per kWh storage capacity and kg battery of the Base Cases (based on the EcoReport calculations)

	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
GWP results per kWh storage capacity [kg CO_2 eq./kWh]							
Raw material	70.57	70.57	93.98	72.75	93.98	89.35	89.35
Manufacturing	36.96	36.96	51.93	41.52	51.93	64.50	64.50
Total production	107.53	107.53	145.91	114.27	145.91	153.85	153.85
GWP results per kg battery application system [kg CO_2 eq./kg]							
Raw material	9.28	9.28	8.95	8.53	8.95	6.99	6.99
Manufacturing	4.86	4.86	4.94	4.87	4.94	5.04	5.04
Total production	14.14	14.14	13.89	13.40	13.89	12.03	12.03

In the recent study in support of the evaluation of the Battery Directive an amount of 26 kg CO_2 eq./kg battery is assumed as a upper range of values for Li-ion batteries (Trinomics, Öko-

Institut and EY 2018) which is almost twice as high as our calculated results. The study did not disclose the details of this assumption. A possible explanation of the big difference could be because of the comparison between cells (Battery Directive) and battery application systems (this study).

5.7. Conclusions

An environmental LCA and economic LCC assessment have been carried out for all seven BCs based on the BOM (see section 5.1.3.1.1 - 5.1.3.1.7, based on Task 4). A complete overview of the assumed parameters of the seven BCs is provided in Table 1.

Detailed results of the LCA and LCC assessments are included in section 5.2 and 5.3 respectively. Table below summarizes the life cycle impact per FU for all BCs.

Table 62: Concluding overview of the LCA and LCC results of the Base Cases

	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
Total energy (GER) per FU [MJ/kWh]	5.69	7.37	5.41	3.29	3.16	2.69	2.19
Water (process + cooling) per FU [L/kWh]	1.26	1.86	1.04	0.55	0.46	0.48	0.37
Waste, non-haz./ landfill per FU [g/kWh]	31.85	46.51	23.87	13.63	10.94	10.51	8.17
Waste, haz./ incinerated per FU [g/kWh]	0.54	0.78	0.61	0.26	0.28	0.36	0.35
Greenhouse Gases in GWP100 per FU [kg CO2 eq./kWh]	0.27	0.35	0.25	0.15	0.14	0.12	0.10
Acidification, emissions per FU [g SO2 eq./kWh]	3.78	5.39	2.20	1.53	1.12	0.85	0.71
Volatile Organic Compounds (VOC) per FU [g/kWh]	0.11	0.15	0.10	0.07	0.06	0.05	0.04
Persistent Organic Pollutants (POP) per FU [ng i-Teq/kWh]	0.07	0.10	0.08	0.03	0.04	0.04	0.03
Heavy Metals to air per FU [mg Ni eq./kWh]	0.75	1.09	0.51	0.28	0.23	0.16	0.13
PAHs per FU [mg Ni eq./kWh]	0.25	0.37	0.26	0.12	0.12	0.11	0.11

Continuation of Table 62: Concluding overview of the LCA and LCC results of the Base Cases

	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
Particulate Matter (PM, dust) per FU [g/kWh]	0.25	0.36	0.19	0.10	0.09	0.08	0.07
Heavy Metals to water per FU [mg Hg/20/kWh]	0.51	0.75	0.34	0.21	0.15	0.14	0.13
Eutrophication per FU [g PO4/kWh]	0.12	0.17	0.08	0.05	0.04	0.03	0.02
LCOE or LCC per FU [EUR/kWh]	0.461	0.547	0.377	0.177	0.125	0.293	0.278
LCC total for all batteries in application per Tapp [EUR/appl.]	20 152	16 179	7 401	166 397	111 511	11 723	33 328 317

The production phase has the biggest contribution on the total life cycle impact in all impact categories. When looking at the production phase in more detail, the cathode active material is noticeable as a big contributor to the environmental impact across different impact categories.

The xEV passenger car BCs result in a bigger environmental impact per kWh delivered over their lifetime in comparison with the truck and ESS BCs.

The BEV passenger car BCs have the highest LCOE and the truck BCs the lowest. However when looking at the total LCC the costs for the commercial ESS (BC7) stands out in comparison with the other BCs, due the big number of batteries in the commercial ESS application.

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Annex A: Materials added to the MEErP EcoReport tool

Due to the structure of the life cycle inventory, it is not possible to distinguish between process water and cooling water. The water input mentioned under process water is an input for both cooling and process water. It is also not possible to make a distinction between primary electric energy and feedstock.

Name material	Primairy Energy (MJ)	Electr energy (MJ)	feedstock	water proces	Water cool	waste haz	waste non	GWP	AD
New Materials production phase (category **'Extra'**)	MJ	MJ	MJ	L	L	g	g	kg CO2 eq.	g SO2 eq.
NCM622	253.17	113.93		190.62		0.46	7 447.29	19.17	1 070.60
NCM424	230.00	110.40		168.93		0.44	6 289.89	17.60	751.10
NCM111	254.44	124.68		196.19		0.47	6 168.18	19.42	669.03
NCM532	244.70	112.56		181.29		0.46	6 897.22	18.53	915.06
LMO	45.34	23.12		53.22		0.12	1 835.15	2.85	11.83
NCA	290.28	124.82		220.87		0.51	8 995.14	22.08	1 405.11
LFP	57.28	9.74		81.76		0.23	3 609.14	3.60	22.12
Carbon	81.67	0.00		2.21		0.02	76.87	1.87	9.85
PVDF	218.38	109.19		171.93		0.30	1 099.65	15.30	71.33
ZrO2	68.56	32.22		84.57		0.14	540.44	4.83	27.04
Graphite	81.67	0.00		2.21		0.02	76.87	1.87	9.85
CMC	88.66	26.60		55.62		0.17	364.92	3.48	21.81
LiPF6	76.99	19.25		83.79		0.66	11 949.90	6.24	35.38
LiFSI	324.36	129.74		377.25		0.62	13 052.61	21.57	199.60
EC (Ethylene carbonate)	41.46	7.05		16.03		0.02	153.20	1.62	5.89
DMC (Dimethyl carbonate)	58.40	10.51		20.29		0.04	206.10	2.21	8.34
EMC (Ethyl methyl carbonate)	58.40	10.51		20.29		0.04	206.10	2.21	8.34
PC (Propylene carbonate)	112.22	22.44		52.85		0.00	150.61	7.87	24.91
Hydrochloric acid	16.41	10.42		24.58		0.05	156.14	0.75	5.92
n-Methylpyrolidone (NMP)	137.80	37.21		283.26		0.14	588.01	7.10	32.13

Name material	VOC	POP	HMa	PAH	PM	HMw	EUP
New Materials production phase (category **'Extra'**)	g	ng i-Teq	mg Ni eq.	mg Ni eq.	g	mg Hg/20	mg PO4
NCM622	9.51	8.31	219.23	5.59	49.37	117.06	21 116.60
NCM424	8.41	6.72	160.78	4.92	42.73	79.96	16 131.82
NCM111	11.06	7.16	154.02	5.76	49.83	67.93	16 018.92
NCM532	9.02	7.56	191.02	5.33	46.33	98.62	18 785.00
LMO	0.76	0.61	8.83	0.95	2.44	1.12	1 395.56
NCA	9.96	10.07	283.14	6.24	55.63	156.50	26 768.56
LFP	1.36	1.25	16.29	1.54	4.56	9.09	4 302.12
Carbon	1.32	0.18	3.87	0.58	2.76	0.21	3 433.80
PVDF	2.47	4.69	36.71	3.23	28.34	2.80	6 993.95
ZrO2	1.47	1.13	18.90	1.93	10.01	1.56	2 778.68
Graphite	1.32	0.18	3.87	0.58	2.76	0.21	3 433.80
CMC	1.08	3.39	13.57	1.58	8.07	0.98	3 488.81
LiPF6	2.09	1.43	35.46	3.13	9.41	6.76	4 099.76
LiFSI	6.28	6.44	127.55	8.48	38.12	9.30	20 341.55
EC (Ethylene carbonate)	1.21	0.25	7.11	0.47	1.87	0.29	598.75
DMC (Dimethyl carbonate)	1.43	0.78	10.02	0.74	2.88	0.52	1 842.94
EMC (Ethyl methyl carbonate)	1.43	0.78	10.02	0.74	2.88	0.52	1 842.94
PC (Propylene carbonate)	4.19	0.08	6.86	0.11	7.72	0.08	625.25
Hydrochloric acid	0.22	0.21	6.68	0.42	1.02	0.86	580.76
n-Methylpyrolidone (NMP)	3.35	3.06	24.60	2.54	11.44	1.44	13 409.32

Annex B: Product environmental footprint compared to MEErP Ecoreport tool

The Product Environmental Footprint (PEF) method[19] was developed by the European Commission as part of the Single Market for Green Products Initiative[20]. The European Commission proposes the PEF method as a common way of measuring environmental performance of products. During several pilot projects[21], Product Environmental Footprint Category Rules (PEFCR) were developed for several product groups. One of these product groups was the product group of ‘Rechargeable batteries’.

In 2005, the Methodology for Ecodesign of Energy-using Products (MEEuP) was developed for assessing whether and which ecodesign requirements are appropriate for energy-using products under the Ecodesign Directive. Following the revision of the Ecodesign Directive and the extension of its scope to energy-related products in 2009, the Commission reviewed the effectiveness of the MEEuP with a view to extend it to energy-related products. The updated methodology MEErP has been endorsed by the Ecodesign Consultation Forum of 20 January 2012 and shall be used as basis for ecodesign and energy labelling preparatory studies. The MEErP methodology consists of seven tasks, of which Task 5 is on ‘Environment and Economics’. For MEErP assessments a reporting tool called EcoReport was developed that facilitates the necessary calculations to translate product-specific characteristics into environmental impact indicators per product.

This annex compares the impact categories used in the PEF methodology and the MEErP methodology (subtask 5.2 environmental impact assessment), which have both been developed to assess the environmental impact of products.

Environmental impact categories

PEF considers 16 environmental impact categories; MEErP considers 13 environmental impact categories. Table 63 gives an overview of the impact categories considered in both methodologies. Common impact categories are ‘Climate change’, ‘Particulate matter’, ‘Acidification’, ‘Eutrophication’ and ‘Water use’. Only the impact category climate change is expressed in a common unit.

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[19] Commission Recommendation 179/2013 on The use of common methods to measure and communicate the life cycle environmental performance of products and organisations

[20] http://ec.europa.eu/environment/eussd/smgp/index.htm

[21] http://ec.europa.eu/environment/eussd/smgp/ef_pilots.htm

Table 63: Impact categories considered in PEF and MEErP

PEF[22]		**MEErP**[23]	
Impact category	**Unit**	**Impact category**	**Unit**
Climate change	kg $CO_{2\,eq}$	Greenhouse Gases in GWP100	kg CO_2 eq.
Ozone depletion	kg CFC-11 $_{eq}$	/	/
Human toxicity, cancer	CTUh	/	/
Human toxicity, non-cancer	CTUh	/	/
Particulate matter	disease incidence	Particulate Matter (PM, dust)	g
Ionising radiation, human health	kBq $U^{235}{}_{eq}$	/	/
Photochemical ozone formation, human health	kg NMVOC $_{eq}$	/	/
Acidification	mol $H+_{eq}$	Acidification, emissions	g SO_2 eq.
Eutrophication, terrestrial	mol N_{eq}	/	/
Eutrophication, freshwater	kg P_{eq}	Eutrophication (water)	g PO_4
Eutrophication, marine	kg N_{eq}	/	/
Ecotoxicity, freshwater*	CTUe	/	/
Land use	• Dimensionless (pt) • kg biotic production • kg soil • m^3 water • m^3 groundwater	/	/

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[22] Impact categories taken from 'Product Environmental Footprint Category Rules Guidance', European Commission, version 6.3 – May 2018.

[23] Impact categories taken from MEErP ecoreport tool version 2014.

PEF[22]		**MEErP**[23]	
Impact category	**Unit**	**Impact category**	**Unit**
Water use	m^3 world $_{eq}$	Process water and cooling water	ltr
Resource use, minerals and metals	kg Sb $_{eq}$	/	/
Resource use, fossils	MJ		
		Total energy	MJ
/	/	Waste, non-haz./ landfill	g
/	/	Waste, hazardous/ incinerated	g
/	/	Volatile Organic Compounds (VOC) to air	g
/	/	Persistent Organic Pollutants (POP) to air	ng i-Teq
/	/	Heavy metals to air	mg Ni eq.
/	/	PAHs to air	mg Ni eq.
/	/	Heavy metals to water	mg Hg/2O

Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage under FWC ENER/C3/2015-619-Lot 1

TASK 6 Report

Design options

VITO, Fraunhofer, Viegand Maagøe

August 2019

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Contents

ABBREVIATIONS

Abbreviations	Descriptions
BAT	Best Available Technologies
BC	Base case
BNAT	Best Not-yet Available Technologies
BOM	Bill-of-Material
Co	Cobalt
CRM	Critical Raw Materials
EoL	End-of-life
EV	Electric vehicle
FU	Functional Unit
LCA	Life Cycle Assessment
LCA	Life Cycle Assessment
LFP	Lithium-Ion Phosphate
LLCC	Least Life Cycle Costs
MEErP	Methodology for Ecodesign of Energy related Products
Mn	Manganese
Ni	Nickel
NMC	Lithium-ion Nickel Manganese Cobalt Oxide
OPEX	Operational expenditure
PEF	Product Environmental Footprint
QFU	Quantity of Functional Units
SOH	State of Health

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6. Task 6: Design options

AIM OF TASK 6:

The aim is to identify design options, their monetary consequences in terms of Life Cycle Cost for the user, their economic and possible social impacts, and pinpointing the solution with the Least Life Cycle Costs (LLCC) and the Best Available Technology (BAT). Therefore, this task relies on input from Tasks 4 and 5.

The BAT indicates a target in the shorter term that would probably be more subject to promotion measures than to restrictive action. The Best Not (yet) Available Technology (BNAT) indicates possibilities in the longer term and helps to define the exact scope and definition of possible measures. Intermediate options between the LLCC and the BAT may also be assessed.

The subsequent Task 7 draws up scenarios quantifying the improvements that can be achieved versus a Business-as-Usual (BAU) scenario and compares the outcomes with EU environmental targets, the societal costs, etc.

SUMMARY OF TASK 6:

In task 6 report three design options are defined for further analyses. They are derived from the insights from previous tasks 4 and 5. The first design option is aiming at a reduction of the active and passive materials, while offering a comparable service and thus on a reduction of the GWP due to the used materials. This approach is based on a substitution of the battery cells in the BOM by its successor. The second design option addresses the extension of a products lifetime beyond its 1st life by reuse of the battery system in a same application. Accordingly, the resulting "additional lifetime" and the FU (Functional Unit) provided during this 2nd life application is calculated. Finally, the third design option focuses on the impact of the energy mix used for the production of the battery system by using a low carbon electricity mix. This last design option is not calculated within this task report due to the limitations of the MEErP EcoReport tool[1], making it impracticable to change the electricity related GHG emissions of the production of all the materials within the tool.

The LCA and LCC analysis revealed that the reduced material design option is the best option for BC1 based on the GWP impact and LCC. For BC3, 5, 6, and 7 this was also the case, however the extended lifetime design option is similar to the BAU situation. In addition, it showed that for BC2 and 4 the reduced material option has the least LCC and the extended lifetime option the lowest GWP impact in comparison with the other options.

Furthermore, also potential rebound effects which might occur due to the design options are mentioned. The report includes a discussion of the long-term technical potentials and changes to the total system.

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[1] EcoReport tool is design for ecodesign, which cannot include requirements for the energy mix during production.

6.1. Subtask 6.1: Design options

AIM OF TASK 6.1:

Available design options have been identified by investigating different design option against each Base-Case (using the MEErP EcoReport 2014).

The design options should not have a significant degradation of the functionality, the quality of the produced products, of the primary or secondary performance parameters compared to the Base-Case.

The design option must have a significant potential for improvement regarding at least one of the following ecodesign parameters without deteriorating others: the consumption of energy, water and other resources, use of hazardous substances, emissions to air, water or soil, weight and volume of the product, use of recycled material, quantity and nature of consumables needed for proper use and maintenance, ease for reuse and recycling, extension of lifetime or amounts of waste generated.

The design option should not entail excessive costs to the end user seen over the lifetime of the product. Therefore, the assessment of the monetary impact for categories of users includes the estimation of the possible price increase due to implementation of the design option and calculation of the LCC.

The aim of this subtask is to identify and describe the design options that can contribute to improve the environmental performance of batteries.

According to the MEErP methodology, typically 3 to 8 design options are considered as manageable number for Ecodesign preparatory studies.

While in most of the previous Ecodesign preparatory studies the major environmental impact was due to the use phase, this study on batteries indicates a different situation. As the results of task 5 point out, the sourcing and production of the battery has a significantly higher environmental impact than the use phase. This also opens the floor for other design options, which are, for example not strictly based on the technical improvement of specific components, but also allows considering conceptual design options on a more aggregated level. Such an approach seems even more reasonable when looking at different LCA studies, which are focusing at a meta-level, e.g. the effect of using a battery with higher energy density, a reduction of amount of materials needed or increased lifetime (Romare and Dahllöf 2017; Hall and Lutsey 2018). Based on the results of task 4 and task 5 in this study, the following design options have been considered:

1. Reduced active and passive materials
2. Extended lifetime, here as "re-use" option
3. Low carbon energy mix for the production of the battery

In the following subsections, the listed design options will be described in more detail. Although a combination of the three or of two out of the three design options is quite possible in reality, combinations are not further elaborated in this task report (in the scenario analysis of task 7 combined options are considered).

6.1.1. Reduction of active and passive materials

This design options are established on the basis of the description of potential improvement options in task 4. Currently many different scientific approaches are pursuing the same goal, to reduce the amount of active and passive materials in the battery, while providing at least the same service. As described in task 4 this can be achieved for example by using improved cell materials, reducing the amount or weight of passive materials, optimizing the design and so on. This also goes along with an increase in energy density of the battery cell, module or system. The aim of this report is not to describe and analyse the potential environmental impact of every single possible improvement option, but rather to assess if such a reduction has a positive influence on the environmental impact at all, how high it is and what the costs are. Such a positive impact may result from lower amount of materials needed to provide the same service or in the case of a mobile application, less mass has to be moved, which improves also the energy efficiency of the vehicle.[2]

For analysing the effect of using a battery with a lower amount of active and passive materials, the BOM for different industrial battery cells as depicted in task 4 is updated. Succeeding generations of the cells used in task 4 were identified and their corresponding BOM displayed. By using this approach, it is possible to analyse the influence of improved and reduced cell materials (e.g. Ni-rich materials, thinner current collectors, etc.) based on the same cell design. This allows to avoid side effects resulting from e.g. a lower or higher amount of materials due to another cell design, which would falsify the assessment of environmental impact. The BOM of the five different cells is depicted in Table 1.

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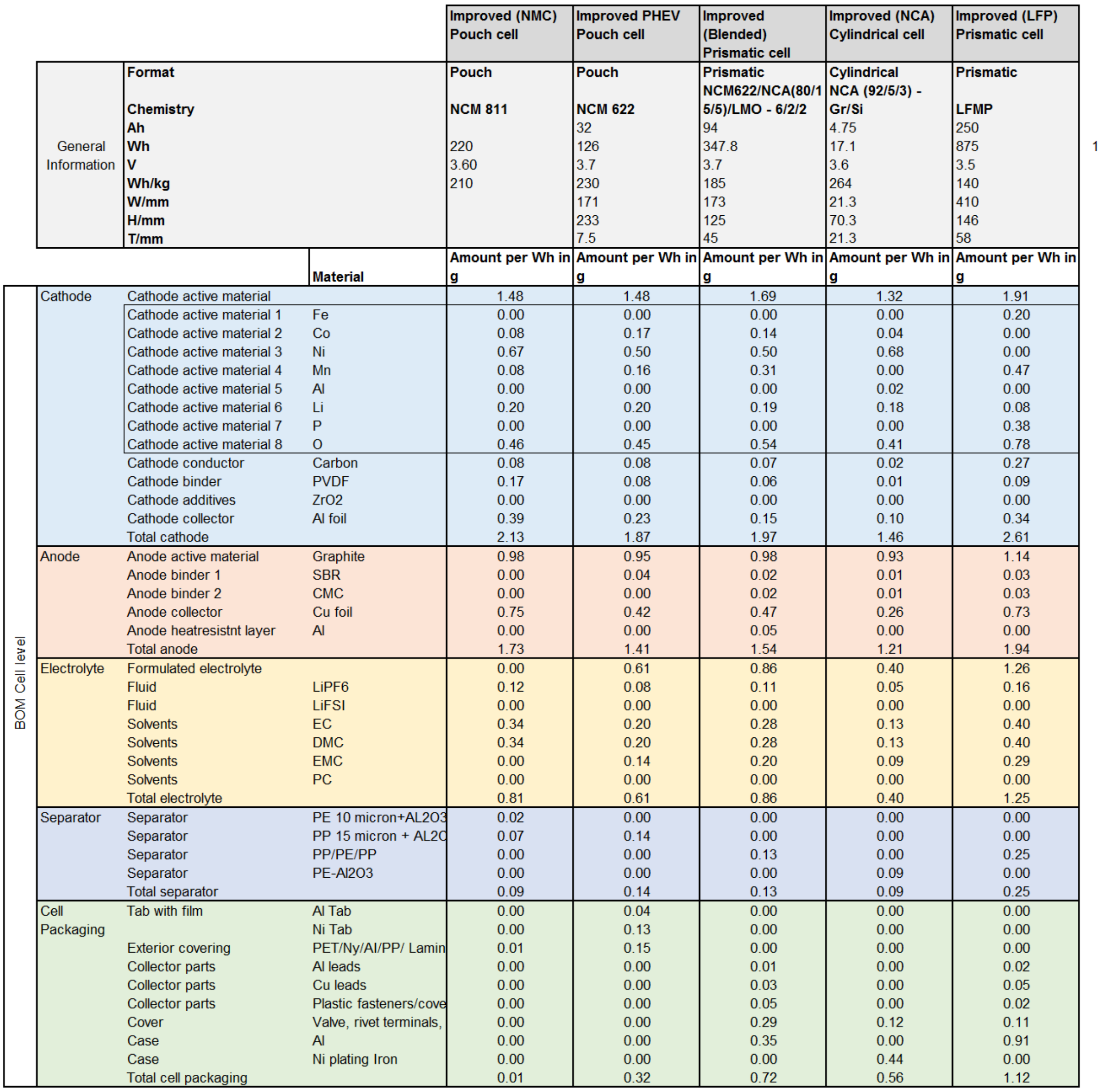
[2] This effect has not been considered in this preparatory study since it is out of the scope of the system boundaries

Table 1: Updated versions of cell types



				Improved (NMC) Pouch cell	**Improved PHEV Pouch cell**	**Improved (Blended) Prismatic cell**	**Improved (NCA) Cylindrical cell**	**Improved (LFP) Prismatic cell**	
General Information	**Format**			**Pouch**	**Pouch**	**Prismatic**	**Cylindrical**	**Prismatic**	
	Chemistry			**NCM 811**	**NCM 622**	**NCM622/NCA(80/15/5)/LMO - 6/2/2**	**NCA (92/5/3) - Gr/Si**	**LFMP**	
	Ah				32	94	4.75	250	
	Wh			220	126	347.8	17.1	875	1
	V			3.60	3.7	3.7	3.6	3.5	
	Wh/kg			210	230	185	264	140	
	W/mm				171	173	21.3	410	
	H/mm				233	125	70.3	146	
	T/mm				7.5	45	21.3	58	
			Material	**Amount per Wh in g**	**Amount per Wh in g**	**Amount per Wh in g**	**Amount per Wh in g**	**Amount per Wh in g**	
BOM Cell level	Cathode	Cathode active material		1.48	1.48	1.69	1.32	1.91	
		Cathode active material 1	Fe	0.00	0.00	0.00	0.00	0.20	
		Cathode active material 2	Co	0.08	0.17	0.14	0.04	0.00	
		Cathode active material 3	Ni	0.67	0.50	0.50	0.68	0.00	
		Cathode active material 4	Mn	0.08	0.16	0.31	0.00	0.47	
		Cathode active material 5	Al	0.00	0.00	0.00	0.02	0.00	
		Cathode active material 6	Li	0.20	0.20	0.19	0.18	0.08	
		Cathode active material 7	P	0.00	0.00	0.00	0.00	0.38	
		Cathode active material 8	O	0.46	0.45	0.54	0.41	0.78	
		Cathode conductor	Carbon	0.08	0.08	0.07	0.02	0.27	
		Cathode binder	PVDF	0.17	0.08	0.06	0.01	0.09	
		Cathode additives	ZrO2	0.00	0.00	0.00	0.00	0.00	
		Cathode collector	Al foil	0.39	0.23	0.15	0.10	0.34	
		Total cathode		2.13	1.87	1.97	1.46	2.61	
	Anode	Anode active material	Graphite	0.98	0.95	0.98	0.93	1.14	
		Anode binder 1	SBR	0.00	0.04	0.02	0.01	0.03	
		Anode binder 2	CMC	0.00	0.00	0.02	0.01	0.03	
		Anode collector	Cu foil	0.75	0.42	0.47	0.26	0.73	
		Anode heatresistnt layer	Al	0.00	0.00	0.05	0.00	0.00	
		Total anode		1.73	1.41	1.54	1.21	1.94	
	Electrolyte	Formulated electrolyte		0.00	0.61	0.86	0.40	1.26	
		Fluid	LiPF6	0.12	0.08	0.11	0.05	0.16	
		Fluid	LiFSI	0.00	0.00	0.00	0.00	0.00	
		Solvents	EC	0.34	0.20	0.28	0.13	0.40	
		Solvents	DMC	0.34	0.20	0.28	0.13	0.40	
		Solvents	EMC	0.00	0.14	0.20	0.09	0.29	
		Solvents	PC	0.00	0.00	0.00	0.00	0.00	
		Total electrolyte		0.81	0.61	0.86	0.40	1.25	
	Separator	Separator	PE 10 micron+AL2O3	0.02	0.00	0.00	0.00	0.00	
		Separator	PP 15 micron + AL2O	0.07	0.14	0.00	0.00	0.00	
		Separator	PP/PE/PP	0.00	0.00	0.13	0.00	0.25	
		Separator	PE-Al2O3	0.00	0.00	0.00	0.09	0.00	
		Total separator		0.09	0.14	0.13	0.09	0.25	
	Cell Packaging	Tab with film	Al Tab	0.00	0.04	0.00	0.00	0.00	
			Ni Tab	0.00	0.13	0.00	0.00	0.00	
		Exterior covering	PET/Ny/Al/PP/ Lamin	0.01	0.15	0.00	0.00	0.00	
		Collector parts	Al leads	0.00	0.00	0.01	0.00	0.02	
		Collector parts	Cu leads	0.00	0.00	0.03	0.00	0.05	
		Collector parts	Plastic fasteners/cove	0.00	0.00	0.05	0.00	0.02	
		Cover	Valve, rivet terminals,	0.00	0.00	0.29	0.12	0.11	
		Case	Al	0.00	0.00	0.35	0.00	0.91	
		Case	Ni plating Iron	0.00	0.00	0.00	0.44	0.00	
		Total cell packaging		0.01	0.32	0.72	0.56	1.12	

Based on these five different cells, a virtual product was calculated for each Base Case considering the share of the different cells according to their market share (calculation is following the same way as described in task 4). For the virtual product the BOM was determined and used to calculate the environmental impact.

Similar as in Task 5, the 2018 version of the GREET2 Model by UChicago Argonne, LLC[3] was used as source of the life cycle inventory (LCI) data of the different battery chemistries. It was modelled and calculated in SimaPro version 8.52 with version 3.4 of the ecoinvent database, and added as extra materials in the EcoReport. Table 2 shows how the data sets of three additional cell chemistries of task 6 were modelled.

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[3] https://greet.es.anl.gov/greet.models

Table 2: Data set of the added successor cell chemistries (modelling all based on GREET2 model)

Chemistries	LCI data record	Amount (/kg product)	Unit
NCM811	NMC811 precursor (see below for LCI)	0.95	kg
	Lithium hydroxide {GLO}| market for | Cut-off, U	0.38	kg
	Electricity, medium voltage {CN}| market group for | Cut-off, U	26.18	MJ
NCM811 precursor	Nickel sulfate {GLO}| market for | Cut-off, U	1.34	kg
	Cobalt {GLO}| market for | Cut-off, U (used as worst proxy for proxy Cobalt Sulfate, like PEF)	0.17	kg
	Manganese sulfate {GLO}| market for | Cut-off, U	0.17	kg
	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	0.89	kg
	Ammonia, liquid {RoW}| market for | Cut-off, U	0.12	kg
	Water, deionised, from tap water, at user {RoW}| market for water, deionised, from tap water, at user | Cut-off, U	0.64	kg
	Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Cut-off, U	0.04	GJ
NCA (92/5/3) [4]	Lithium hydroxide {GLO}| market for | Cut-off, U	0.25	kg
	Oxygen, liquid {RoW}| market for | Cut-off, U	0.04	kg
	NCA (91/2/3) precursor (see below for LCI)	0.95	kg
	Electricity, medium voltage {CN}| market group for | Cut-off, U	26.18	MJ
NCA (92/5/3) precursor	Ammonia, liquid {RoW}| market for | Cut-off, U	0.37	kg
	Nickel sulfate {GLO}| market for | Cut-off, U	1.55	kg
	Cobalt {GLO}| market for | Cut-off, U (used as worst proxy for proxy Cobalt Sulfate, like PEF)	0.08	kg
	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	0.87	kg
	Aluminium sulfate, without water, in 4.33% aluminium solution state {GLO}| market for | Cut-off, U	0.06	kg
	Water, deionised, from tap water, at user {RoW}| market for water, deionised, from tap water, at user | Cut-off, U	0.64	kg
	Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Cut-off, U	0.04	GJ

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[4] NCA (92/5/3) and its precursor are not such modelled within the GREET2 model. Therefore the LCI of NCA (92/5/3) is drafted based upon the modelling of the NCA (80/15/5) composition that is included in the GREET2 model and the chemical equation of NCA (92/5/3).

Chemistries	LCI data record	Amount (/kg product)	Unit
LFMP (proxy)[5]	Lithium hydroxide {GLO}| market for | Cut-off, U	0.27	kg
	Phosphoric acid, industrial grade, without water, in 85% solution state {GLO}| market for | Cut-off, U	0.37	kg
	Iron sulfate {GLO}| market for | Cut-off, U	0.17	kg
	Manganese(III) oxide {GLO}| market for | Cut-off, U	0.40	kg
	Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Cut-off, U	0.03	GJ

6.1.2. Extended lifetime

While the first design option mainly addressed the composition of batteries and thus focused on the environmental impact due to sourcing and production of the materials, the second option sets the focus at extending the useful lifetime. As reported in task 4, this can be achieved by increasing the durability and the first lifetime of the battery or by 2nd life application. The latter one offers the possibility to prolong the service life of a product and thus enables it to increase the QFU (Quantify of Functional Unit). Task 4 report points out that there are different possibilities for 2nd life applications such as repurposing and reuse. Out of the perspective of wanting to assess the environmental impact of these possibilities, both options are heading into the same direction. While repurposed batteries are rather used in stationary applications, reused batteries are used again in the same application e.g. automotive (also if not in the same vehicle). A difference lies in the effort to enable a reuse or repurposing. In the latter case, the effort is a bit higher since some components may have to be changed (what also may be the case for the first option if they are e.g. damaged). Cusenza et al. 2018 are listing the additional inventory (although this might differ from case to case) needed to enable a repurposing for 2nd life stationary application, see Table 3.

Table 3: Components inventory for repurposing (based on Cusenza et al. 2018)

Components	Unit of measure	Mass	Source
Battery tray	[kg]	14.88	(Ellingsen et al., 2014)
Battery retention	[kg]	5.45	(Ellingsen et al., 2014)
Electricity consumption	[kWh]	8.72	Calculation based on JRC Petten data
* For the analysis, only the electricity consumption of testing is considered; the disassembly is assumed to be a manual disassembly			

Apart of the higher QFU of the battery system, the main difference between reuse and repurposing regarding the environmental impact may lie in these additional components.

However, as in the case of the first design option, it is not the aim of this report to conduct an in-depth analyses of the environmental impact of different 2nd life options but rather to assess the general potential of such a prolonged product lifetime. For this reason, this report focusses

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[5] LFMP is not included in the GREET2 model, to model LFMP the LFP composition within the GREET2 model was taken as starting point and changed by replacing 70% of the Iron sulfate input by Manganese oxide.

on the effect of an extended lifetime due to battery reuse on the environmental impact of the batteries.

The design option offers the possibility to reuse a battery, which reaches the end of its 1st life (mostly at 70 % to 80 % SOH) in the same application. An example would be to reuse the battery of a high capacity EV in a smaller city car (as initial or battery or replacement). Although the capacity may not decrease in a linear manner anymore, the remaining capacity might still be sufficient to fulfil the expected service of the vehicle. This option becomes even more reasonable when looking at Figure 1 that compares the annual travel distances of different vehicle segments.

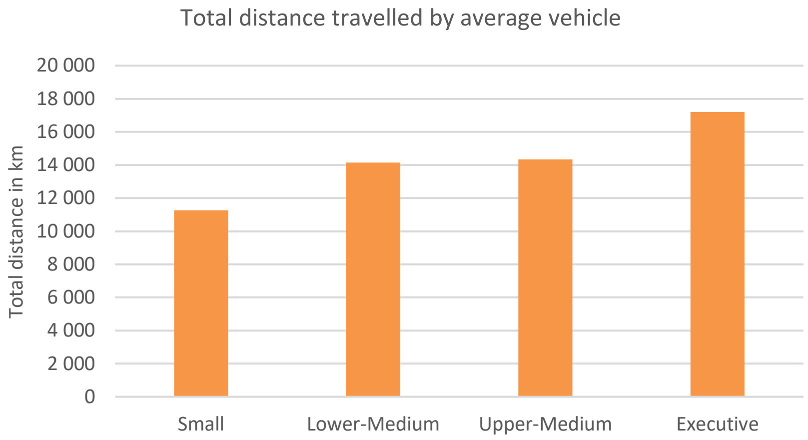

Figure 1: Average annual driven kilometres of a small car in the EU (Papadimitriou 2013)

The figure illustrates that smaller cars are less driven.[6] Thus it could make economically less sense to install a new battery system, since a reused battery would also be sufficient for only a part of the costs[7].

To analyse the potential impact of a prolonged battery life-time due to reuse, we considered for the PC BEV and Truck BEV a prolonged lifetime of the battery. For the PHEV versions the end-of-first life was assumed at ~ 60% SOH. Due to this low SOH a further reuse seems not applicable.

For the stationary systems, the reuse of batteries in other systems does not seem to be appropriate and is not further investigated here. Also the reuse of a battery from a BEV in a ESS is according to a stakeholder not appropriate since the used BEV battery won't meet the requirements of the ESS in terms of cycle lifetime. Anyhow, since the point of interest is whether or not there is a positive influence on the environmental impact, the focus on BEV appears suitable. For the BEV it is assumed, that after the battery reaches its end of first life, the battery is reused until it reaches ~ 60% SOH. Afterwards, the batteries are disposed.

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[6] Please note, that this figure does not say anything about the typical driving distance of the vehicles per trip. But it can be assumed that the driving range of smaller cars is comparatively lower than the one of higher segments.

[7] Thereby it is assumed, that with increasing age of the car, the km per trip are also decreasing (A lot of cars are used in fleets at the beginning of their lifetime or are used for long range purpose, where a high reliability of the car is needed. With growing age, cars change hands and the new users may have another pattern of usage and the car is rather used for short distance trips.

6.1.3. Low carbon energy mix for the production of the battery

The analyses in task 4 regarding the most relevant contributors of GWP revealed that the electricity consumption during the manufacturing process of the cell plays a crucial role and contributes greatly to the overall greenhouse gas emissions during production (see figure 21 in task 4 report). Furthermore, this is also backed by the calculations conducted in task 5. Considering that, and as depicted in task 4, the electricity consumption has next to the cathode materials the highest GWP impact, it seems inevitable to consider the reduction of the environmental impact due to electricity consumption as another relevant design option.

This is an issue that has been observed by many other studies (see for example Romare and Dahllöf 2017, Thomas et al. 2018; Ellingsen et al. 2014). Furthermore those studies identified the electricity mix as the biggest lever for reducing the GWP. Ellingsen et al. 2014 provided within one of their studies a sensitivity analysis based on different energy sources.

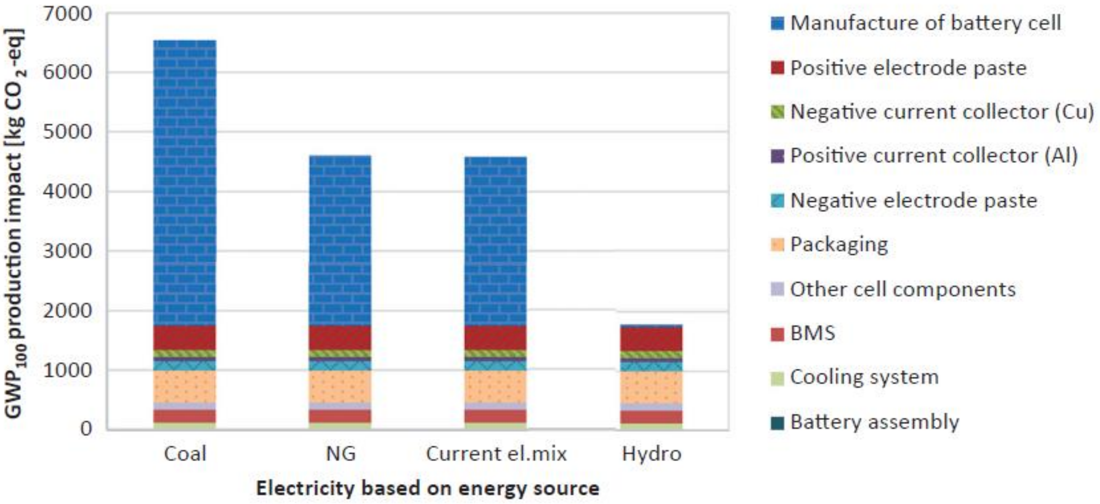

Figure 2: Influence of different energy sources on the GWP (based on Ellingsen et al. 2014)

The figure reveals that depending on the energy source used for the production of the battery, the GWP emissions differ significantly. The lowest emissions can be observed in the case on hydro energy[8]. Considering this, the use of low-carbon energy during the production of the batteries also contains a high potential to reduce the environmental impact and should thus be considered as a design option and be further analysed.

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[8] Which should rather be seen here as a proxy for renewable energy.

6.2. Subtask 6.2: Impacts of the design options

AIM OF TASK 6.2:

The aim of this subtask is to describe the impacts of the design options on the base cases. With regard to the analysis of impacts, it should be noted that the analysis is done from a perspective where the design options are directly “designed and built-into” new batteries.

6.2.1. Performance

In this chapter the influence of the design options on the performance indicators and the BOM will be displayed.

6.2.1.1. Reduction of active and passive materials

Reducing the amount of active and passive materials in a battery system is one of the previously listed most promising design options. To determine the effect of this option, the cells used for determining the BOM of the virtual battery in the task 4 report are replaced by the improved successors of these cells. The reason to use similar cells from the same product line, is that these cells mostly are similar or at least only show minor modifications regarding their design. The difference mainly comes from another used cell chemistry or the reduction of passive materials. However, both effects also lead to an increased gravimetric and volumetric energy density and thus to the effect that a less materials are used to provide the same battery capacity as defined in task 4. This design option has the highest influence on the environmental impact of the material consumption. Hereby it has to be noted, that it is not simply a reduction of the formerly used materials[9] but also a substitution by new materials (e.g. Mn in the case of LFMP) or an increase in the share of formerly used materials (e.g. the share of Ni in the case NMC). Thus, in general, one cannot be sure if the reduction in the demand for materials used is not countered by a potentially higher environmental impact due to the new or higher share of materials (which is not the case here as Table 8 indicates). The corresponding performance indicators to this design options are listed in Table 4.

The overview of the performance indicator for this design options reveals, that the indicators are quite similar to those of the BAU of the Base Cases. However, as already addressed before, the major difference lies in the BOM and thus in the amount and kind of materials used, which can be found in in the last 8 lines of Table 4. Furthermore, the use of such materials as well as the reduction of passive materials leads to a reduction in the costs per kWh[10] as listed in the line named "Battery systems costs".

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[9] By using materials with a higher energy density (kg/kWh) less materials (in kg) are needed to realize the same required battery capacity (in kWh) as with materials with a lower energy density.

[10] It should be noted, that one stakeholder raised doubts regarding the cost decrease for ESS cell materials, especially LFMP.

Table 4: Performance indicators for design option with reduced active and passive materials

BaseCase		BC 1	BC 2	BC 3	BC 4	BC 5	BC6	BC7
Short Description		**PC BEV HIGH**	**PC BEV LOW**	**PC PHEV**	**Truck BEV**	**Truck PHEV**	**Residential ESS**	**Commercial ESS**
Main application		eMobility					stationary	
Parameter	unit	BC 1	BC 2	BC 3	BC 4	BC 5	BC6	BC7
Typical capacity of the application	[kWh]	80	40	12	360	160	10	30 000
Economic life time of application (Tapp)	[y]	13	14	13	14	12	20	20
Percent of braking energy recovery in AS	[-]	20%	20%	20%	12%	6%	n.a.	n.a.
Application service energy (AS)	[kWh/Tapp]	43 680	29 568	19 656	940 800	890 400	40 000	120 000 000
Charger Efficiency (ηcharger)	[-]	85%	85%	85%	92%	92%	98%	98%
Consumption	[kWh/km]	0.2	0.16	0.18	1.2	1.4	n.a.	n.a.
Annual kilometers	[km/a]	14000	11000	7000	50000	50000	n.a.	n.a.
C-rate for charging	[-]	0.2 - 0.5	0.2 - 0.5	0.5	1.0	1.0	0.5	1.0
C-rate for normal discharge	[-]	0.33 - 1	0.33 - 1	1.0	1.0	1.0	1.0	1.0
C-rate for braking	[-]	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Nominal battery system capacity according to ISO ..	[kWh]	80	40	12	30	20	10	10
Number of battery systems per application	[-]	1	1	1	12	8	1	3 000
Maximum calendar life-time of the installed battery (no cycling ageing)	[year]	20	20	20	20	20	25	25
Maximum SoC - maximum DoD (Stroke)	[-]	80%	80%	75%	80%	75%	80%	80%
Average stroke (SoC - DoD)	[-]	24%	31%	73%	50%	69%	60%	75%
Energy delivered in first cycle (Edc).	[kWh/cycle]	64	32	9	24	15	8	8
Number of cycles per year (#)	cycles	120	120	120	300	600	250	250
Maximum number of cycles for battery system until EoL (no calendar ageing)	[-]	1 500	1 500	2 000	2 000	3 000	8 000	10 000
SoH @ EoL of battery system relative to declared capacity (SoHcap)	[-]	80%	80%	60%	80%	60%	70%	70%
Average energy delivered per average cycle until EoL	[kWh/cycle]	19.44	12.22	8.75	178.57	110.06	6.00	22 500.00
number of batteries in the application	[-]	1.00	1.00	1.00	12.00	8.00	1.00	3 000.00
Actual quantity of functional units (QFU) over battery system lifetime (per battery) *(1 FU = 1 kWh over battery lifetime)*	[-]	40 320	23 642	13 440	482 297	373 177	25 532	95 744 681
Service life of first battery (years)	[year]	14.40	13.43	10.67	8.04	5.33	17.02	17.02
Battery system costs	[€/kWh]	140	140	185	129	185	499	499
CAPEX for decomissioning	[EURO/ battery]	1 200	600	180	450	300	150	150
OPEX replace battery	[EURO/ battery]	700	700	700	400	400	100	100
ηcoul x ηv =average energy efficiency of battery system over life time	[-]	92%	92%	92%	92%	92%	92%	92%
Auxiliary heating energy for a battery system relative to functional unit	kW	5.0	5.0	-	5.0	-	-	-
Self discharge per month(@STC)	[-]	2%	2%	2%	2%	2%	2%	2%
Total weight of a battery system	[kg]	521	261	98	221	163	101	101
Total weight of cells	[kg]	391	195	68	166	114	66	66
Specific energy density cell level	[Wh/kg]	205	205	176	181	176	152	152
Weight of Cobalt (pro battery system)	[kg]	5	3	1	1	1	0	0
Weight of Graphite (pro battery system)	[kg]	79	40	13	31	21	11	11
Weight of Nickel (pro battery system)	[kg]	44	22	4	12	6	1	1
Weight of Manganese (pro battery system)	[kg]	12	6	4	7	6	4	4
Weight of Lithium (pro battery system)	[kg]	13.9	7.0	1.7	4.5	2.8	1.0	1.0

6.2.1.2. Extended lifetime

The design option of a prolonged lifetime aims on increasing the QFU of the battery since it is used for a longer period of time. As described in task 4 and the previous section, there are different options existing to extend the 1st and 2nd lifetime of the battery. While naturally also the options to extend the 1st life are of interest, this design options deals with the extension of the 2nd lifetime of the battery. For this assessment we focused on the reuse of the battery e.g. in a smaller city car. Since it is assumed that also in this application the SOH should not fall below 60% SOH we calculated the additional lifetime based on this restriction. Furthermore, this also means that the PHEV applications are not considered for since it was assumed, that these batteries are already used until they reach the 60 % SOH. Same for the stationary applications: The SOH of battery systems used in stationary applications may also go below 70% SOH and thus make a reuse of the battery rather difficult and up to now, according to a stakeholder, no 2nd life approaches are known for stationary systems. The following Table 5 shows how this design option influences the different performance indicators.

The major difference (compared to BAU or for the design option of reduced active and passive materials) of this design options can be observed in the additional lines in Table 5 marked in red[11]. These lines are used for the calculation of the additional lifetime, the average energy delivered per cycle considering the lower SOH of the battery and finally the resulting additional FU provided by the battery in this timeframe. The total QFU is then considered as the sum of both: the QFU from the first lifetime and from the re-use phase. However, this design option has a low influence on the BOM (also there might be some exchanges to enable the reuse) and thus, the BOM and the connected data are the same as for the Base Case. Only a slightly higher OPEX was considered for some additional adjustments.

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[11] Between the lines "Service life of first battery" and "Battery system costs"

Table 5: Performance indicators for design option with extended lifetime

BaseCase		BC 1	BC 2	BC 3	BC 4	BC 5	BC6	BC7
Long Description		**Passenger Car - BEV high battery capacity**	**Passenger Car - BEV lower battery capacity**	**Passenger Car PHEV**	**Truck BEV**	**Truck PHEV**	**Residential ESS**	**Grid supporting ESS**
Main application		eMobility					stationary	
Parameter	unit	**BC 1**	**BC 2**	**BC 3**	**BC 4**	**BC 5**	**BC6**	**BC7**
Typical capacity of the application	[kWh]	80	40	12	360	160	10	30 000
Economic life time of application (Tapp)	[y]	13	14	13	14	12	20	20
Percent of braking energy recovery in AS	[-]	20%	20%	20%	12%	6%	n.a.	n.a.
Application service energy (AS)	[kWh/Tapp]	43 680	29 568	19 656	940 800	890 400	40 000	120 000 000
Charger Efficiency (ηcharger)	[-]	85%	85%	85%	92%	92%	98%	98%
Consumption	[kWh/km]	0.2	0.16	0.18	1.2	1.4	n.a.	n.a.
Annual kilometers	[km/a]	14000	11000	7000	50000	50000	n.a.	n.a.
C-rate for charging	[-]	0,2 - 0,5	0,2 - 0,5	0.5	1.0	1.0	0.5	1.0
C-rate for normal discharge	[-]	0,33 - 1	0,33 - 1	1.0	1.0	1.0	1.0	1.0
C-rate for braking	[-]	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Nominal battery system capacity according to ISO ..	[kWh]	80	40	12	30	20	10	10
Maximum calendar life-time of the installed battery (no cycling ageing)	[year]	20	20	20	20	20	25	25
Maximum SoC - maximum DoD (Stroke)	[-]	80%	80%	75%	80%	75%	80%	80%
Average stroke (SoC - DoD)	[-]	24%	31%	73%	50%	69%	60%	75%
Energy delivered in first cycle (Edc).	[kWh/cycle]	64	32	9	24	15	8	8
Number of average cycles per year (#)	cycles	120	120	120	300	600	250	250
Maximum number of full cycle equivalents for battery system until EoL (no calendar ageing)	[-]	1 500	1 500	2 000	2 000	3 000	8 000	10 000
SoH @ EoL of battery system relative to declared capacity (SoHcap)	[-]	80%	80%	60%	80%	60%	70%	70%
Average energy delivered per average cycle until EoL	[kWh/cycle]	19.44	12.22	8.75	178.57	110.06	6.00	22 500.00
number of batteries in the application	[-]	1.00	1.00	1.00	12.00	8.00	1.00	3 000.00
Actual quantity of functional units (QFU) over battery system lifetime (per battery) *(1 FU = 1 kWh over battery lifetime)*	[-]	40 320	23 642	13 440	482 297	373 177	25 532	95 744 681
Service life of first battery (years)	[year]	14.40	13.43	10.67	8.04	5.33	17.02	17.02
Prolonged lifetime due to Reuse (quadratic aging)	[y]	3.60	3.36	0.00	2.01	0.00	0.00	0.00
Load level as compared to first life (e.g. lower maximum energy per cycle)	[%]	70%	70%	70%	70%	70%	70%	70%
Average SoH during Reuse-phase	[%]	0.70	0.70	0.00	0.70	0.00	0.00	0.65
SoH @ EoL of re-use-phase	[%]	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Maximum energy deliverable per cycle @ Reuse phase	[kWh/cycle]	56.00	28.00	0.00	252.00	0.00	0.00	0.00
Average energy delivered per cycle @ Reuse phase	[kWh/cycle]	13.61	8.56	0.00	125.00	0.00	0.00	0.00
Maximum additional FU due to Reuse	[-]	19 353.60	9 026.87	0.00	121 538.76	0.00	0.00	0.00
Actual additional FU due to Reuse	[-]	5 880.00	3 447.76	0.00	75 358.85	0.00	0.00	0.00
Actual QFU including first use and re-use of battery	[-]	46 200	27 090	13 440	557 656	373 177	25 532	95 744 681
battery system cost/declared initial capacity	[EURO/kWh]	206	206	254	220	212	683	683
CAPEX for decomissioning	[EURO/ battery]	1 200	600	180	450	300	150	150
OPEX replace battery	[EURO/ battery]	840	840	840	480	480	120	120
ηcoul x ηv =average energy efficiency of battery system over life time	[-]	92%	92%	92%	92%	92%	92%	92%
Auxiliary heating energy for a battery system relative to functional unit	kW	5.0	5.0		5.0			
Self discharge per month(@STC)	[-]	2%	2%	2%	2%	2%	2%	2%
Total weight of a battery system	[kg]	609	304	126	256	210	128	128
Total weight of cells	[kg]	456	228	88	192	147	83	83
Specific energy density cell level	[Wh/kg]	175	175	136	156	136	120	120
Weight of Cobalt (pro battery system)	[kg]	10	5	1	3	2	0	0
Weight of Graphite (pro battery system)	[kg]	87	44	16	36	26	14	14
Weight of Nickel (pro battery system)	[kg]	36	18	3	10	6	1	1
Weight of Manganese (pro battery system)	[kg]	17	9	3	2	4	0	0
Weight of Lithium (pro battery system)	[kg]	14	7	2	5	3	1.2	1.2

6.2.1.3. Usage of low carbon electricity mix

The usage of low-carbon electricity mix has no direct influence on the materials or energy consumption and hence the BOM and the performance indicators are identical with those of the BAU for the Base Cases (see Table 6). This option has an environmental impact through reducing the emissions caused by the electricity used for the battery production. The resulting environmental impact strongly depends on the current electricity mix (as also Figure 2 indicates). For this design option the impact of the usage of two different electricity mixes and their corresponding GHG emissions are calculated. The first one is intended to reflect the current electricity mix. According to the PRIMES model, the electricity mix in the EU28 accounts currently for about 0.38 kg CO_2eq/kWh. However, depending on the technology, GHG emissions power generation can range between 1.284 kg CO_2eq/kWh and 0.004 kg CO_2eq/kWh[12]. In addition, many batteries are currently produced outside the EU with other electricity mixes and carbon emissions. Based on two values values taken from ecoinvent, the resulting GHG emissions during the production are calculated in the scenario analysis of task 7 with a different separate spreadsheet than the MEErP EcoReport tool. Due to the limitations of the MEErP EcoReport tool, it is impracticable to change the electricity related GHG emissions of the production of all the materials. Therefore, there are no EcoReport results included on the usage of a low carbon electricity mix in this task 6 report and we refer you to the figures included in task 7.

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[12] To determine this range, the GWP impact of the available high voltage electricity generating technologies within the ecoinvent LCI database (version 3.4) were calculated within SimaPro (version 8.52). In ecoinvent there are 21 high voltage power generating processes. Germany was taken as region to represent a European average, as there are no European mixes available of the high voltage power generating processes only country-specific processes. The power generator with the highest GWP impact is electricity production from lignite and the one with the lowest is run-of-river hydroelectricity. The impact was increased with 5% in order to include the losses when transforming high voltage electricity to medium voltage electricity.

Table 6: Performance indicators for base cases and design option low-carbon electricity mix

BaseCase		BC 1	BC 2	BC 3	BC 4	BC 5	BC6	BC7
Long Description		**Passenger Car - BEV with higher battery capacity**	**Passenger Car - BEV with lower battery capacity**	**Passenger Car PHEV**	**Truck BEV**	**Truck PHEV**	**Residential ESS**	**Grid stabilisation ESS**
Main application		eMobility					stationary	
Parameter	unit	BC 1	BC 2	BC 3	BC 4	BC 5	BC6	BC7
Typical capacity of the application	[kWh]	80	40	12	360	160	10	30 000
Economic life time of application (Tapp)	[y]	13	14	13	14	12	20	20
Percent of braking energy recovery in AS	[-]	20%	20%	20%	12%	6%	n.a.	n.a.
Application service energy (AS)	[kWh/Tapp]	43 680	29 568	19 656	940 800	890 400	40 000	120 000 000
Charger Efficiency (ηcharger)	[-]	85%	85%	85%	92%	92%	98%	98%
Consumption	[kWh/km]	0.2	0.16	0.18	1.2	1.4	n.a.	n.a.
Annual kilometers	[km/a]	14000	11000	7000	50000	50000	n.a.	n.a.
C-rate for charging	[-]	0.2 - 0.5	0.2 - 0.5	0.5	1.0	1.0	0.5	1.0
C-rate for normal discharge	[-]	0.33 - 1	0.33 - 1	1.0	1.0	1.0	1.0	1.0
C-rate for braking	[-]	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Nominal battery system capacity according to ISO ..	[kWh]	80	40	12	30	20	10	10
Number of battery systems per application	[-]	1	1	1	12	8	1	3 000
Maximum calendar life-time of the installed battery (no cycling ageing)	[year]	20	20	20	20	20	25	25
Maximum SoC - maximum DoD (Stroke)	[-]	80%	80%	75%	80%	75%	80%	80%
Average stroke (SoC - DoD)	[-]	24%	31%	73%	50%	69%	60%	75%
Energy delivered in first cycle (Edc).	[kWh/cycle]	64	32	9	24	15	8	8
Number of cycles per year (#)	cycles	120	120	120	300	600	250	250
Maximum number of cycles for battery system until EoL (no calendar ageing)	[-]	1 500	1 500	2 000	2 000	3 000	8 000	10 000
SoH @ EoL of battery system relative to declared capacity (SoHcap)	[-]	80%	80%	60%	80%	60%	70%	70%
Average energy delivered per average cycle until EoL	[kWh/cycle]	19.44	12.22	8.75	178.57	110.06	6.00	22 500.00
number of batteries in the application	[year]	1.00	1.00	1.00	12.00	8.00	1.00	3 000.00
Actual quantity of functional units (QFU) over battery system lifetime (per battery) *(1 FU = 1 kWh over battery lifetime).*	[-]	40 320	23 642	13 440	482 297	373 177	25 532	95 744 681
Service life of first battery (years)	[year]	14.40	13.43	10.67	8.04	5.33	17.02	17.02
battery system cost/declared initial capacity	[EURO/ kWh]	206	206	254	220	212	683	683
CAPEX for decomissioning	[EURO/ battery]	1 200	600	180	450	300	150	150
OPEX replace battery	[EURO/ battery]	700	700	700	400	400	100	100
ηcoul x ηv =average energy efficiency of battery system over life time	[-]	92%	92%	92%	92%	92%	92%	92%
Auxiliary heating energy for a battery system relative to functional unit	kW	5.0	5.0		5.0			
Self discharge per month(@STC)	[-]	2%	2%	2%	2%	2%	2%	2%
Total weight of a battery system	[kg]	609	304	126	256	210	128	128
Total weight of cells	[kg]	456	228	88	192	147	83	83
Specific energy density cell level	[Wh/kg]	175	175	136	156	136	120	120
Weight of Cobalt (pro battery system)	[kg]	10	5	1	3	2	0	0
Weight of Graphite (pro battery system)	[kg]	87	44	16	36	26	14	14
Weight of Nickel (pro battery system)	[kg]	36	18	3	10	6	1	1
Weight of Manganese (pro battery system)	[kg]	17	9	3	2	4	0	0
Weight of Lithium (pro battery system)	[kg]	14	7	2	5	3	1.2	1.2

6.2.2. Selection of the key environmental impact category and supplementary parameters

MEErP considers 13 environmental impact categories. Each impact category has its own unit, e.g. global warming potential is characterised as kg CO_2 eq. and acidification potential in g SO_2 eq. Due to the different units, it is difficult to compare the different impact categories to know which category is most decisive. To make comparison possible, characterised LCA results can be normalised and/or weighted so they are expressed in a similar unit. Therefore, normalising LCA results also allows aggregation of the different environmental indicators into a single score. External environmental costing is a method to normalise and weigh characterised environmental indicators in one step into monetary values. This step is also included in the MEErP EcoReport tool as “calculation of the marginal external damages” also mentioned as societal LCC (see section 5.3.2 of the task 5 report for explanation on how the societal LCC are calculated within the EcoReport).

When looking at the detailed societal LCC results of all seven BCs (see Task 5 report, sections 5.3.2.1 – 5.3.2.7), the top three impact categories with the highest societal LCC are: acidification potential, greenhouse gases/global warming potential, and particulate matter. However, the external marginal costs rates are outdated when comparing them to more recent studies on external environmental costing[13].

The review paper by Peters et al. (2017) mentions that the majority of existing LCA studies on Li-ion batteries focus on greenhouse gas emissions or energy demand, despite the high relative importance of environmental impacts related to human toxicity, acidification, and resource depletion[14]. The relative importance of the latter impact categories is shown by Peters et al. by normalising the mean value of the environmental impacts over the reviewed studies by comparing to the average annual impacts in Europe in 1995. According to Peters et al. it is mainly the mining and production of materials such as nickel or cobalt that cause significant toxicity impacts. They also noted that few data points are available for the categories acidification and resource depletion. Thus the results in these categories have a very high uncertainty and further research would be needed in that area.

In the position paper “(Right) indicators needed on sustainable batteries” by EUROBAT (2019) considering CO_2 eq. content is communicated as one of the key priorities in the framework of the current discussion on battery sustainability. In addition, they believe that recyclability and socio-economic considerations are important indicators that need to be included when addressing the sustainability of batteries. Regarding socio-economic considerations, EUROBAT sees it involving both the environmental conditions of mines and the social conditions of workers.

Based on the above, the results of Task 4 and 5, and seeing Commission communications that mentions that sustainable batteries are linked to a low carbon footprint and seen as one

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[13] E.g. De Nocker & Debacker, 2018; The Bruyn et al., 2018; Korzhenevych et al., 2014

[14] The impact category depletion of abiotic resources includes substances such as CRMs.

of the technologies to mitigate climate change[15], the following key environmental impact category and supplementary indicator are selected:

Key environmental impact category

- Global warming potential [kg CO2 eq.]

Supplementary indicator:

- The (non-)critical raw materials ((n-)CRM) within batteries
  - Cobalt [kg]
  - Lithium [kg]
  - Manganese [kg]
  - Natural graphite [kg]
  - Nickel [kg]

6.2.3. Summary of key performance indicators and results

The following two tables summarise all key performance indicators from the analysed design improvement options and Business-As-Usual (BAU) BCs. Table 7 gives the key performance indicators and Table 8 the results of the key environmental impact category, global warming potential.

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[15] EC COM(2019) 176 final, p. 6: “Sustainable batteries – produced with responsible sourcing, the lowest carbon footprint possible and following a circular economy approach, can be at the core of the EU’s competitive advantage.”.

Europe on the Move - Clean Mobility – Implementing the Paris Agreement (2018): “Why Europe needs a ‘battery ecosystem’: • Improve air quality & mitigate climate change → Protecting public health and environment means drastically cutting greenhouse gas emissions […]”.

Table 7: Overview of the key performance indicators

Performance indicator	**Design option**	**BC1** PC BEV HIGH	**BC2** PC BEV LOW	**BC3** PC PHEV	**BC4** Truck BEV	**BC5** Truck PHEV	**BC6** Resid. ESS	**BC7** Comm. ESS
Actual quantity of functional units per battery application system (QFU for total number of battery systems in its application) [kWh]	BAU	40 320	23 642	13 440	482 297	373 177	25 532	95 744 681
	Low carbon	40 320	23 642	13 440	482 297	373 177	25 532	95 744 681
	Reduced materials	40 320	23 642	13 440	482 297	373 177	25 532	95 744 681
	Extended lifetime	46 200	27 090	13 440	557 656	373 177	25 532	95 744 681
Battery system costs per declared initial capacity [EUR/kWh]	BAU	206	206	254	220	212	683	683
	Low carbon	206	206	254	220	212	683	683
	Reduced materials	140	140	185	129	185	499	499
	Extended lifetime	206	206	254	220	212	683	683
Specific energy density on cell level [Wh/kg]	BAU	175	175	136	156	136	120	120
	Low carbon	175	175	136	156	136	120	120
	Reduced materials	205	205	176	181	176	152	152
	Extended lifetime	175	175	136	156	136	120	120
Weight of cobalt (pro battery system) [kg]	BAU	9.6	4.8	1.3	2.8	2.1	0.3	0.3
	Low carbon	9.6	4.8	1.3	2.8	2.1	0.3	0.3
	Reduced materials	5.3	2.7	0.8	1.2	1.4	0.1	0.1
	Extended lifetime	9.6	4.8	1.3	2.8	2.1	0.3	0.3
Weight of lithium (pro battery system) [kg]	BAU	14.4	7.2	2.0	4.7	3.4	1.2	1.2
	Low carbon	14.4	7.2	2.0	4.7	3.4	1.2	1.2
	Reduced materials	13.9	7.0	1.7	4.5	2.8	1.0	1.0
	Extended lifetime	14.4	7.2	2.0	4.7	3.4	1.2	1.2
Weight of manganese (pro battery system) [kg]	BAU	17.1	8.6	2.6	1.9	4.3	0.2	0.2
	Low carbon	17.1	8.6	2.6	1.9	4.3	0.2	0.2
	Reduced materials	11.9	5.9	3.5	6.5	5.9	3.8	3.8
	Extended lifetime	17.1	8.6	2.6	1.9	4.3	0.2	0.2
Weight of graphite (pro battery system) [kg]	BAU	87.3	43.6	15.9	36.4	26.5	14.5	14.5
	Low carbon	87.3	43.6	15.9	36.4	26.5	14.5	14.5
	Reduced materials	79.2	39.6	12.5	31.1	20.9	11.1	11.1
	Extended lifetime	87.3	43.6	15.9	36.4	26.5	14.5	14.5
Weight of nickel (pro battery system) [kg]	BAU	35.9	18.0	3.4	10.0	5.7	1.2	1.2
	Low carbon	35.9	18.0	3.4	10.0	5.7	1.2	1.2
	Reduced materials	43.7	21.8	3.8	12.1	6.4	1.3	1.3
	Extended lifetime	35.9	18.0	3.4	10.0	5.7	1.2	1.2

Table 8: Overview of the key environmental impact category global warming potential, impact per FU (kWh delivered over application lifetime) [kg CO_2 eq./FU] and battery system [kg CO_2 eq./battery][16, 17]

Performance indicator	**Design option**	**BC1** PC BEV HIGH	**BC2** PC BEV LOW	**BC3** PC PHEV	**BC4** Truck BEV	**BC5** Truck PHEV	**BC6** Resid. ESS	**BC7** Comm. ESS
GWP production + distribution phase [kg CO_2 eq./FU]	BAU	0.19	0.29	0.18	0.09	0.08	0.08	0.08
	Reduced materials	0.17	0.26	0.14	0.08	0.06	0.06	0.06
	Extended lifetime	0.17	0.24	0.18	0.08	0.08	0.08	0.08
GWP use phase [kg CO_2 eq./FU]	BAU	0.09	0.09	0.09	0.07	0.07	0.05	0.05
	Reduced materials	0.09	0.09	0.09	0.07	0.07	0.05	0.05
	Extended lifetime	0.09	0.08	0.09	0.06	0.07	0.05	0.05
GWP EOL phase [kg CO_2 eq./FU]	BAU	-0.02	-0.04	-0.03	-0.01	-0.01	-0.01	-0.01
	Reduced materials	-0.02	-0.03	-0.02	-0.01	-0.01	-0.01	-0.01
	Extended lifetime	-0.02	-0.03	-0.03	-0.01	-0.01	-0.01	-0.01
GWP total life cycle [kg CO_2 eq./FU]	BAU	0.27	0.35	0.25	0.15	0.14	0.12	0.12
	Reduced materials	0.25	0.32	0.21	0.14	0.13	0.11	0.11
	Extended lifetime	0.25	0.28	0.25	0.12	0.14	0.12	0.12
GWP production + distribution phase [kg CO_2 eq./battery]	BAU	8 619	4 312	1 759	3 438	2 929	1 546	1 546
	Reduced materials	7 640	3 824	1 391	3 040	2 315	1 241	1 241
	Extended lifetime	8 619	4 312	1 759	3 438	2 929	1 546	1 546
GWP use phase [kg CO_2 eq./battery]	BAU	4 117	1 402	925	2 859	2 761	1 061	1 061
	Reduced materials	4 117	1 402	925	2 859	2 761	1 061	1 061
	Extended lifetime	4 663	1 406	925	2 522	2 761	1 061	1 061
GWP EOL phase [kg CO_2 eq./battery]	BAU	-1 051	-525	-253	-437	-422	-192	-192
	Reduced materials	-925	-462	-207	-390	-346	-166	-166
	Extended lifetime	-1 051	-525	-253	-437	-422	-192	-192
GWP total life cycle [kg CO_2 eq./battery]	BAU	11 685	5 189	2 431	5 860	5 269	2 415	2 415
	Reduced materials	10 833	4 763	2 108	5 508	4 731	2 135	2 135
	Extended lifetime	12 231	5 192	2 431	5 518	5 269	2 415	2 415

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[16] As mentioned in section 6.2.1.3 it is impracticable to calculate tool the impacts of using low carbon electricity mix for the complete production mix with the MEErP EcoReport and are therefore excluded from this overview.

[17] The figures of the extended lifetime design option of BC3, 5, 6, and 7 are coloured grey, as the lifetime of these base cases cannot be extended usefully thus cannot have additional QFU; in other words the extended lifetime option is similar to the BAU option.

6.3. Subtask 6.3: Costs

6.3.1. Introduction to calculating the Life Cycle Costs

As explained in more detail in Task 5, section 5.1.2, Life Cycle Costing (LCC) is a concept that aims to estimate the full cost of a system. Therefore, the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) are calculated and converted to their net present value (NPV) with a discount rate.

The consumer LCC in MEErP studies is to be calculated using the following formula:

$$[€]= \Sigma CAPEX + \Sigma(PWF\ x\ OPEX)$$

where,

LCC is the life cycle costing,
CAPEX is the purchase price (including installation) or so-called capital expenditure,
OPEX are the operating expenses per year or so-called operational expenditure,
PWF is the present worth factor with PWF = $1/(1+ r)^N$
N is the product life in years,
r is the discount rate which represents the return that could be earned in alternative investments.

The Levelized Cost Of Energy (LCOE) is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment, operations and maintenance, cost of fuel, and cost of capital. The LCOE is defined for the purpose of these calculations as:

$$\mathrm{LCOE}[€/\mathrm{kWh}] = \frac{\text{net present value of sum of costs of electricty stored over its lifetime}}{sum\ of\ electrical\ energy\ deliveredover\ its\ life\ time}$$

The LCOE calculation of costs per kWh generated aligns with the FU defined in Task 1. In this definition the life cycle environmental impacts of the battery system or component are normalized to 1 kWh of electricity stored.

As a consequence there is a direct relationship between LCOE, LCC and the quantity of FUs of a battery system:

LCOE = LCC/QFU [euro/kWh]

Using this approach allows comparison between the LCC of different design options per FU or in other words the LCOE.

For the LCC calculations of this task, the same economic parameters as in Task 5 are used (for more explanation on these parameters, see section 5.1.2.5 of Task 5):

- Discount rate: 4% (expect for electricity costs which is calculated with 0% discount rate following the MEErP methodology and are based on the PRIMES electricity rates which are already recalculated to an NPV).
- Electricity rate industry: 0.101 EUR per kWh.
- Electricity rate households: 0.213 EUR per kWh.

Extending these user-based LCC**,** societal LCC are calculated, as well. These include the costs for external damage of air emissions based on a given list of fixed prices (see section 5.3.2 of the task 5 report). These values are to be multiplied with the total mass of emissions calculated in the EcoReport tool and are added to the consumer LCC to sum up to the total LCC.

6.3.2. Life cycle costs of the individual design options

This section presents four tables: first table (Table 9) is an overview of the CAPEX and OPEX assumptions per BC and design option used in the LCC calculations, followed by three results tables with the consumer LCC results (Table 10), societal LCC results (Table 11), and the total LCC (Table 12), i.e. consumer plus societal LCC. For more explanation on the economic input parameters, please go to section 5.1.2 of the task 5 report, and on the LCC and societal cost calculations to section 5.3 of task 5.

Table 9: Overview of CAPEX and OPEX assumptions of the BCs for BAU, low carbon, reduced materials, and extended lifetime design options (based on Task 3 and Table 7)

Performance indicator	**Design option**	**BC1** PC BEV HIGH	**BC2** PC BEV LOW	**BC3** PC PHEV	**BC4** Truck BEV	**BC5** Truck PHEV	**BC6** Resid. ESS	**BC7** Comm. ESS
CAPEX battery system cost per declared initial capacity [EUR/kWh]	BAU	206	206	254	220	212	683	683
	Low carbon	206	206	254	220	212	683	683
	Reduced materials	140	140	185	129	185	499	499
	Extended lifetime	206	206	254	220	212	683	683
OPEX battery replacement [EUR/service]	All options	700	700	700	400	400	100	100
CAPEX decommissioning at EOL [EUR/battery sys.]	All options	1 200	600	180	450	300	150	150

Table 10: Overview of the consumer life cycle costing results per BC for BAU, low carbon, reduced materials, and extended lifetime design options (calculation based application level)

Performance indicator	**Design option**	**BC1** PC BEV HIGH	**BC2** PC BEV LOW	**BC3** PC PHEV	**BC4** Truck BEV	**BC5** Truck PHEV	**BC6** Resid. ESS	**BC7** Comm. ESS
Consumer LCOE or LCC per FU [EUR/kWh delivered]	BAU	0.461	0.547	0.377	0.177	0.125	0.293	0.278
	Reduced materials	0.340	0.404	0.306	0.117	0.113	0.223	0.208
	Extended lifetime	0.410	0.453	0.377	0.155	0.125	0.293	0.278
Consumer LCC total for all batteries in application per Tapp [EUR]	BAU	20 152	16 179	7 401	166 397	111 511	11 723	33 328 317
	Reduced materials	14 872	11 954	6 014	109 699	100 722	8 938	24 974 497
	Extended lifetime	20 327	16 520	7 401	168 926	111 511	11 723	33 328 317

Table 11: Overview of the societal life cycle costing results per BC for BAU, low carbon, reduced materials, and extended lifetime design options (calculation based application level)

Performance indicator	**Design option**	**BC1** PC BEV HIGH	**BC2** PC BEV LOW	**BC3** PC PHEV	**BC4** Truck BEV	**BC5** Truck PHEV	**BC6** Resid. ESS	**BC7** Comm. ESS
Societal LCC per FU [EUR/kWh delivered]	BAU	0.050	0.072	0.034	0.021	0.017	0.013	0.013
	Reduced materials	0.052	0.075	0.031	0.021	0.015	0.012	0.012
	Extended lifetime	0.045	0.058	0.034	0.018	0.017	0.013	0.013
Societal LCC total for all batteries in application per Tapp [EUR]	BAU	2 189	2 119	663	19 924	14 830	531	1 582 515
	Reduced materials	2 277	2 209	611	20 059	13 785	471	1 413 800
	Extended lifetime	2 291	2 120	663	19 522	14 830	531	1 582 515

Table 12: Overview of the total (consumer + societal) LCC results per BC for BAU, low carbon, reduced materials, and extended lifetime design options (calculation based application level)

Performance indicator	**Design option**	**BC1** PC BEV HIGH	**BC2** PC BEV LOW	**BC3** PC PHEV	**BC4** Truck BEV	**BC5** Truck PHEV	**BC6** Resid. ESS	**BC7** Comm. ESS
Total LCC per FU [EUR/kWh delivered]	BAU	0.511	0.619	0.410	0.198	0.142	0.306	0.291
	Reduced materials	0.393	0.409	0.337	0.138	0.129	0.235	0.220
	Extended lifetime	0.455	0.511	0.410	0.173	0.142	0.306	0.291
Total LCC total for all batteries in application per Tapp [EUR]	BAU	22 341	18 299	8 064	186 321	126 341	12 254	34 920 832
	Reduced materials	17 148	14 163	6 625	129 758	114 507	9 410	26 388 296
	Extended lifetime	22 545	18 640	8 064	188 448	126 341	12 254	34 920 832

6.4. Subtask 6.4: Analysis of BAT and LLCC

AIM OF TASK 6.4:

The aim of this task is to combine the previous design options (if possible) and to identify the Best Available and also the Least Life Cycle Cost (LLCC) solution.

Therefore, the design option identified in subtask 6.1 should be ranked regarding the Best Available Technology (BAT) and the Least (minimum) Life Cycle Costs.

6.4.1. Ranking of individual design options

The following seven figures show the ranking of the design options per BC. Based on the ranking, it can be concluded that:

- The reduced material option is the best design option from an environmental point of view based on the GWP impact and from an economical point of view based on the least LCC for BC1, BC3, BC5, BC6, and BC7. However, it needs to be noted that for the BC3, BC5, BC6, and BC7, the extended lifetime option is similar to BAU.

- For BC2 and BC4, the reduced material option has the least LCC but not the lowest GWP impact as the extended lifetime option has the lowest GWP impact in comparison.

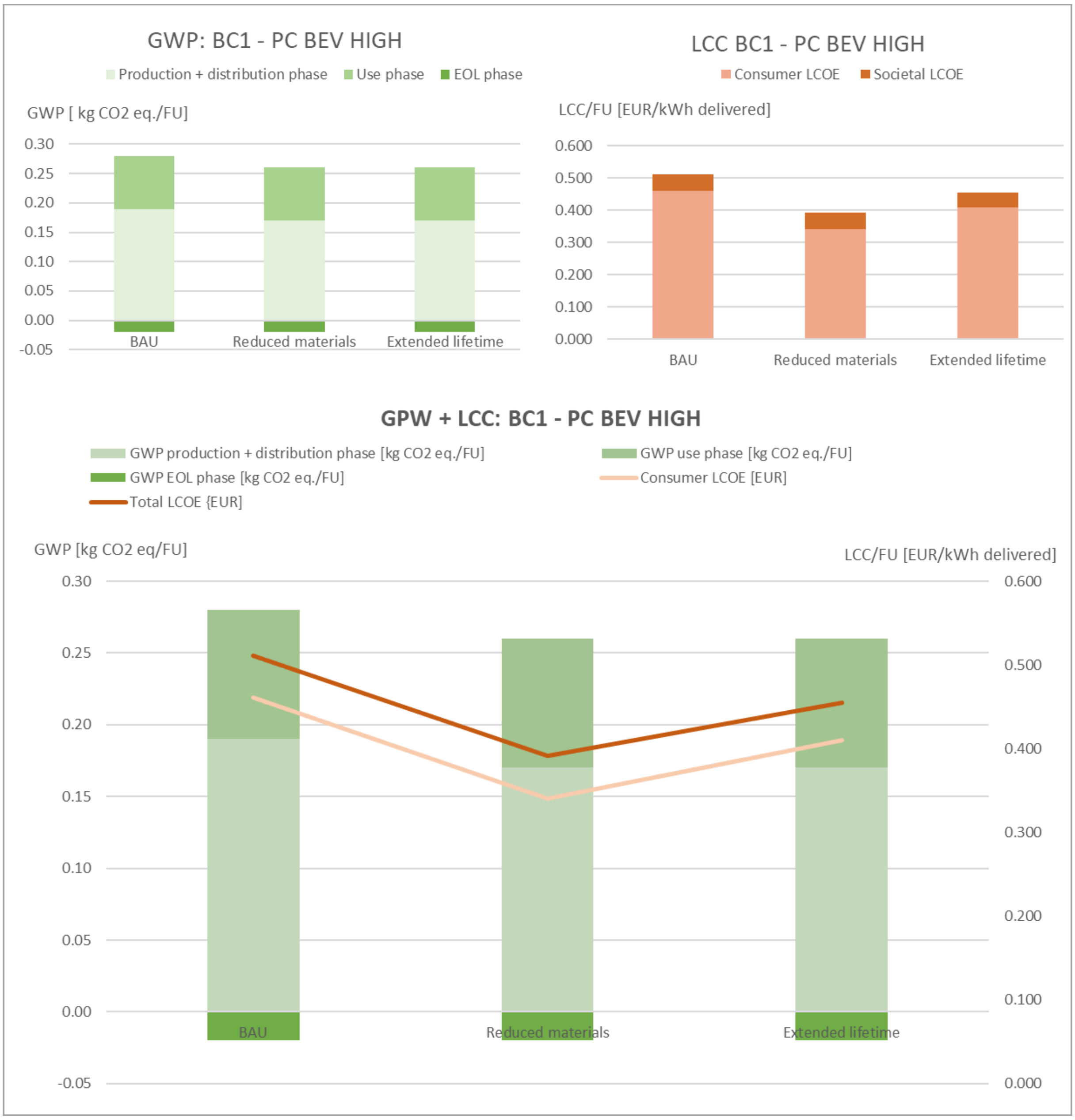

Figure 3: Ranking of the design options for BC1 – passenger car BEV with a high battery capacity.

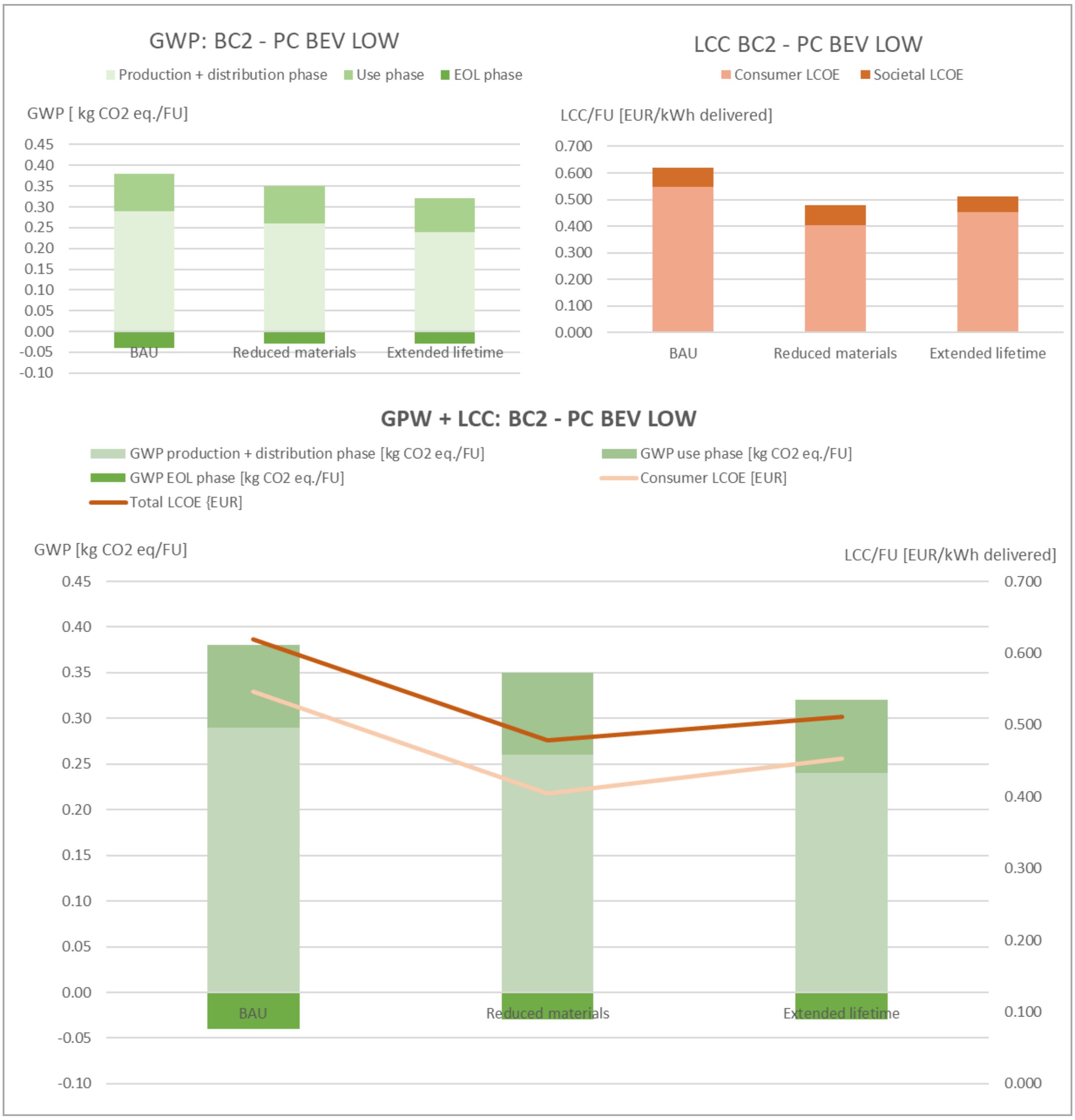

Figure 4: Ranking of the design options for BC2 – passenger car BEV with a low battery capacity.

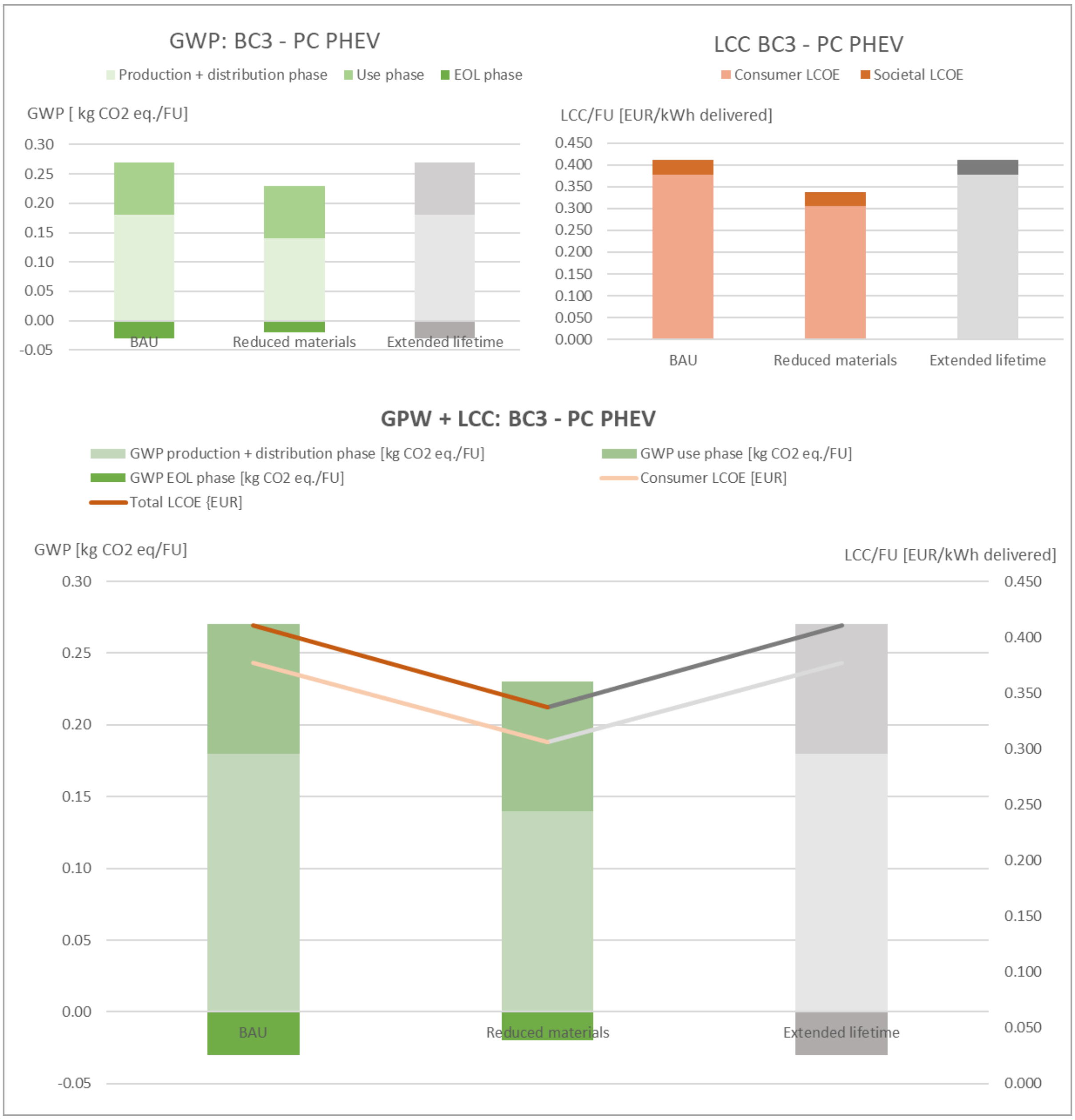

Figure 5: Ranking of the design options for BC3 – passenger car PHEV[18].

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[18] The figures of the extended lifetime design option are coloured grey, as the lifetime of this BC cannot be extended usefully thus cannot have additional QFU; in other words the extended lifetime option is similar to the BAU option.

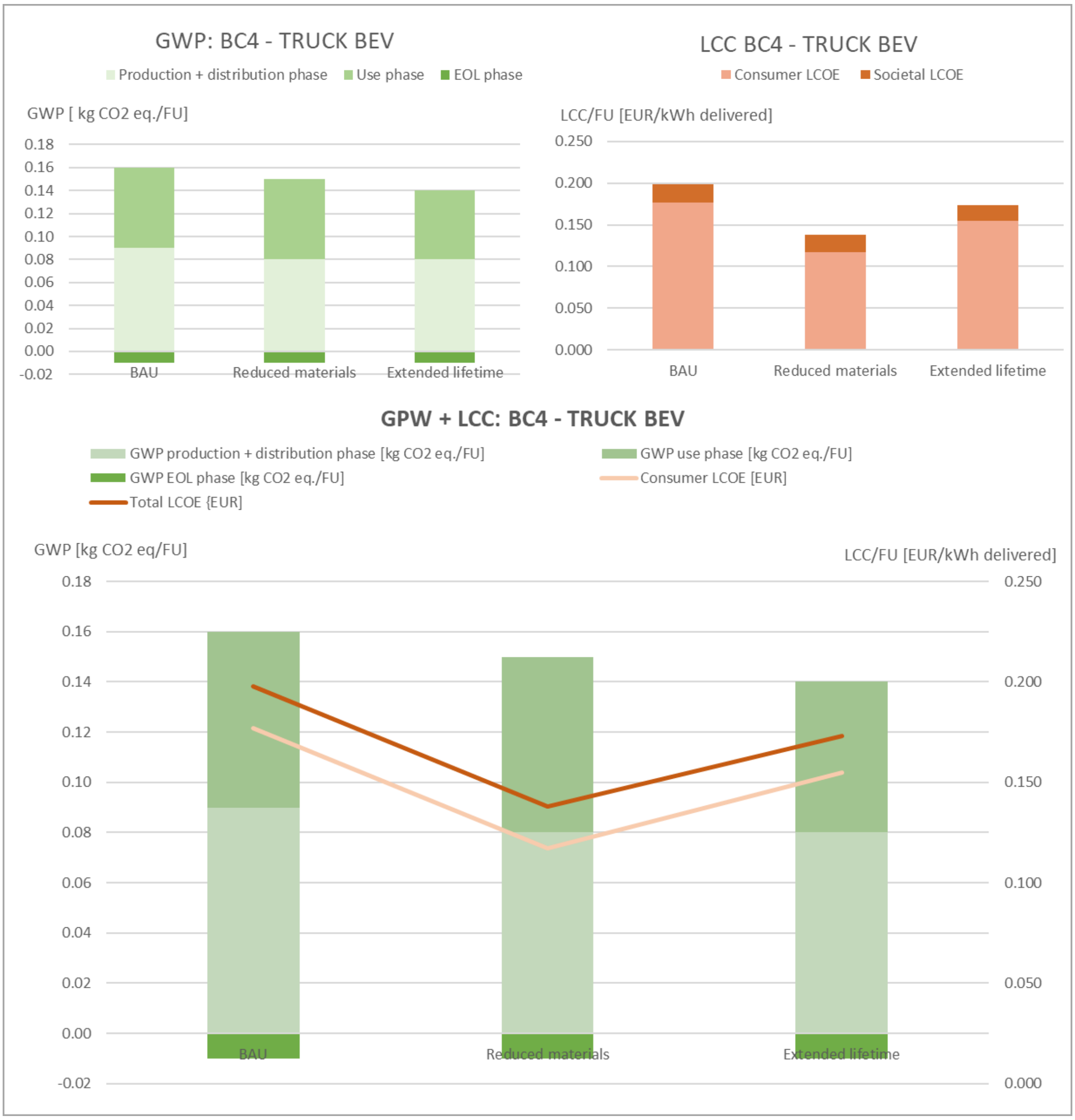

Figure 6: Ranking of the design options for BC4 – truck BEV

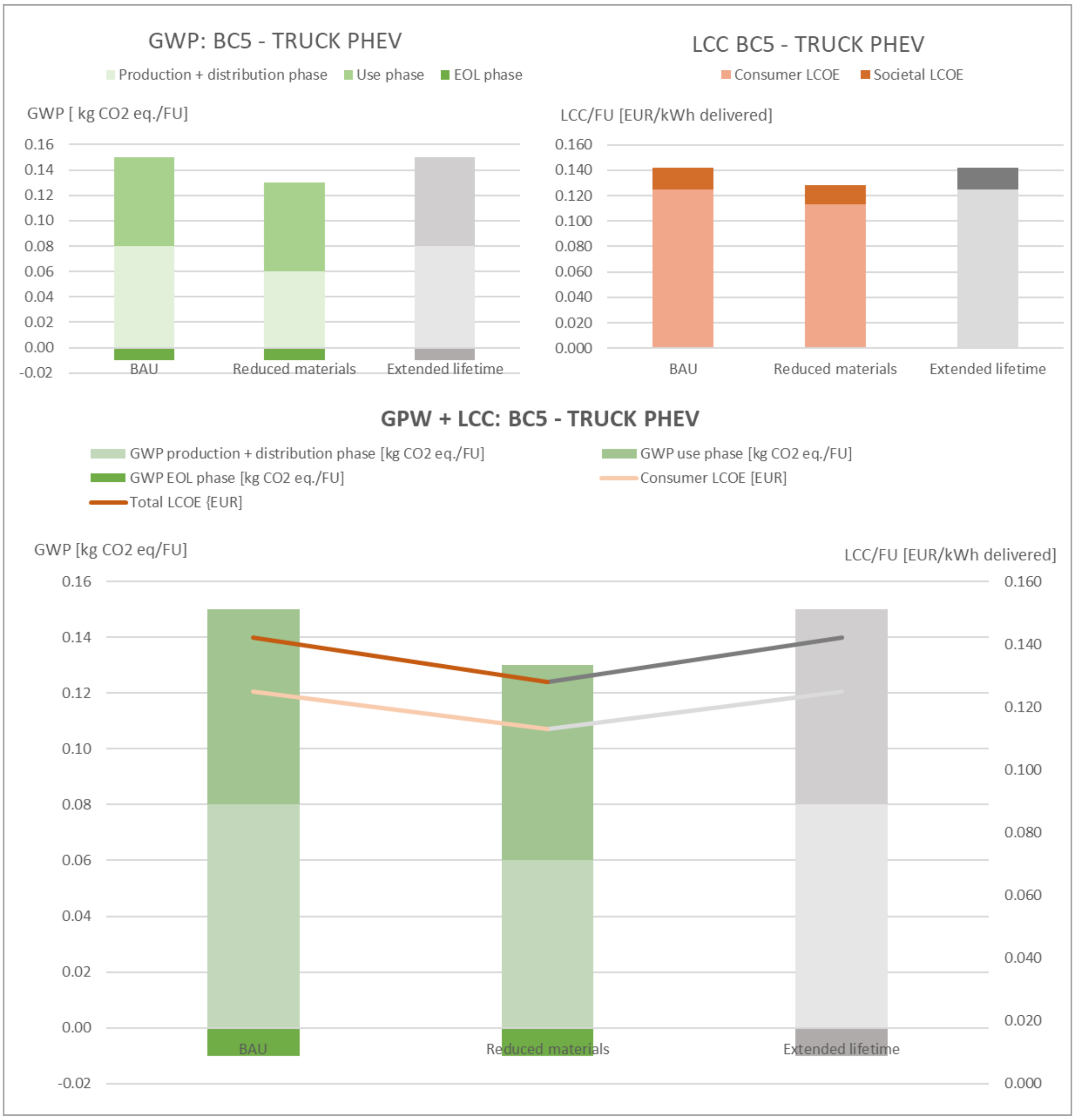

Figure 7: Ranking of the design options for BC5 – truck PHEV[19]

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[19] The figures of the extended lifetime design option are coloured grey, as the lifetime of this BC cannot be extended usefully thus cannot have additional QFU; in other words the extended lifetime option is similar to the BAU option.

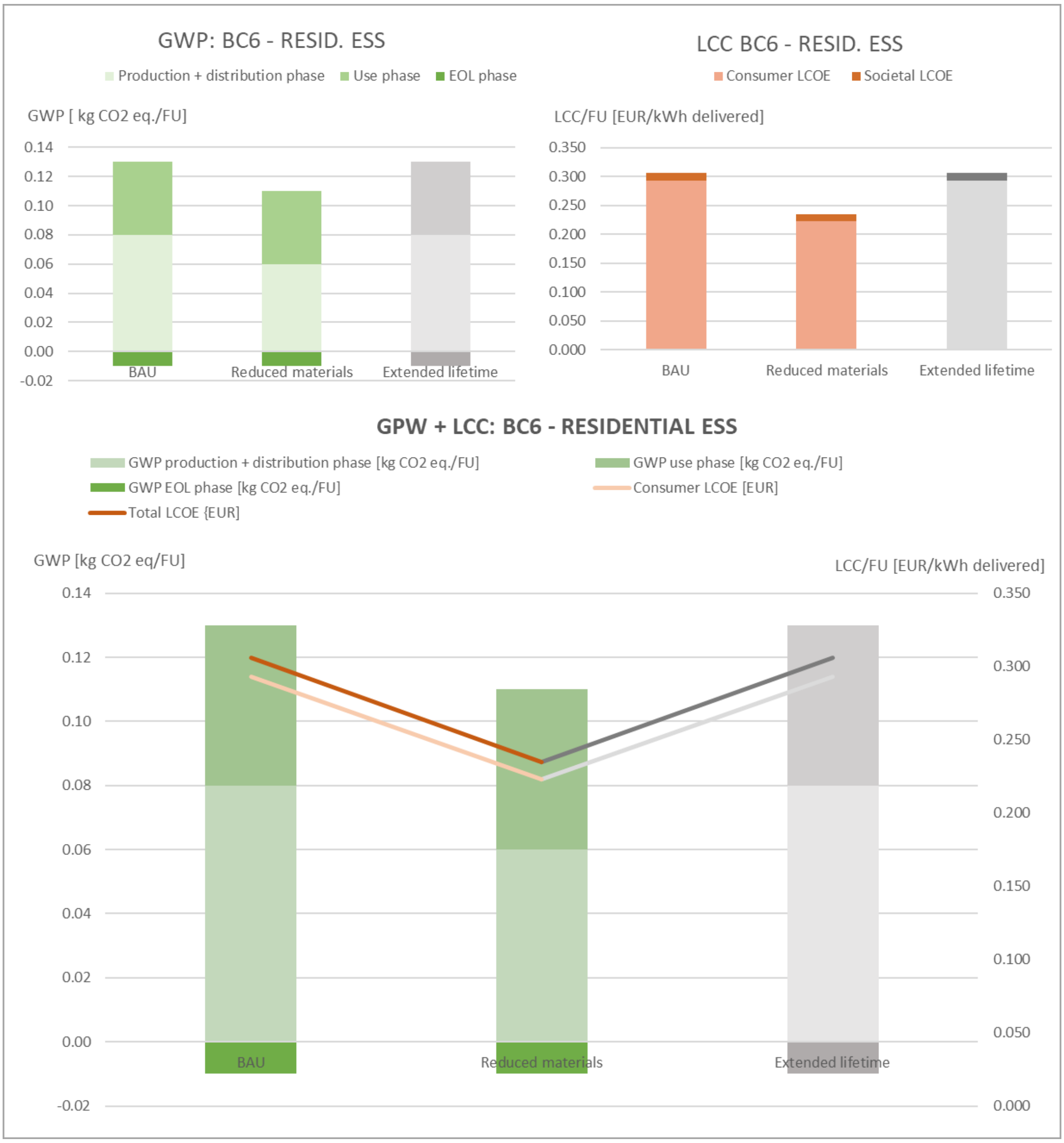

Figure 8: Ranking of the design options for BC6 – residential ESS[20]

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[20] The figures of the extended lifetime design option are coloured grey, as the lifetime of this BC cannot be extended usefully thus cannot have additional QFU; in other words the extended lifetime option is similar to the BAU option.

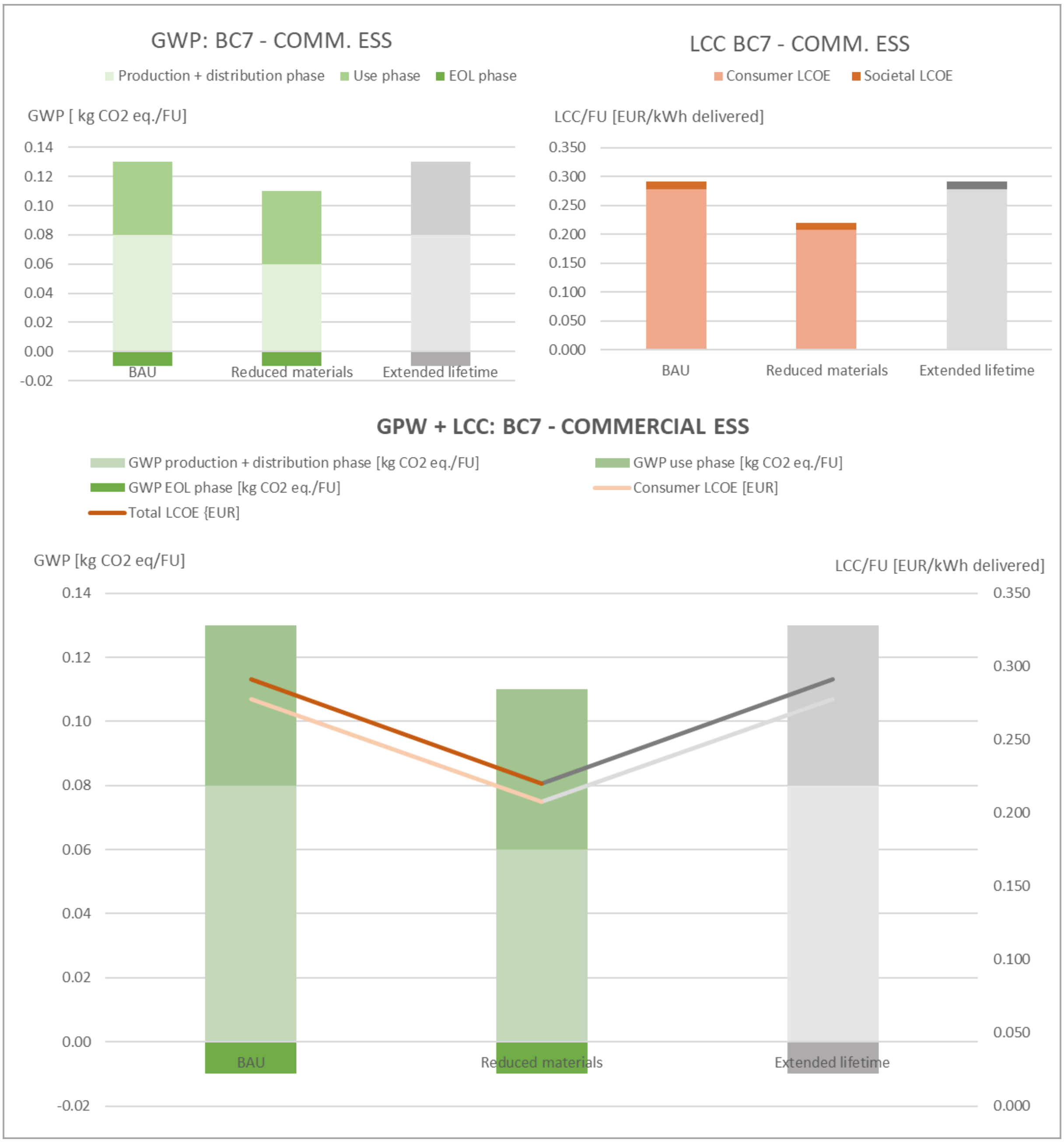

Figure 9: Ranking of the design options for BC7 – commercial ESS[21]

6.4.2. Possible positive or negative ('rebound') side effects of the individual design measures

The previous chapter highlighted the positive influence of the design options on the environmental impact of batteries. Anyhow, besides this positive effect the design options also

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[21] The figures of the extended lifetime design option are coloured grey, as the lifetime of this BC cannot be extended usefully thus cannot have additional QFU; in other words the extended lifetime option is similar to the BAU option.

bear the potential for negative side effects. Those effects will be briefly discussed in the following.

Reduction of active and passive materials

Improvements in cell chemistry and design leads to an increasing energy density out of a gravimetric and volumetric perspective. A general potential rebound effect might thereby result from the substitution of materials with a low environmental impact by materials with a higher impact, which could counter the positive effect from the reduction of material content. This potential effect was considered and as Table 8 indicates is not the case at this point. Furthermore, it should also be considered, that (as described in task 4 report) there might also occur issues regarding safety and durability by reducing the active and passive materials and especially when changing or substituting the cell chemistries. Another potential rebound effect may result from the fact that the volumetric energy density directly influences the volume of the final battery pack. Thus, the volume of the battery pack might be reduced or some additional cells might be installed in the gained space to increase the battery capacity. If the user does not use the product according to the additional higher capacity, this could also lead to an increased environmental impact.

Prolonged lifetime

The reuse and repurposing of batteries offer the possibility to extend the battery lifetime and thus to increase the QFU. However, also for this design options some negative side effects might occur. One aspect might be, that batteries containing a high amount of materials with a relatively high environmental impact (such as cobalt) could have a potentially higher positive influence if they are directly recycled instead of reused. An example therefore are batteries containing a relative high share of cobalt (such as those using NMC111). If those batteries are recycled instead of used for 2nd life, the recovered cobalt could be used again to produce a higher amount of cathode materials (with a lower share of cobalt), since newer cell chemistries typically need a lower share of cobalt (such as NMC 532or NMC622). Another rebound effect might be that batteries are removed before they are reaching a SOH of 70-80%, the guarantee that the batteries are still usable for 2nd life applications. In such a case, the battery might have been able to deliver some additional QFU in the first usage, which is lost when the battery system is removed too early. On the contrary it is also thinkable that a battery is used for a 2nd life application, although it is not anymore in the condition to provide the necessary service. This might lead to an unplanned exchange of the battery system.

Low-carbon energy mix

The usage of low-carbon energy mix might have a direct effect on the production costs of a battery system, even if low carbon electricity can be cheap in some regions. This is especially the case when regenerative energies are used which are still mostly more expensive than the conventional electricity mix. This might also affect the final product such as cars or ESS and might hinder the diffusion of these products. In the case of ESS this could also go along with a reduction of solar panels installed on rooftops, which again might affect the share of renewable energy available. Furthermore, it also possible that rebound effects might occur from the usage of “unsustainable” low GWP electricity sources, such as ecosystem losses or nuclear waste generation.

6.5. Subtask 6.5: Long-term targets (BNAT) and systems analysis

AIM OF TASK 6.5:

The aim of this final subtask within Task 6 is twofold by looking beyond the specific design options that are available as BAT in the long term. First, the long-term technical potentials based on outcomes of applied and fundamental research which still address the context of the present product archetype as best not yet available technologies (BNAT) are discussed. Second, the long-term potential based on changes to the total system to which the present archetype product belongs is discussed.

6.5.1. Long-term technical potentials based on BNAT

Based on the analysis of resources in the context of setting up the design options, two kinds of different BNAT design options could be identified. The first kinds are based on the steadily improvement of already used components such as cell chemistries or passive components. The second kind of BNAT therefore are based on a new kind of cell designs such as all-solid-state batteries or even more ambitious designs such as Li-air. Yet their impacts on energy demand are not yet known, since there is a lack of information regarding the corresponding performance indicators. All-solid-state batteries for example will offer the opportunity to connect a high number of electrode packages in parallel already at room temperature without the necessity for an intermediate housing of the cells. This offers a high freedom in design.

Anyhow, considering those developments, it furthermore seems inevitable to revise this study periodically to adapt the analyses to the new insights on technologies and testing methods. Out from today's perspective the long-term potentials can hardly be quantified.

6.5.2. Long-term changes to the total system

The performance of future battery systems will have to follow the requirements of the final applications they are used for. In the case of automotive applications, the batteries will have to be able to be charged in a shorter time and thus the batteries will have to be able to deal with comparatively high currents. Also this is already of relevance for today it will become even more important in future. This also sets high requirements regarding the battery management and the external cooling of the battery system. Furthermore, the current discussion points out that customers product awareness is rising steadily and "green" products might play a more prominent role in the future. This means that not only the vehicle has to be charged with low-carbon energy but also the whole battery has to be produced with a low environmental impact. In the case of stationary applications, a cost reduction of the systems may be in the focus for the upcoming years, to increase the economic benefit of stationary systems. However, the listed changes will play a crucial role in the future for the battery system. But a fundamentally long-term change, especially in the design of battery systems is rather unlikely (except for a continuous downsizing and standardization).

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TASK 7 Report

Policy Scenario Analysis

VITO, Fraunhofer, Viegand Maagøe

August 2019

Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs

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Project website:	https://ecodesignbatteries.eu/

Version history:

Version 1: Draft for discussion in the stakeholder meeting of 2/5/2019

Version 2: Updated version taking into account the written feedback from the stakeholders and those of the stakeholder meeting.

Main changes in the policy analysis are:

- In the carbon footprint requirements some recommendations are added to review/simplify the PEFCR to be used.
- Separate information requirements are added for battery cells to be used in the intended application.
- The information requirements are split in a list with information about batteries and cells to be stored in a European database, and in traceability of battery modules and packs to be stored with help of a public-private initiative.
- The minimum warranty has been better clarified.
- The proposed Recyclability index is renamed to R-R-R-R index, since it sustains all phases of repair, re-use, repurpose and recycle.
- In the other minimum battery pack design and construction requirements a requirement has been added to provide a vehicle-to-grid (V2G) and complementary vehicle-to-test (V2test) interface.

EUROPEAN COMMISSION

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Contents

ABBREVIATIONS

Abbreviations	Descriptions
AC	Alternating current
AD	Acidification
ADR	European Agreement Concerning the International Carriage of Dangerous Goods by Road
Ah	Ampere-hour
Al	Aluminum
ADN	European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways
AS	Application service energy
BAT	Best Available Technologies
BAU	Business As Usual
BC	Base case
BEV	Battery Electric Vehicle
BJB	Battery junction box
BMS	Battery Management System
BNAT	Best Not-yet Available Technologies
BOM	Bill-of-Materials
C	Capacity
CAPEX	Capital Expenditure
Cd	Cadmium
CE	European Conformity
CED	Cumulative energy demand
CF	Characterisation Factor
CIT	International Rail Transport Committee
CMC	Carbon methyl cellulose
C_n	Rated capacity
CNT	Carbon nanotube
Co	Cobalt
CPA	Statistical Classification of Products by Activity
CPE	Composite polymer electrolytes
CPT	Cordless Power Tools
CRM	Critical Raw Materials
DC	Direct Current
DEC	Diethyl carbonate
DG	Directorate General
DMC	Dimethyl carbonate
DoC	Declaration of Conformity
DOD	Depth of Discharge
E	Energy
EC	European Commission
EC	Ethylene carbonate
ECHA	European Chemicals Agency
ED	Ecodesign Directive

Abbreviations	Descriptions
EDLC	Electrical Double-Layer Capacitor
EEI	Energy efficiency index
EGDME	1, 2-dimethoxyethane or ethylene glycol dimethyl ether
ELR	Energy Labelling Regulation
ELV	End of Life of Vehicles
EMC	Ethyl Methyl Carbonate
EOL	End-of-Life
EPA	Environmental Protection Agency
EPD	Environmental Product Declaration
EPTA	European Power Tool Association
eq.	equivalent
E_{Rated}	Rated energy
ESS	Electrical Energy Storage Systems
EU	European Union
EU-28	28 Member States of the European Union
EUP	Eutrophication
EV	Electric vehicle
FC	Full cycle
Fe	Iron
FESS	Flywheel energy storage systems
FTP	Federal Test Procedure
FU	Functional Unit
GER	Gross Energy Requirements
GHG	Greenhous Gases
GVW	Gross vehicle weight
GWP	Global warming potential
HDT	Heavy-duty truck
HDTU	Heavy-duty tractor unit
HE	High-energy
HEV	Hybrid Electric Vehicle
Hg	Mercury
HMa	Heavy metals to air
HMw	Heavy metals to water
HREEs	Heavy rate earth elements
HV	High-voltage
I	Current
IATA	International Air Transport Association
ICEV	Internal combustion engine vehicles
ICT	Information and Communications Technology
IEC	International Electrotechnical Commission
IM	Implementing Measure
IMDG	International Maritime Dangerous Goods Code
IMO	International Maritime Organization
ISO	International Organization for Standardization
I_t	Reference test current
JRC	Joint Research Centre

Abbreviations	**Descriptions**
kWh	Kilowatt hour
LCA	Life Cycle Assessment
L_{Cal}	Calendar life
LCC	Life Cycle Costs
LCI	Life Cycle Inventory
LCO	Lithium-ion Cobalt Oxide
LCOE	Levelized Cost Of Energy
LCV	Light commercial vehicles
L_{Cyc}	Cycle life
LFP	Lithium-Ion Phosphate
Li	Lithium
LIB	Lithium ion battery
Li-Cap	Lithium-ion Capacitor
LiFSI	Lithium bis(fluorosulfonyl) imide
LiPF6	Lithium Hexaflurophosphate
LLCC	Least Life Cycle Costs
LMNO	Lithium-Ion Manganese Nickel Oxide
LMO	Lithium Manganese Oxide
LMP	Lithium-Metal-Polymer
LREEs	Light rare earth elements
LTO	Lithium-Ion Titanate Oxide
LVD	Low Voltage equipment
MEErP	Methodology for Ecodesign of Energy related Products
MEEuP	Methodology for Ecodesign of Energy-using Products
Mn	Manganese
NACE	Statistical Classification of Economic Activity
$NaNiCl_2$	Sodium nickel chloride
NaS	Sodium-sulphur
nC	C-rate
NCA	Lithium Nickel Cobalt Aluminium
NCM	Lithium Nickel Manganese Cobalt Oxide
NEDC	New European Driving Cycle
Ni	Nickel
NiCd	Nickel-Cadmium
NiMH	Nickel-metal hydride
NMC	Lithium-ion Nickel Manganese Cobalt Oxide
NPV	Net Present Value
OCV	Open Circuit Voltage
OPEX	Operational expenditure
P	Phosphor
PAH	Polycyclic Aromatic Hydrocarbons
Pb	Lead
Pb	Lead-acid
PBB	Polybrominated biphenyls
PBDE	Polybrominated diphenyl ethers
PC	Passenger car

Abbreviations	Descriptions
PC	Propylene Carbonate
PCM	Protection Circuit Module
PCR	Product Category Rules
PE	Polyethylene
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
PEm	Primary energy for manufacturing
PEM-FC	Proton exchange membrane fuel cell
PEr	Primary energy for recycling
PGMs	Platinum Group metals
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matter
POP	Persistent Organic Pollutants
PP	Polypropylene
PRODCOM	Production Communautaire
PTC	Positive Thermal Coefficient
PV	Photovoltaic
PVD	Physical vapour deposition
PVDF	Polyvinylidene fluoride
PWF	Present Worth Factor
Q_{FU}	Quantity of functional units
R	Internal resistance
R&D	Research and Development
RE	Round-trip efficiency
REACH	Regulation on the registration, evaluation, authorisation and rustication of chemicals
RFB	Redox-flow battery
RID	International Carriage of Dangerous Goods by Rail
RoHS	Restriction of hazardous substances
RRR	Recyclability, Recoverability, Reusability
RT	Room temperature
SASLAB	Sustainability Assessment of Second Life Application of Automotive Batteries
Sb	Antimony
SBR	Styrene-Butadiene Rubber
SD	Self-discharge
SEI	Solid-electrolyte interphase
Si	Silicon
SOC	State of Charge
SOH	State of Health
SOH_{cap}	Capacity degradation
SPE	Solid polymer electrolyte
SVHC	Substances of Very High Concern
T	Time
TIM	Thermal interfacial material
TMS	Thermal Management System
TOC	Total Cost of Ownership

Abbreviations	**Descriptions**
TRL	Technology Readiness Level
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UPS	Uninterruptible Power Supply
V	Voltage
VAT	Value Added Tax
VKT	Vehicle kilometres travelled
V_L	Voltage limits
V_{OC}	Open circuit voltage
VOC	Volatile Organic Compounds
vPvB	Very persistent and very bio accumulative
V_R	Rated voltage
WEEE	Waste electrical and electronic equipment
WLTP	Worldwide Harmonized Light Vehicle Test Procedure
WVTA	Whole Vehicle Type-Approval System
ZrO2	Zirconium Oxide
ZVEI	Zentralverband Elektrotechnik- und Elektronikindustrie e. V.
η_E	Energy efficiency
η_V	Voltaic efficiency

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7. Task 7: Policy Scenario Analysis

AIM OF TASK 7

This task identifies and discusses in Task 7.1 policy options aimed at reducing the impacts on the environment as analysed in previous tasks. It provides in Task 7.2 and Task 7.3 an analysis of the impacts of future scenarios in line with policy measures that could be introduced at EU level. This is a key task as it combines the results of the previous tasks. It discusses potential Ecodesign and/or Energy Labelling Regulation policy measures, and it is aimed at providing an analytical basis in support of the Ecodesign decision-making process. Therefore, a set of quantitative scenarios is defined. To this end, a stock model has been developed to estimate environmental and economic impacts according to future stocks and to different improvement scenarios. The outcomes of the expected improvement are compared with a Business-as-Usual scenario.

SUMMARY OF TASK 7

This document describes a set of policy options for battery systems, packs and cells within the scope proposed in Task 1, i.e. high energy rechargeable batteries of high specific energy with lithium chemistries for e-mobility and stationary energy storage batteries excluding power electronics and heat or cool supply systems. The environmental impact improvement and the key parameters to do this were previously discussed in Task 6, while this Task 7 discusses how they can potentially be converted into policy. For defining policy measures this task is built on previous work done by JRC[1] on 'Standards for the performance assessment of electric vehicle batteries (2018)'. Relative to the proposed policy options this task also analyses and models impact scenarios. This is a reviewed version elaborated after consulting stakeholders in a meeting and collecting feedback in writing. A summary of stakeholder positions with regards to the proposed policy is included as a support to the subsequent policy making process.

Be aware that in parallel to this study the EC hosts a website that provides the latest information for the related regulation making process and that information included in this report can be outdated, therefore please consult also:

https://ec.europa.eu/info/law/better-regulation/initiatives/ares-2018-5951053_en

Please consult the EC website for a summary on proposed policy and expected impact.

7.1. Policy Analysis

Aim of Task 7.1:

The aim is to identify policy options considering the outcomes of all previous tasks.

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[1] http://publications.jrc.ec.europa.eu/repository/bitstream/JRC113420/kjna29371enn.pdf

7.1.1. Scoping of possible policy requirements and key definitions

Objective:

This section describes the prospective boundaries or 'battery' definitions to address the eco-design performance improvement from this study. The proposed policy measures themselves and potential legislative instruments to be used are discussed in subsequent sections.

Proposal:

In line with Task 1 the proposed scope is 'high energy rechargeable batteries of high specific energy with solid lithium cathode chemistries for e-mobility and stationary energy storage (if any)'.

High specific energy is hereby defined by a gravimetric energy density 'typically' above 100 Wh/kg at cell level.

High capacity means that a total battery system capacity between 2 and 1000 kWh.

(see Task 1 for more details).

This does not include power electronics neither heat or cool supply systems for thermal management which can be part of what the study defined as a battery *application* system.

Note that a scope extension for certain of the proposed policy measures will be discussed in a later section 7.1.3.

Terms and definitions can be in line with IEC/ISO standards (see Task 1); however there is still a lack of clear definitions regarding some material efficiency issues. The following definitions are proposed for the terms repair, reuse, remanufacture and repurposing. They are in line with the draft standards on material efficiency under preparation as part of request (M/543) to develop horizontal, generic standards for future product publications covering a specific energy-related product (ErP) or group of related ErPs.

Note: A new complementary study is launched to explore the extension of the scope and to work as technology neutral as possible in formulating the scope of any future regulation. For this consult the project website: https://ecodesignbatteries.eu/planning

7.1.2. Proposed requirements to consider in policy measures

Note that this section is independent of the later policy instruments to be used and several aspects could be implemented under the scope of other legislation e.g.: Battery Directive, ELV Directive, UNECE Regulation, etc. This will need to be considered in a later stage of policy making. For more information on this please consult the website of the European Commission: https://ec.europa.eu/info/law/better-regulation/initiatives/ares-2018-5951053_en

Requirements are proposed on the following topics:

- Minimum battery pack/system lifetime
- Battery management systems
- Providing information about batteries and cells to be stored in a European database
- Traceability of battery modules and packs to be stored with help of a public-private initiative
- Carbon footprint information and considering the option for a threshold

- Minimum battery pack design and construction to support reusability/recyclability/recoverability.
- A ‘R-R-R-R’ index that follows from previous subject supporting all phases of repair, re-use, repurpose and recycle.
- Hardware requirements for a BMS open data diagnostics connector and for Vehicle to Grid and Vehicle to Test mode DC interface.

At the end of the section policy requirements are discussed that were considered but not proposed.

7.1.2.1. Minimum battery pack/system lifetime requirements

Rationale:

The switch from fossil-fuelled vehicles to battery-based vehicles should win the trust of the European public. The same applies to batteries that are used in stationary applications linked to the electricity grid such as storage of PV energy in households. To gain this trust, it must be demonstrated that the batteries have a long service life and that energy waste is minimised. High upfront cost and lack of confidence can be important barriers hindering the uptake of e-mobility solutions and of domestic/community energy storage solutions. Additionally, prolonging the lifetime of batteries into a second life application is an intuitive approach to reduce its carbon footprint and also economic value along the life cycle provided that the battery is prepared for this change.

Hence the main objective of requirements is to reduce the carbon footprint per functional unit as modelled in Task 5 by warranting its projected useful lifetime. The rationale is clear: it serves to ensure that those products at least perform as they were assumed in previous tasks for the base case in a first Tier (see timing), see Table 7-1.

Table 7-1 Battery pack/system Lifetime related performance data from previous Tasks

	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
Max. calendar lifetime installed battery (no cycling ageing) [yr]	20	20	20	20	20	25	25
Max. number of cycles for battery system until EOL (no calendar ageing) [-]	1,500	1,500	2,000	2,000	3,000	8,000	10,000
Service life of battery (Tbat) [y]	14.40	13.43	10.67	8.04	5.33	17.02	17.02
Number of battery application systems per Tapp (Ass) [-]	1	2	2	2	3	2	2
Average efficiency of battery system [%]	92	92	92	92	92	92	92
Self-discharge (@STC) [%]	2	2	2	2	2	2	2

In order to support the previous lifetime and related performance assumptions, the following technical parameters are important to consider:

- Capacity, expressed in Ah as is common practice for batteries.
- Energy expressed in kWh. From the energy also the study's base criterion (100 Wh/kg at cell level) can be examined.
- Power capability, especially of importance for power intensive applications like PHEV cars, since power capability can be limiting before the capacity decrease limits the battery use in such an application.
- Energetic efficiency, expressed as a percentage, of importance for the carbon footprint during use phase. It is the ratio of discharge and charge energy. The value is influenced by power profile for charging and discharging, cut-off voltage and temperature. The method has thus to be described.

The last two parameters are closely related to the internal ohmic resistance of the battery. That is why an additional requirement can be imposed on resistance. Internal ohmic resistance was also recommended in the EU funded H2020 Everlasting project[2], see Deliverable 'D8.7 – White Paper 04: Definition of SOH' (5/2018)'.

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[2] https://everlasting-project.eu/results/deliverables-reports/

An important criterion for batteries is calendar life. Batteries age over time despite that they are not used. However it is hardly covered by test standards: only one standard prescribes such a test (see the Appendix to Task 1). At 25°C a calendar life test takes the time of the envisaged application, so at least 13 years. Increasing the temperature reduces the test time but the predictability is subject of debate. Moreover, by reducing the SOC during periods of rest, the battery ageing can be slowed down. This allows for intelligent control. Since calendar life ageing is a main source of battery deterioration, while test methods with threshold values are difficult to envisage, an alternative approach is prerequisite, which we propose to be a warranty by the manufacturer. The manufacturer declares and warrants a calendar life before which the battery has a capacity fade of less than 20% of the declared capacity. This capacity is not necessarily the initial capacity of the battery. In this way the effect of a possible quick initial capacity fade before entering a steady capacity reduction over time can be taken into account by setting the declared capacity lower than the initial capacity. This is elucidated by Figure 7-1. In future new ownership models for passenger cars will appear that increase their utilisation. The maximum number of cycles will be reached in a shorter time-span, reducing the influence of calendar life on ageing.

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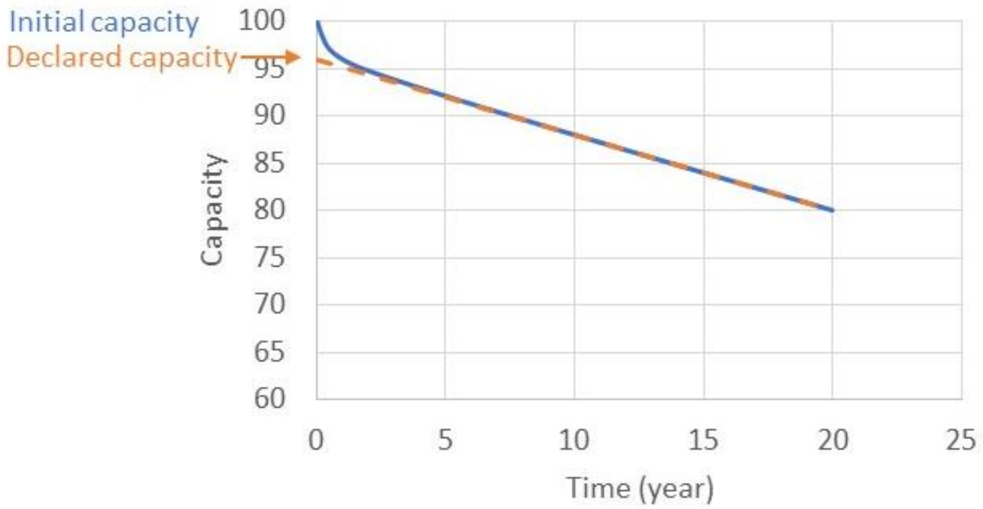

Figure 7-1: Concept of initial capacity and declared capacity based on an exemplary ageing curve for batteries.

When defining the requirements, see Table 7-2, the following aspects were taking into account:

- Preference was given to shorter lifetime test period with increased thresholds, e.g. 90 % instead of 80 % of declared capacity, because this can shorten laboratory and market surveillance testing.
- They are in the parameters of the Business as Usual scenario in Task 5. They are however not the Task 6 options because they were based on own assumptions which is too weak to provide a threshold. Hence in a later policy Tier only, those requirements could be raised when more data and validation becomes available.
- They are in line with but more ambitious than warranty claims currently offered.
- The relative short lifetime test period used to set requirements are still in line with their new defined 'functional Energy Efficiency Index (fEEI)', see later section 7.1.2.4. It

refers to the kWh stored over its lifetime relative to the embodied primary or gross energy requirement (GER) for manufacturing.

Note that when defining requirements it should also be considered that:

- The calendar life warranty depends on the application.
- With both e-mobility and stationary energy storage in scope, the study scope covers a wide range of applications, such as battery-powered passenger cars and trucks, their plug-in vehicle variants, and also grid stabilization support and home batteries. This is described in task 5 with the selection of base cases. The subjects listed for which requirements are needed, must have test methods related to the requirements in available standards or, in the absence of them, be included in standards. This can be a new European standard or an extension of current standards. Both approaches fall under a future standardisation mandate to CEN and CENELEC[3]. Transitional test methods may be established until the needed harmonised standards have been developed. Since the wide range of applications imposes different requirements on lifespan, a good understanding of them is essential to characterise requirements properly.
- When proposing potential criteria, it is possible to consider different levels of the battery scope: cells, modules, packs and battery system (see also figure 8 in task 1). This excludes power electronics and heating + cooling system (in the study defined as battery *application* system), which is outside the study boundary. The focus is on Li-ion.

Proposal:

Proposal for maximum capacity fade, internal resistance increase and round-trip efficiency for battery systems/modules/packs brought on the market for the intended applications (see Scope Task 1):

The proposed values are based on ensuring that at 50 % of the cycle-life performance can be proven under applicable laboratory test conditions, e.g. 90 % at 750 cycles instead of 80 % remaining capacity at 1500 cycles. The cycles are based on the base case values, see Table 7-1. The standards refer to the applicable standards as given in the Annex to Task 1 and summarised in annex A at the end of this document.

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[3] Standardisation mandates, like for product groups in ecodesign are found here: https://ec.europa.eu/growth/tools-databases/mandates/index.cfm

Table 7-2 Proposal for minimum cycle-life performance or state of health compliance test for battery systems/packs depending on their declared application(s). A type test for batteries introduced on the European market.

Application	**Remaining capacity** (relative to the declared value)	**Maximum internal resistance increase**	**Minimum round-trip energy efficiency**	**Standards** (provisional -see notes on review)
PC BEV	90 % @ 750 cycles	30 % @ 750 cycles	90 % @ 750 cycles	ISO 12405-4:2018 Cycle-life test according to Dynamic discharge application
PC PHEV	90 % @ 1000 cycles	30 % @ 1000 cycles	90 % @ 1000 cycles	ISO 12405-4:2018 Cycle-life test according to Dynamic discharge application
Trucks BEV	90 % @ 1000 cycles	30 % @ 1000 cycles	90 % @ 1000 cycles	Standard to be developed
Trucks PHEV	90 % @ 1500 cycles	30 % @ 1500 cycles	90 % @ 1500 cycles	Standard to be developed
ESS	90 % @ 2000 cycles	NA	94 % @ 2000 cycles	IEC 61427-2 Cycle-life test according to declared application(s)

The threshold value is defined for each test standard separately since both the ageing procedure and the measurement prescription of each test topic is dissimilar. This does not allow direct comparisons of results between different standards. Research is necessary before setting the values. At the moment it is a conceptual proposal. The values should be verifiable, therefore the manufacturer must prescribe a test method so that the conformity with the threshold values can be measured. The installed heat or cool supply systems for thermal management can be used for the test if necessary.

For cars and trucks no public data was found that could be traced to specific batteries (see also the Task 3 report). However, as can be concluded from the EU funded H2020 Everlasting project, Deliverable D8.7 – White Paper 04: Definition of SOH' (5/2018), apart from capacity fade, internal resistance increase is also an important state of health (SOH) parameter, see Table 7-2.

The Battery Test Centre of ITP Renewables in Australia has set up a public test for stationary batteries, as proposed in Table 7-2. They published very recently (June 2019) a monitoring study on batteries used for ESS[4]. From this publication It can be concluded that apart from capacity fade, round trip efficiency fade is an important state of health (SOH) parameter for the intended application, see Table 7-2. In the study, they applied constant current charge and discharge test cycles of approximately 3 h each. This is not following the mentioned standard in Table 7-2. It represents an accelerated test cycle, but within the allowed limits of the products. A round-trip efficiency of 85 to 95% was found based on 11 battery types.

The test prescriptions in the given standards involve information that must be provided by the manufacturer like declared capacity, the applied discharge rate and charge rate, the ratio between maximum allowed battery power (W) and battery energy (Wh), the DOD in the cycle-life test and the power capability at 80% and 20% SOC. It is proposed here to cover this information demand in the chapter about 'Requirements for providing information on batteries and cells', 7.1.2.3.

Since the proposal is a type test a quality management system is needed to ensure the conformity of all produced battery systems/packs of identical type.

Proposal for a minimum battery pack/system warranty per product:

As discussed in the rationale the warranty is not only related to cycle-life warranty by previous requirements but also to the calendar life warranty. A battery should be able to offer a minimum throughput of energy, but it ages also over time when not being used. Therefore a warranty period should take both aspects into account. A calendar life warranty has to be given for half of the economic application lifetime. The minimum warranted values are based Table 7-2 and the difference with 100% is doubled in value. The proposal is in As given in the rationale, the cycle-life test threshold and the warrantee requirement are necessary to create a firm base of the functional unit used in the calculation of the carbon footprint indicator. Only if a manufacturer shows a better result of the cycle-life test and gives a better warranty than the proposed minimum, he can use the improved lifetime in the calculation of the functional unit, leading to a lower value of the carbon footprint indicator (see §7.1.2.5).

Timing of policy measure:

Should take effect as soon as possible, e.g. 2021.

A second Tier with more ambitious requirements could be considered later in time, e.g. from 2025 onwards.

For all other battery levels and applications new standards and test methods, at least transitional methods, must be defined before thresholds can be determined. Also, the mentioned two standards do not cover all test requirements.

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[4] http://batterytestcentre.com.au/wp-content/uploads/2017/07/Battery-Testing-Report-6-June-2019.pdf

Table 7-3.

As given in the rationale, the cycle-life test threshold and the warrantee requirement are necessary to create a firm base of the functional unit used in the calculation of the carbon footprint indicator. Only if a manufacturer shows a better result of the cycle-life test and gives a better warranty than the proposed minimum, he can use the improved lifetime in the calculation of the functional unit, leading to a lower value of the carbon footprint indicator (see §7.1.2.5).

Timing of policy measure:

Should take effect as soon as possible, e.g. 2021.

A second Tier with more ambitious requirements could be considered later in time, e.g. from 2025 onwards.

For all other battery levels and applications new standards and test methods, at least transitional methods, must be defined before thresholds can be determined. Also, the mentioned two standards do not cover all test requirements.

Table 7-3 Proposal for minimum battery pack/system warranty

Application	**Warranty period** (whatever reached first)		**Minimum warranty**				**Methods**
	Calendar life[5] warranty	Exceedance of minimum warranted amount of stored energy during the lifetime	Minimum energy that can be stored over life time in kWh	Remaining capacity (relative to the declared value)	Maximum internal resistance increase	Minimum round-trip energy efficiency	Standards (provisional -see notes on review)
PC BEV	10 years	See prescription at the right	Declared capacity [kWh]x750	80%	60%	80%	ISO 12405-4:2018 Cycle-life test according to Dynamic discharge application
PC PHEV	10 years	See prescription at the right	Declared capacity [kWh]x1000	80%	60%	80%	ISO 12405-4:2018 Cycle-life test according to Dynamic discharge application
Trucks BEV	10 years	See prescription at the right	Declared capacity [kWh]x1000	80%	60%	80%	Standard to be developed
Trucks PHEV	10 years	See prescription at the right	Declared capacity [kWh]x1500	80%	60%	80%	Standard to be developed
ESS	12 years	See prescription at the right	Declared capacity [kWh]x2000	80%	NA	88%	IEC 61427-2 Cycle-life test according to declared application(s)

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[5] Measured from the manufacturing time (see information proposal)

Challenges and standardisation needs:

See the identified gaps as given in the Annex on standardisation to Task 1. It appeared that for most applications and battery levels no standards are available for the test requirements in this study. The standard IEC 62620 for industrial Li-ion batteries (from cell to system level) can be taken as a valid base. However, for energy efficiency, no reference method is available. The cycle-life test in IEC 62620 seems too different from the envisaged applications (too much DOD and too few cycles). Furthermore, it allows more capacity loss (60% remaining capacity) than is acceptable in most of those applications. Only once the test requirements have agreed test methods, the threshold values can be determined after a measurement campaign.

Test cycles must be in line with test standards which are defined for each application, see Annex to Task 1. In brief, only two standards appear to cover a substantial part of the test requirements but for a limited amount of base cases (BC1, 2 and 3): IEC 62660-1 and ISO 12405-4. DOE-INL/EXT-15-34184 (2015) covers the same number of topics (and includes calendar life) for BC1 and BC2. IEC 62620 covers also many test =requirements. The other standards are too limited for the study scope. Calendar life tests are often lacking although both cycle life and calendar life tests are necessary to cover the ageing behaviour. The test profiles for cycle life tests for the EV applications take around 3 h per cycle. This leads to a total test time of around 100 days for PC BEV and 130 days for BC PHEV. This seems acceptable given the long lifetime expectations aimed for in these applications.

Another concern is the experienced difference between ageing according to ISO 12405-4 and in real use situations. The technical research done in UN IWG EVE (battery durability) and the recommendation of this expert group, i.e. on deterioration factors on vehicle level, must be considered.

The standard for stationary on-grid applications, IEC 61427-2 has unfortunately no clear end of life criteria (to be negotiated between vendor and battery user). On the other side, the standard is strict in the applicable power levels. Scaling of the battery system and power level is not possible. Moreover, one cycle takes 24 h, with approximately half of the time the battery being in idle mode in discharged condition. This leads to a many-year test duration. An accelerated test method seems obligatory, like prescribed in IEC 62620 for industrial batteries with C-rates of C/5 to 1C, but also in ISO 18243 for electrically propelled mopeds and motorcycles where a continuously repeated 1C discharge rate is applied as test cycle. The Danish Technological Institute has developed more realistic and workable tests – in particular for residential systems. If another test method is used, then also a new test method for round-trip efficiency has to be worked out.

7.1.2.2. Requirements for battery management systems

Rationale:

Related to BMS with partially open data

A BMS with partially open data has multiple benefits:

- Create consumer confidence to invest in such applications, allowing feedback on the battery status including ageing.
- Increase the residual value of electric vehicles, ESSs and their battery packs by the reduced risk thanks to partially open information on the use history.

- Support lifetime warranty and claims (see other policy).
- Support transparency of battery information for used cars.
- Reduce repair costs.
- Enhance second-hand applications for e-mobility in less demanding applications (remanufacturing).
- Enhance second life applications for a different application (repurposing).
- Extend battery lifetime by aforementioned possibilities and therefore reduce the carbon footprint per functional unit.
- Provide individual product information that is complementary to the list of information about batteries and cells, which is discussed in subsequent section 7.1.2.3.

In general, extending the lifetime of EV battery application through for example re-purposing, 2nd hand applications, etc. may offer environmental and economic benefits as well as reducing the need for primary resources. The criterion will create the conditions for a more efficient management of batteries after 1st life. The information will help in understanding the condition of the batteries.

Related to firmware updates for BMS

Since the BMS designed for an EV application would probably not be suitable for a second use application, the possibility of uploading adapted firmware must be considered. This avoids the exchange of the BMS and the effort in re-attaching every single voltage measurement wire. If the battery is not changed physically, it also does not necessarily need to undergo UN 38.3 testing. However, this assumes that the firmware update has no considerable impact on the safety performance. It must be proven that the update does not change the battery's response to different stressors and abuse. This testing is a requirement in the regulations on transporting lithium batteries. All batteries to be transported must be tested. Tests at lower level e.g. cell tests although modules are transported, are not accepted. Since several tests involve the BMS on the battery, replacing the BMS automatically means that the UN38.3 tests must be redone, which is expensive.

Proposal:

Requirements for partially open data:

Requirements on data storage, and access to the data stored in the BMS to facilitate the determination of the State of Health (SoH). State of health includes several aspects and cannot be reduced to one figure. This would have to be e.g. the average of some ageing phenomena or the minimum of them. There is no consensus on this. To evaluate the possibility for second life applications it enough data should be available. This will create new business models. For specific applications a single health indicator is the state of function that e.g. expresses the remaining driving range. This is based on a combination of ageing phenomena like power fade and capacity decrease [6].

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[6] https://everlasting-project.eu/wp-content/uploads/2018/05/EVERLASTING_D8.7_final_20180531.pdf

Battery ageing is path dependent and thus statistics cannot lead to a perfect ageing estimation[7][8]. Still, they are good indicators but only within the same battery type population and knowing for that type what are the most prominent ageing factors. This cannot be generalised to all batteries.

The data stored during the life of the battery in the BMS may include the following parameters (at battery system, battery pack and module level):

- State of health-related information:
    - the (remaining) capacity, both in Ah and kWh, for each module in a battery pack. The relation between module number and physical location inside the pack must be specified and made publicly available.
    - and/or capacity fade;
    - internal resistance in mΩ for each module in a pack
    - and/or its increase;
    - remaining power capability and/or power fade;
    - actual cooling demand;
    - remaining efficiency and/or efficiency reduction;
    - self-discharge information and/or its evolution;
    - additional indicators like information from advanced measurement methods such as electrochemical impedance measurement.
- Lifetime information:
    - calendar age including manufacturing date and start of service
    - energy throughput and capacity throughput;
    - number of normal charges and fast charges;
    - overall kilometres (pack level) and the average kilometres per charge;
    - temperature statistics. The following data must be logged: ambient temperature, module temperature, maximum instantaneous temperature difference between modules in a battery pack. This data is stored in a cumulative fashion, counting the time spent in a range of intervals. Proposed as counter is a 32 bit integer representing seconds spent in each interval. Figure 7-2 shows the proposed principle. The position of the modules in the battery system must be known. It is proposed to include this in the information requirement (§7.1.2.3).

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[7] Z. Ma et al, Investigation of path dependence in commercial lithium-ion cells for pure electric bus applications: Aging mechanism identification, Journal of Power Sources 274, 2015

[8] M. Dubarry et al, Durability and Reliability of EV Batteries under Electric Utility Grid Operations: Path Dependence of Battery Degradation, ECS 165, 2018

  - negative events during lifetime (over-voltage, under-voltage, close situations to over-voltage and under-voltage, low temperature charging, high temperature charging and discharging, overtemperature, long periods of empty battery, long periods of fully charged battery).
  - errors from BMS
  - number of balancing actions on cells in a module
  - statistics on the battery use, such as the time being in a certain voltage interval and/or SOC, the time being at a certain power level, the time being at a certain charge rate level. This must be implemented in the same way as proposed for the battery temperature above.
- Coupling to the information about traceability of battery modules and packs:
  - It is proposed to allow the traceability of battery modules and packs (§ 7.1.2.4). The BMS can accelerate the traceability by storing the module IDs of the modules attached to the BMS and if applicable the battery pack ID if one BMS is in the pack.

A complementary source of back up information for the case the BMS would fail is recommended. The proposed traceability of battery modules and packs (§ 7.1.2.4) may be used for this back-up possibility.

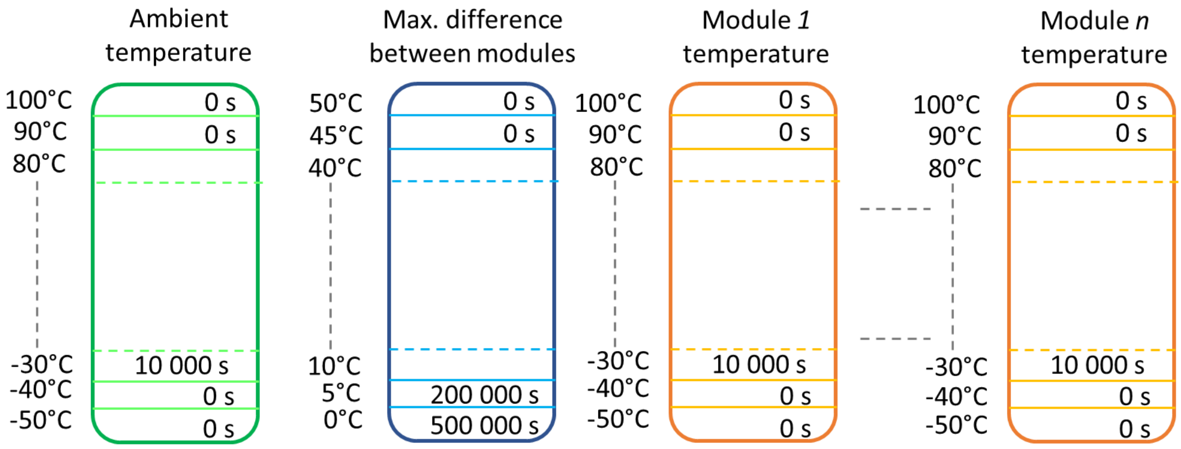

Figure 7-2: Temperature statistics with help of storing data in a cumulative fashion during the lifetime, counting the time spent in a range of intervals.

General information on the battery can be in the open data of BMS instead of in a central database. The advantage is that the necessary information on the battery remains attached to it whereas no agreement on a central system is needed. This information could be:

  - design capacity
  - minimal, nominal and maximum voltage, maybe temperature dependent
  - original power capability and limits, maybe temperature dependent
  - capacity threshold at which the cell is considered exhausted
  - C-rate of cycle-life test

  - battery type, and chemistry
  - battery manufacturer
  - manufacturing place.
  - carbon footprint information and reference to the list of information about batteries and cells (see 7.1.2.3).

If partially open data by the BMS is not possible, alternatively an additional electronics board can be required that logs the proposed statistics and keeps the needed data.

The overall objective is to enable the determination of the state of health of a used battery as well as sufficient reference information, for the purpose of repair, reuse, remanufacture, reconditioning, or recycling.

Requirement on diagnostics connector:

To allow access to the open data a diagnostics connector on each BMS must be present. The data transmission should go over CAN, a widely used communication standard. In vehicles open data is standardised via the OBD connector and OBD protocol, the open data from the BMS must be reachable over the OBD connector. Only after dismantling an EV the diagnostics connector will be used. In other applications than EVs, the diagnostics connector on the BMS is the only way of access.

Requirement on BMS update possibilities:

It is possible that the BMS cannot suitably work after repurposing the battery. This can be related to the SOC determination algorithms but also due to the cell balancing strategy. In these cases, the hardware can be correct but the firmware not. A requirement or a bonus for the upgradability of the BMS is needed by possibility of a firmware update allowing the BMS to work satisfactory after the repurposing operation. An additional advantage can be that no new UN 38.3 test is needed since the battery did not change physically (see previous explanation).

Timing:

The timing is one to one related to the standardisation need, typically this will take 2 to 4 years to develop.

Challenges and standardisation needs:

Related to partially open data:

The format for data access, and test protocols would need to be developed. A major challenge may be the stakeholders' agreement regarding the parameters to be disclosed, the format and the protocol are also many factors can impact the SoH.

Apart from the data a more general uncertainty on SOH exists. No clear definition of SOH is available and it is differently used over applications and manufacturers. Battery degradation is a combination of phenomena as capacity fade, power fade, efficiency reduction and rise in cooling demand. A more elaborate approach to tackle SOH is therefore needed than only referring to capacity fade, what is the most used method. Even if SOH only refers to capacity fade then still the calculation method has to be clarified since the nominal capacity can be taken or the capacity related to the needed power.

New methods to determine the SOH of a battery are under development, e.g. by analysing the change in electrochemical impedance spectrum response. This may be a methodology that cannot be performed by the BMS in interaction with the battery load, but that is executed off-line.

For the individual parameters a similar uncertainty exists, e.g. for the efficiency information a representative standard should provide objective information that allows to be a benchmark.

In principle an open versus a closed BMS system should not entail extra product cost, nevertheless a closed system can be part of the business model of the manufacturer to create revenue from services and repair.

Related to supporting second life applications through an open BMS system:

While there is a number of potential benefits to reusing, remanufacturing and repurposing EV batteries, there are also a number of challenges that needs to be considered when introducing such aspects in ecodesign regulation. Key challenges cover health and safety concerns, regulatory and technical ones, which are highlighted along the proposed criteria. This includes battery liability from the original producer to second use distributor.

Related to the diagnostics connector on the BMS:

The proposed diagnostics connector on each BMS must be standardised. It gives access to the open data. The CAN IDs to request the required information must be standardised. Since in vehicles open data is standardised via the OBD connector and OBD protocol, the open data from the BMS must be reachable over the OBD connector.

Related to the update of the BMS:

In case that BMS firmware can be updated, it must be ensured that the functional safety is not endangered. Several solutions are possible: the algorithms have to be outside the safety critical processing area, only parameters are updated within restrained limits, or the new firmware is developed conform functional safety design.

Related to using the BMS to source some important battery data:

A possible concern is the link between warranty and information registration in the BMS. The registration of lifetime information can be an invitation to have the system manipulate this information, so as to avoid warranty claims. Also, if the battery management system breaks down, the battery owner will no longer have the data necessary for a warranty claim. Likely also a certified print out and/or a kind of back up of the data will need to be supplied with the battery at the time of purchase. The information about declared capacity and test method is also stored in the proposed European database with battery information (§7.1.2.3). The lifetime information may be periodically stored in the proposed battery traceability set-up (§7.1.2.4).

7.1.2.3. Requirements for providing information about batteries and cells

Rationale:

To allow repair, reuse, remanufacturing and repurposing but also recycling of batteries data and information about the battery is required. The current information requirement involves the battery capacity, the collection symbol and an indication of the battery type (Li, Pb or Ni). Recycling with a high material recovery rate needs more information to sort batteries. For the lifetime extension possibilities still more information about the battery is required.

This section deals with information that can be included per model or type and not per individual battery to reduce the amount of database entries. Individual battery information should be stored in the open BMS proposal in previous section 7.1.2.2. In the next section requirements are proposed to track individual battery modules and packs.

The battery information can provide end users with standardized and comparable expected lifetime information, stimulate market competition and avoid overstated performance claims.

Battery information is also essential for a repair, e.g. to replace a defected battery pack in a car. It is also part of the car type approval. The newly formed worldwide Platform for Accelerating the Circular Economy (PACE), as an outcome of Davos 2015, has already identified the issues on battery collection, repurposing and recycling as one of their first projects[9], stating the importance of this information.

EV batteries come in a variety of chemistries and forms. Whilst there are some differences in content, the material composition of the various lithium ion battery (LIB) chemistries that currently dominate the marketplace are generally quite similar with the exception of the active materials for the cathode (i.e. Cobalt, Nickel and other active materials). Therefore, traceable information on type level can play an important role in a circular economy approach for EV and ESS batteries.

It will facilitate the End-of-Life (EoL) treatment for sustainable collection-sorting-recycling, which can be better performed based on the available composition information at all product levels. The information seems useful for metal recycling to maximise substance reclamation, avoid the contamination of the waste streams, minimise downcycling issues and metal losses by compositionally closing the recycling loops. The data should also deliver the information likely needed for efficient recycling, or better sorting battery pack or modules for 2nd life applications and potentially a larger repair market.

Encouraging the emergence of a circular economy for batteries and their constituent materials in the EU can be supported introducing mandatory requirements for provision of information about recycled content for certain materials including CRM. Assessing CRM availability in stocks is an important objective of pillar 1 of the European Battery Alliance, thus, it could be important to declare their indicative quantities (or indicative range of quantities) in products put on the market.

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[9] https://www.acceleratecirculareconomy.org/global-battery-alliance-index

The policy measures on product performance and on partially open data from the BMS is dependent on some essential manufacturer dependent parameters. These must be included in the list of information about batteries and cells.

For the purpose of battery system and cell information, the European product database for energy labelling (EPREL) could be used. Encouragement in this direction is found by a similar implementation [10,11].

For cells brought on the market separate requirements are formulated to support vehicle and ESS battery system manufacturers to source cells suitable for their systems.

Proposal for battery systems, packs and modules:

The proposal is that the individual battery should carry at all levels (battery system, battery pack and module) a bar code, QR code or similar with an EAN number and serial number.

This code provides access to European database with information on batteries and cells, which the manufacturer or supplier bears the responsibility of updating, e.g. such as the European Product Database for Energy Labelling (EPREL[12]), in three levels of:

Level 1: Public part (no access restriction):

- carbon footprint information in CO_2eq including primary energy in MJ and kWh electricity used during manufacturing, see specific criteria proposed in section 7.1.2.4, including the capacity Energy Efficiency Index (cEEI) which refers to the ratio of declared storage capacity relative to the embodied primary gross energy requirement (GER) for manufacturing (see also later section 7.1.2.4).
- battery manufacturer
- battery type, and chemistry
- design capacity and declared capacity
- conditions to derive the above-mentioned capacities such as the C-rate and ambient temperature.
- minimal, nominal and maximum voltage, with temperature range
- original power capability and limits, maybe temperature dependent
- capacity threshold at which the cell is considered exhausted (for electrical vehicles batteries only)
- temperature range when in use (min, max, optimal)
- temperature (min and max) that the battery can withstand not in use

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[10] https://www.idtechex.com/research/articles/all-ev-batteries-born-after-august-2018-in-china-will-have-unique-ids-00015455.asp

[11] https://uk.reuters.com/article/us-china-autos-batteries/china-launches-pilot-ev-battery-recycling-schemes-idUKKBN1KF375

[12] https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/european-product-database-energy-labelling_en

- battery lifetime expressed in cycles that followed from the type test proposed in Table 7-2 and the test method used to obtain this value.
- the estimation by the manufacturer of minimum number of cycles that the battery can withstand until end of life including its criterion like a remaining capacity of 80 or 70% of the declared capacity.
- provide end users with standardized and comparable lifetime information, stimulate market competition and avoid overstated performance claims.
- Percentage of recycled materials used in the cathode and anode material
- A reference to a recycling method that can be used.
- if found appropriate, the proposed criteria related to recyclability (dismantling, labelling and declaration of materials) could be combined and transformed into an aggregated requirement or index like a R-R-R-R index (§7.1.2.6).

Level 2: Data available to third party accredited professionals:

- C-rate of cycle-life test
- results from test requirements in this study:
  - Calendar life warranty period.
  - Battery efficiency information.
  - Power
  - Energy efficiency
  - Internal battery cell, module and pack (if applicable) resistance
  - Cycle life test standard and remaining capacity that followed from this test
- information needed to perform and to interpret the test requirements, such as:
  - the applied discharge rate and charge rate
  - the ratio between maximum allowed battery power (W) and battery energy (Wh)
  - the DOD in the cycle-life test
  - the power capability at 80% and 20% SOC
- information need following from partially open data from BMS:
  - The link between module number and its physical position in the battery system
- The physical position of each cell inside the battery module shall be made available and traceable to the BMS open data (see 7.1.2.2).
- The composition by means of standardised composition categories (e.g. NMC, LTO etc.), that facilitate identification of the main chemistry of the battery, and the substances contained.
- The precise content of critical raw materials (e.g. cobalt, natural graphite) as well as other important raw materials (e.g. lithium, nickel).

- Repair information including:
    - exploded diagrams of the battery system/pack (showing the location of battery cells);
    - disassembly sequences;
    - type and number of fastening technique(s) to be unlocked;
    - tool(s) required;
    - warnings if delicate disassembly operations are involved (risk of damaging a part).
    - Amount of cells used and lay out.
- Dismantling information for recyclers in the form of, safety instructions, a tools list and a time laps video to show how a product can be dismantled for recycling (<5 minutes).
- Repair information.

Level 3: Compliance part (Information available for market surveillance authorities only, protected access for intellectual property reasons):

- Detailed assembly drawing and material list.
- Test reports proving compliance with the requirements in the proposed regulation.

Proposal for requirements on suitable battery cell type information

Level 1: Public part (no access restriction):

- carbon footprint information in CO_2eq including primary energy in MJ and kWh electricity used during manufacturing, see specific criteria proposed in section 7.1.2.4, including the capacity Energy Efficiency Index (cEEI) which refers to the ratio of declared storage capacity relative to the embodied primary gross energy requirement (GER) for manufacturing (see also later section 7.1.2.4).
- battery cell manufacturer
- battery cell type, and chemistry
- design capacity and declared capacity
- minimal, nominal and maximum voltage, with temperature range
- original power capability and limits, maybe temperature dependent
- temperature range when in use (min, max, optimal)
- temperature (min and max) that the battery can withstand not in use
- battery cell lifetime expressed in cycles and the reference test used for this statement, including for electric vehicles the minimum number of cycles the battery can withstand before SOH drops below 80 and 70 %.
- % of recycled materials used in the cathode and anode material, including a reference to a recycling method that can be used.

Level 2: Data available to third party accredited professionals:

- C-rate of cycle-life test
- results from test requirements in this study:
    - Calendar life warranty period.
    - Battery efficiency information.
    - Power
    - Energy efficiency
    - Internal battery cell resistance
    - Cycle life test standard and remaining capacity
- information needed to perform and to interpret the test requirements, such as:
    - the applied discharge rate and charge rate
    - the ratio between maximum allowed battery power (W) and battery energy (Wh)
    - the DOD in the cycle-life test
    - the power capability at 80% and 20% SOC
- The composition by means of standardised composition categories (e.g. NMC, LTO etc.), that facilitate identification of the main chemistry of the battery cell, and the substances contained.
- The precise content of critical raw materials (e.g. cobalt, natural graphite) as well as other important raw materials (e.g. lithium, nickel).

Level 3: Compliance part (Information available for market surveillance authorities only, protected access for intellectual property reasons):

- Test reports proving compliance with the requirements in the proposed regulation.

Timing:

From 2021 onwards on declared suitable cells for the intended application.

From 2022 onwards on battery systems, packs and modules.

Challenges and standardization needs:

For recycled content it relies on a credible traceability system throughout the value chain and existing volumes for recycled materials, neither of which are available at present. No traceability system for recycled materials is currently operational in the context of eco-design implementing measures. This topic is a core theme of the traceable battery information of next section (§ 7.1.2.4).

There might be standards needed for the traceability, an analysis might be needed in a later review. As the battery manufacturer (final assemblers) is not the point of the supply chain where the origin of the materials is easily traceable, the criteria need to address the upstream phases of the supply chain.

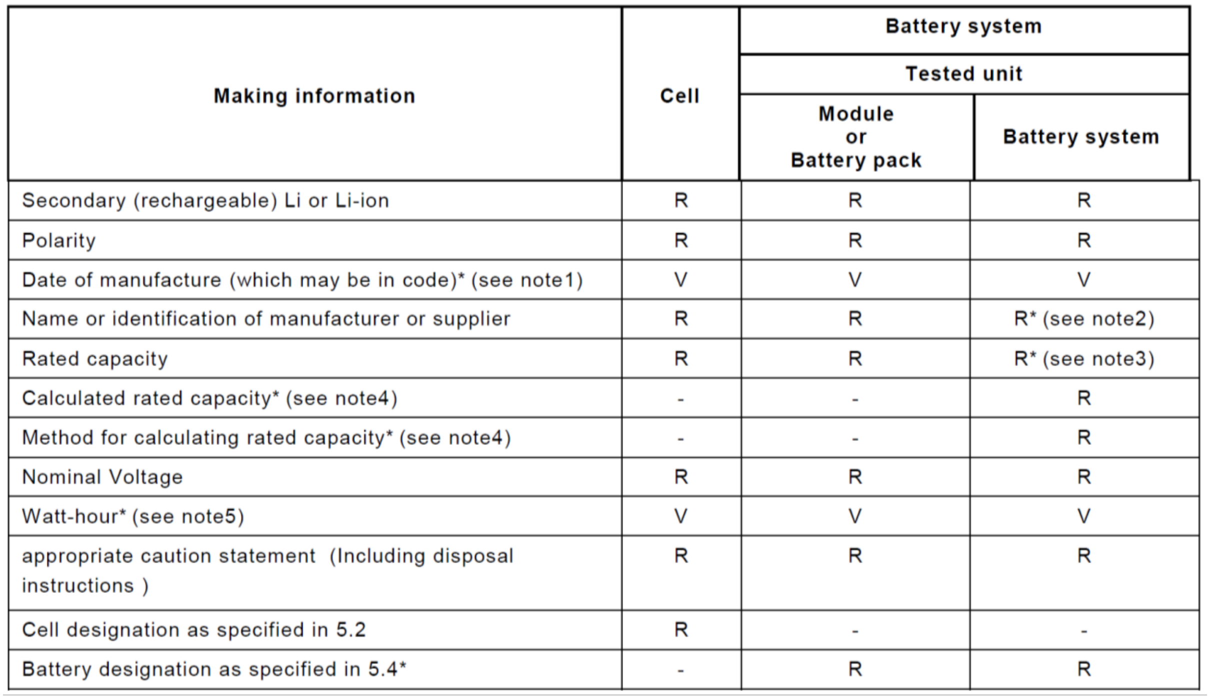
Facilitating access to high-voltage and/or potentially corrosive battery components by untrained personnel conflicts with safety objectives.

The proposed contents differ from other product groups so far in the European product database for energy labelling (EPREL) and the database might need to be reworked or extended for the proposed content.

Requiring to detailed information on battery pack design might compromise or conflict intellectual property rights and harm the competitive advantage of the inventor.

The marking of batteries can be supported by future (updates of) standards. Several standards cover the topic: in IEC TC 21 the international standard titled Secondary batteries: Marking symbols for identification of their chemistry (IEC 62902) has been developed. It obliges to indicate whether the battery is lithium, lead or nickel based including a background colour for fast identification. In IEC SC21A a standard on environmental aspects of portable batteries is proposed, IEC 63218. It contains a similar identification of the battery type, but with a two-digit extension that represents the anodic and cathodic chemistry like iron-based or cobalt-based cathode. In the same commission another standard with an elaborate battery marking requirement has been developed, being IEC 62620: Secondary lithium cells and batteries for use in industrial applications. The marking subjects are represented in the next table.

Table 7-4: Marking subjects in IEC 62620 for industrial lithium batteries.



Making information	**Cell**	**Battery system**	
		Tested unit	
		Module or Battery pack	**Battery system**
Secondary (rechargeable) Li or Li-ion	R	R	R
Polarity	R	R	R
Date of manufacture (which may be in code)* (see note1)	V	V	V
Name or identification of manufacturer or supplier	R	R	R* (see note2)
Rated capacity	R	R	R* (see note3)
Calculated rated capacity* (see note4)	-	-	R
Method for calculating rated capacity* (see note4)	-	-	R
Nominal Voltage	R	R	R
Watt-hour* (see note5)	V	V	V
appropriate caution statement (Including disposal instructions)	R	R	R
Cell designation as specified in 5.2	R	-	-
Battery designation as specified in 5.4*	-	R	R

As starting point several reference documents could be used:

i. IEC 62902: Secondary batteries: Marking symbols for identification of their chemistry,

ii. the newly proposed standard on environmental aspects of portable batteries IEC 63218 that contains a two-digit extension to declare the main cathode and anode material.

iii. Guideline for Recycle Marking on Li-ion Batteries for the Japanese Market [8]. In the latest one it is recommended to industry to add a two-digit code to the logo for LIB chemistries to specify, with the first digit, the metal predominantly found (by mass) in the cathode (such as Co, Mn, Ni, or Fe), and whether tin or phosphorous exceeding a specified threshold are contained in the battery.

iv. IEC 62620: Secondary lithium cells and batteries for use in industrial applications. This standard contains an elaborate battery marking including the main anode and cathode material as an alphabetic code.

The issue raised in 7.1.2.2 on SOH has to be elaborated further within standardisation.

The proposed Recyclability index is based on criteria related to recyclability (dismantling, labelling and declaration of materials). They can be combined and transformed into an aggregated requirement or index. A wider scope in addition to recycling is possible by considering multiple 2nd life options, i.e. reuse, repair and purposing. This index and the criteria must be worked out within standardisation.

7.1.2.4. Requirements on the traceability of battery modules and packs

Rationale:

The previous section dealt with information that can be included per model or type and not per individual battery. This allowed to extend a European database with information that is essential for battery repair, EOL treatment and the cycle-life test on battery systems. Also the provision of information about recycled content for certain materials including CRM was proposed as part of the battery type information.

In the public debate on Li-ion batteries emphasis is laid on the labour conditions in the extraction of the raw materials needed for these batteries, including child labour, health and safety hazards[13][14]. In the Netherlands companies must be able to prove that products are free from child labour (‘Wet zorgplicht kinderarbeid’). Materials may also come from conflict zones, as covered by the Conflict Minerals Regulation[15] for tin, tungsten, tantalum and gold. For several materials like diamond auditing schemes and material traceability has been set-up by private initiatives, like a diamond passport based on block chain technology[16]. The ITRI Tin Supply Chain Initiative (iTSCi) tracks and traces tin from mines, processors and exporters in African countries by allocating tracing numbers to each bag and storing them in a database.[17] For EV manufacturers responsibly mined lithium and cobalt is a discerning selling offer, setting up transparent supply chains including NGOs[18]. The automotive manufacturer’s partnership

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[13] Reported by Amnesty International in ‘This is what we die for’, https://www.amnesty.org/en/documents/afr62/3183/2016/en/

[14] https://drivesustainability.org/raw-materials/

[15] https://ec.europa.eu/trade/policy/in-focus/conflict-minerals-regulation/regulation-explained/

[16] https://www.tracr.com/

[17] https://www.chainpoint.com/our-customers/itsci/

[18] https://sonomotors.com/en/sion/battery/

Drive Sustainability together with the Responsible Minerals Initiative (RMI) have analysed 37 automotive materials on environmental, social and governance issues. For the battery these are cobalt, graphite, lithium and nickel.[19]

Tracing the raw materials can be set further to tracing battery modules and packs. This promotes the statistics on and implementation of Li-ion battery recycling in Europe. It may help reducing illegal traffic of batteries at EOL to other continents. Inappropriate recycling over there leads to severe health risks. The Global Battery Alliance is setting up a passport for batteries[20] to address these challenges.

For the lifetime extension possibilities, the needed information about the battery's life was proposed to be stored in the proposal on partially open BMS data in section 7.1.2.2. In that section an information back-up possibility was suggested by using the set-up of traceability of battery modules and packs.

In China already a traceability system started. The "traceability management platform" covers the entire lifecycle of batteries from production to recycling, clarifying who is responsible for handling and recycling spent batteries and establishing a formal monitoring system.[21][22]

The issues in this Rationale go beyond the Ecodesign framework. However, the European Commission considers to broaden the scope of battery regulation to sustainable batteries. This initiative is in parallel to the Task7 report.[23]

Proposal for battery systems, packs and modules:

The proposal is that battery modules and packs have an individual serial number that is linked to a database system that tracks the battery modules and packs that come on the European internal market. This database can be a public-private cooperation. This database has to be linked to material databases for ethical mining. The suitability of initiatives from the European Battery Alliance and the Global Battery Alliance should be examined. The serial number is apart from the EAN number proposed in § 7.1.2.3. In § 7.1.2.2 it was required to encode these serial numbers also in the attached BMS to accelerate battery identification.

Timing of policy measure:

This policy measure is supported by public-private initiatives. The timing is therefore less in own hands. A target date of 2023 seems feasible.

Challenges and standardisation needs:

A large challenge exists since both auditing schemes and databases for traceability must be developed. Nevertheless, examples for several materials like diamonds and gold exist. Labour circumstances are part of ISO standardisation progress. However, the proposal goes much further than raw materials since it includes the battery modules and packs.

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[19] https://drivesustainability.org/wp-content/uploads/2018/07/Material-Change_VF.pdf

[20] https://www.weforum.org/projects/global-battery-alliance

[21] https://chargedevs.com/newswire/china-developing-battery-tracking-system-to-manage-recycling/

[22] https://www.reuters.com/article/us-china-batteries-recycling/china-puts-responsibility-for-battery-recycling-on-makers-of-electric-vehicles-idUSKCN1GA0MG

[23] https://ec.europa.eu/info/law/better-regulation/initiatives/ares-2018-5951053_en

7.1.2.5. Specific requirements for carbon footprint information and considering the option for a threshold

Rationale:

Task 6 showed that manufacturing a battery requires far more energy compared to its storage capacity, typically 500 to 900 times, see capacity EEI in Table 7-5. Herein the newly defined capacity Energy Efficiency Index (cEEI) refers to the ratio of declared storage capacity relative to the embodied primary or gross energy requirement (GER) for manufacturing. Therefore embodied energy and its carbon footprint cannot be neglected. It is also possible to define a ‘functional Energy Efficiency Index (fEEI)’ which refers to the ratio between functional unit or kWh stored over its lifetime relative to the embodied primary or gross energy requirement (GER) for manufacturing. For the Base Case 1 BEV modelled in Task 5 this fEEI was below 100 %, which means that the primary energy source in such a car is for the production of the battery and not the energy supplied during use. Task 4 also illustrated in Figure 21 that electricity takes a large share in the carbon footprint and this opens the opportunity to use low carbon electricity, this green electricity in battery manufacturing is likely the most important improvement option but not yet included in Table 7-5. EVs are therefore game changers to use renewables. However, similarly they are able to propel cars with lignite and hard coal. Therefore, requiring more accurate information on carbon footprint is recommended and on the long term even a threshold could be considered.

This carbon footprint information will help to promote "cleaner" BEV and might be a useful benchmarking between car manufacturers. This information could in future also support a car label based on an LCA carbon footprint replacing the current tail pipe CO_2 emission approach, tax incentives or green procurement.

When considering a carbon footprint information requirement, it is also useful to ask complementary information on electricity used for manufacturing, this can simplify market surveillance.

Table 7-5: Overview of carbon footprint, improvement options (excl. green energy) and primary energy results from Task 6.

	GWP [kg CO2 eq/FU (kWh)]				GWP [kg CO2 eq/cap. (kWh)]	GWP [kg CO2 eq/kg product]	functional EEI [%] *FU [MJ]/GER [MJ]*	capacity EEI [ratio] *GER [MJ]/capacity [MJ]*
Base case	Prod. + distr.	Use	EOL	TOTAL	Prod. + distr.	Prod. + distr.	Prod. + distr.	Prod. + distr.
Business As Usual (Task 5)								
1 PC BEV-HIGH	0.214	0.094	-0.026	0.282	108	14.164	86.14	585
2 PC BEV-LOW	0.183	0.094	-0.022	0.255	108	14.190	100.88	586
3 PC PHEV	0.131	0.094	-0.019	0.206	147	14.021	134.69	832
4 Truck BEV	0.086	0.073	-0.011	0.148	115	13.442	210.22	637
5 Truck PHEV	0.063	0.074	-0.009	0.128	146	13.942	281.63	828
6 res. ESS	0.061	0.053	-0.008	0.106	155	12.089	286.87	890
7 comm. ESS	0.048	0.053	-0.006	0.095	155	12.089	358.58	890
Reduction of active and passive materials design option (Task 6)								
1 PC BEV-HIGH	0.190	0.094	-0.023	0.261	96	14.667	98.60	511
2 PC BEV-LOW	0.162	0.094	-0.020	0.236	96	14.699	115.44	512
3 PC PHEV	0.104	0.094	-0.015	0.183	117	14.340	171.45	653
4 Truck BEV	0.076	0.073	-0.009	0.139	101	13.769	240.58	557
5 Truck PHEV	0.050	0.074	-0.007	0.117	116	14.238	358.91	650
6 res. ESS	0.049	0.053	-0.006	0.096	124	12.257	360.15	709
7 comm. ESS	0.039	0.053	-0.005	0.087	124	12.257	450.19	709
Extended lifetime design option (Task 6)								
1 PC BEV-HIGH	0.187	0.094	-0.023	0.258	108	14.164	98.70	585
2 PC BEV-LOW	0.159	0.094	-0.019	0.234	108	14.190	115.59	586
3 PC PHEV	0.131	0.094	-0.019	0.206	147	14.021	134.69	832
4 Truck BEV	0.074	0.068	-0.009	0.132	115	13.442	243.07	637
5 Truck PHEV	0.063	0.074	-0.009	0.128	146	13.942	281.63	828
6 res. ESS	0.061	0.053	-0.008	0.106	155	12.089	286.87	890
7 comm. ESS	0.048	0.053	-0.006	0.095	155	12.089	358.58	890
Combined design option								
1 PC BEV-HIGH	0.165	0.094	-0.020	0.239	96	14.667	112.98	511
2 PC BEV-LOW	0.141	0.094	-0.017	0.218	96	14.699	132.28	512
3 PC PHEV	0.104	0.094	-0.015	0.183	117	14.340	171.45	653
4 Truck BEV	0.065	0.068	-0.008	0.125	101	13.769	278.17	557
5 Truck PHEV	0.050	0.074	-0.007	0.117	116	14.238	358.91	650
6 res. ESS	0.049	0.053	-0.006	0.096	124	12.257	360.15	709
7 comm. ESS	0.039	0.053	-0.005	0.087	124	12.257	450.19	709

Proposal:

Requirement on carbon footprint information:

Carbon footprint calculated according to the Product Environmental Footprint Category Rules (PEFCR[24]) for high specific energy rechargeable batteries for mobile applications. The carbon footprint is therefore part of a life cycle approach, and the PEF, among other impact categories, defines how to calculate the GWP. The PEFCR has also defined a representative product (the average product sold in EU), for different types of batteries, including for EV. It provides the calculations of the corresponding benchmark, including the Global Warming Potential (GWP). It also includes LCI data for lithium batteries.

Also to be provided are the calculated Primary Energy (MJ) and the share of electricity (MJ) according to the PEFCR and compatible with the MEErP.

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[24] PEFCR available at http://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_Batteries.pdf

When the PEFCR carbon footprint calculation is not based on the local electricity mix, a warranty should be provided that the low carbon electricity (if any) has been supplied based on hourly net metering[25]. Country specific residual electricity grid mix could be considered for the production this would encourage battery manufacturers to seek clean (provided it is additional) electricity supply, thus putting pressure on member states to increase their investment in renewable power generation. This can be for done by installing a battery ESS on the production plant itself to cope with variable supply of renewables[26] and preferably second life EV batteries that return to plant before remanufacturing. Also information could be provided more specific on the share of renewable energy used in the electricity mix.

Carbon footprint (gCO_2eq/kWh) should be calculated both; first relative to the minimum functional unit based on the product warranty and also relative to the specified average lifetime based on laboratory tests and the applicable test cycles from EN standards.

Potential (long term) minimum carbon footprint threshold:

It is not recommended to put a minimum carbon footprint threshold in the short term, because there are several challenges to be addressed for the carbon footprint information first (see later section).

Thresholder and timing:

Carbon footprint Information requirements for all lithium cells should start from 2021.

Carbon footprint Information for packs and systems should start from 2022.

It is recommended to reconsider the option to set a minimum threshold on carbon footprint 2 years after that this information is made available based on the information provided by the manufacturers.

Challenges and standardisation needs:

So far, such a product related carbon footprint requirement has not yet been implemented in European product regulation before and it cannot build on lessons learnt. Therefore, it will need a close follow up and a gradual implementation is recommended with the focus on a few primary applications first to learn from and extending the scope afterwards. Note however that some battery manufacturers were already involved in the Product Environmental Footprint Category Rules (PEFCR[27]) for high specific energy rechargeable batteries for mobile applications and therefore they should already have knowledge and competences to provide this type of information.

The carbon footprint improvement potential does heavily rely on carbon footprint of electricity and therefore the following issues needs to be further defined:

- Which electricity mix-emission factor will be used (EU, country, local production, etc.)?
- If the electricity mix is considered at country level, there could also be issues of conflict and competitiveness among EU member states, in case manufacturing is in the EU.
- Emission factors change as the electricity mix change over time, how this effect will be captured?

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[25] This excludes Electricity Guaranties of Origin that are based on annual green energy production

[26] Likely in a circular economy approach these are second life EV batteries that return to the plant and are used in grid ESS before remanufacturing

[27] PEFCR available at http://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_Batteries.pdf

- if there is energy generation in-house of a manufacturing plant will this be accounted and how?
- Today much of the manufacturing is outside the EU and therefore its carbon footprint reduction does not contribute to the EU 2030 targets.

The PEFCR method can be exhaustive and elaborate work, while only the carbon footprint is needed. Hence a simplification could be considered that focuses on the most dominant manufacturing stages and simplifies less relevant components. For the PEFCR, primary Life Cycle Inventory (LCI) data is an important issue as well as the verification of this data. Carrying out an LCA with this data remains complex and there is a risk this may end up in the use of non-accurate and non-quality assured LCI data using several proxies and assumptions which can result in inaccuracy, creative accounting methods and circumvention. A close follow up of the PEFCR applicability will be needed. The PEFCR methodology is compatible with ISO 14040/44 but reduces the flexibility of the standard and does therefore not automatically provide a global level of playing field for ISO 14040/44 compliant data.

For the carbon footprint calculation of the batteries to be more accurate, simple to verify/elaborate and trustworthy, the following points could to be improved/reviewed:

- Data from background processes should be disaggregated to provide more accuracy and robustness to the carbon footprint calculation.
- More company-specific PEF values for key products along the value chain could be made be publicly available, in particular in the upstream processes. In a future regulation, this information will enable all actors to undertake PEF assessments.
- The LCA databases necessary to undertake the PEFs are not all publicly accessible and free of use.
- The complexity of the PEF could be reduced by focusing on CO_2 hotspots to have a realistic and practical implementation and enforcement of the regulation and could be a benefit for market surveillance. Hereby
- Nevertheless, some other significant impact categories might be maintained for a check that this is no disproportionate negative impact. For example, a low carbon footprint should not permit a higher water footprint.
- The carbon footprint indicator is the carbon footprint per functional unit. Since the functional unit is based on the envisaged lifetime of the battery, the lifetime has to be embedded by a cycle-life test and a warranty (7.1.2.1). Only if a manufacturer shows a better result of the cycle-life test and gives a better warranty than the proposed minimum, he can use the improved lifetime in the calculation of the functional unit, leading to a lower value of the carbon footprint indicator.
- It is also worth considering a functional unit change to per storage capacity because this decouples the information to be provided when the product comes on the market from the use phase which is complex because this depends on the application dependent lifetime. This means that carbon footprint information would focus on the cell production step only. Given that the minimum life time warranty requirements are likely to be included, this is an overlapping requirement (see requirements in 7.1.2.1).
- If the scope of the study is extended to other batteries, that do not necessarily have a similar lifetime as the Li-ion batteries under current focus, the functional unit change

leads to incomparable results and maybe false optimism for certain battery chemistries.

- Focusing exclusively on the production phase eliminates the geographical and temporal uncertainty on the carbon intensity of the electricity used during the use phase for charging batteries. Finally the recycling route at the end of life is also not a priori known when batteries are brought on the market. Focusing on the cell manufacturing and its storage capacity as a functional unit, avoids the complexity that from creative accounting based on assumptions on the use and end of life of batteries.

The PEFCR have been only elaborated for mobile application batteries with high energy density, if the scope is broadened (see 7.1.3) to Energy Storage Systems(ESS) it will require new PEFCR.

Effective carbon footprint market surveillance can be a challenge and further research might be needed to elaborate verification procedures.

7.1.2.6. Other minimum battery pack design and construction requirements to support reusability/recyclability/recoverability including a R-R-R-R index

Rationale:

A design with harmonized physical requirements has multiple benefits:

- simplify recycling at the end of life
- create a more competitive market and level of playing field for OEM, repair, upgrade, recyclers and reuse
- Support 2nd life applications/ownership, e.g. as a second hand car or into another applications
- create consumer confidence by having a second source supplier (multiple vendors), which avoids a vendor lock in effects and/or provides a second supplier to repair the car in case of bankruptcy

Modular design can help in the safety during disassembly by streamlining procedures and training for the personnel involved in recycling/reuse.

For 2nd life applications and consumer confidence it is important that an independent workshop can verify the state of health of a battery.

It should be noted that all vehicles have already such a recycling information system in place, called IDIS[28]. Hence what is discussed hereafter are more particular requirements that differ from ICE vehicles.

The proposed ‘R-R-R-R’ index could be connected to taxes, levies and subventions.

When considering policy also the Battery Directive (2006/66/EC), which is currently under review and the end-of-life vehicles (ELV) Directive (2000/53/EC) should be considered to avoid any overlap or contradiction.

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[28] https://www.idis2.com/discover.php

Proposal:

Mandatory adding dismantling information to an open access database such as IDIS[28], it should be at least demonstrated how cells can be removed from packs/systems with common tools.

A mandatory DC charging/discharging interface that supports vehicle-to-grid mode (V2G) and a vehicle-to-test mode (V2test) to verify the performance and information criteria previously proposed in this study is likely the most important issue to warrant a long product lifetime.

Introduce a R-R-R-R index (derived from repair, re-use, repurpose and recycle) wherein at least the following aspects are considered:

- Use of technical design features of the product (battery) that enable assembly/disassembly, e.g. reversible joints, joints that can be fastened/unfastened.
- Standardised interfaces for hardware and software including connectors in a bonus/malus system
- Standardised thermal interface in a bonus/malus system
- Standardised dimensions and connections in an open multi-vendor system in a bonus/malus system
- Use of standard cell formats that fit in different applications in a bonus/malus system
- Use of multi-vendor modular battery packs
- Calculation of the amount of material that can be recycled

Timing and threshold:

The mandatory requirements can be introduced only at earliest after 2022 to allow manufacturers to update the software to allow V2G and V2test mode DC interfaces. Vehicles with battery packs below 10 kWh that have not yet a DC interface could be temporarily exempted.

It is recommended to start developing a standard for two main applications before introduction (see next paragraph). It is also recommended to introduce this requirement first for vehicle applications due to the size of the market volume and they are familiar with the concept due to Directive 2005/64/EC.

Challenges and standardization needs:

Most vehicles today have DC mode charging, hence adding a V2G and V2test mode is probably a software issue, to be verified are safety features involved. It is recommended to develop a standard or harmonized method for this, this will develop a larger economy of scale for car workshops (mostly SMEs) that can run the test mode.

This new concept to be developed should also fit to the Directive 2005/64/EC on the type-approval of motor vehicles with regard to their usability, recyclability and recoverability wherein Annex I states that:

> 1. Vehicles belonging to category M and those belonging to category N shall be so constructed as to be:
>
> — reusable and/or recyclable to a minimum of 85 % by mass, and
>
> — reusable and/or recoverable to a minimum of 95 % by mass.

> 2. For the purposes of type-approval, the manufacturer shall submit a data presentation form duly completed, established in accordance with Annex A to the standard ISO 22628: 2002. It shall include the materials breakdown. It shall be accompanied by a listing of the dismantled component parts, declared by the manufacturer with respect to the dismantling stage, and the process he recommends for their treatment.
>
> 3. For the application of points 1 and 2, the manufacturer shall demonstrate to the satisfaction of the approval authority that the reference vehicles meet the requirements. The calculation method prescribed in Annex B to the standard ISO 22628: 2002 shall apply.

This work to develop a recycling index can built on the ISO 22628:2002 on ‘Road vehicles -- Recyclability and recoverability - Calculation method’ but also IEC/TR 62635:2012 on ‘Guidelines for end-of-life information provided by manufacturers and recyclers and for recyclability rate calculation of electrical and electronic equipment’. A key challenge will lie on the data(base) on recycling rates of materials to be used for the calculation. The data will need to be the most recent and appropriate, it has to be representative, it could come from waste data reporting, from modelling, etc. CEN/CENELEC JTC 10 on ‘Material Efficiency Aspects for Ecodesign’ also deals with source of data for recyclability calculations but does not come to final data sources. This data needs to be agreed by the sector.

Some construction requirements could potentially be sourced from ANSI/CAN/UL 1974 on the repurposing of batteries.

For residential stationary energy storage applications, a similar standard and method could be developed.

On the negative side is that EV batteries are a relative new market and setting such strong reusability/recyclability/recoverability requirements could hamper innovation. A too detailed requirement might also limit the possible design options and compromise the new development of optimal vehicle considering customer usage, driving distance and cost. For niche markets (e.g. specific garden equipment), this might be a cost burden and there is not a benefit in the economy of scale for re-use. Therefore, this policy measure might not be recommendable for a large scope of potential applications.

Second sourcing of battery packs for EVs might result in lower performance and in worst cases can lead to safety issues. For example many historic safety failures in portable electronics (mobiles and laptops) often were associated with second source batteries. Lithium battery cells for electrical vehicles neither for ESS are not simple exchangeable components.

Note that car manufacturers already have a long-standing track record in providing service and repair manuals with software support, e.g. with a database to link their Vehicle Identification Number (VIN) to all parts numbers and step by step manuals for repair. Car manufacturers already provide digital Information on disassembly/dismantling is via IDIS[29]. Therefore the proposed policy herein might be redundant and superficial.

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[29] https://www.idis2.com/#

7.1.2.7. Policy requirements considered but not proposed

Minimum initial energy efficiency

This is not considered because it is redundant with energy efficiency threshold after the cycle-life test. Hence there is no evidence that setting such requirements can have an additional impact.

Minimum gravimetric energy density for e-mobility (Wh/kg)

This is not considered because the market for e-mobility today covers already high gravimetric density as an important design parameter and there is no evidence that setting a minimum requirement will be useful to influence the market.

Minimum self-discharge (loss at storage) [% SoC/time]

It is a relatively easy test. However, it is not recognized as a problem for the lithium batteries cells and packs. The no-load losses in battery application systems are usually attributed to power electronics, which are out of the scope.

Maximum auxiliary power consumption of the battery management system

When using a battery system, insight in the auxiliary power consumption might also be needed, especially the Battery Management System (BMS). If the BMS power is drained from the battery it can lead to a problematic self-discharge: the consumption of the BMS can be too high to bridge standstill periods. This applies to both BMSs that are powered from the main battery and that those powered from an external source such as an auxiliary battery. Despite this demand, no solid base was found in a threshold value. A large variation seems to exist ranging from 10 $W/kWh_{battery}$ down to a fraction of a watt. The standards do not prescribe a measurement methodology, complicated by the many possible BMS topologies and by the power going to cell balancing.

Maximum auxiliary power for heating and cooling

Auxiliary power for heating and cooling is left out of the scope of this proposal because for vehicles this is redundant requirement with WLTP driving range and for LiB in residential storage systems it was not identified as a relevant issue [30].

Requiring all environmental impact parameters instead of focusing on carbon footprint

The previous section proposed to focus on carbon footprint based on the PEFCR, however also other environmental impact parameters are included in the PEFCR and in principle they could be included in the data information requirements, but it was not proposed because:

- It would complicate market surveillance;
- It was not the primary optimization parameter of the study in Task 6
- Most of these parameters relate to local emissions and impact that can be addressed by local factory regulations. This could therefore result in a requirement that all imported battery cells in accordance to the related European environmental regulations or have locally similar manufacturing standards in place, i.e. the Industrial

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[30] Up to our knowledge the LiB system for residential ESS only the Tesla Powerwall has heating-cooling systems added It might become an issue when considering other high temperature chemistries.

Emissions Directive (Directive 2010/75/EU) and the European Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)((EC) No 1907/2006). Because most of the cells are manufactured today outside the EU this would jeopardize the supply and for this type of products it was not judged realistic for the time being.

7.1.3. Recommendations on opportunities to extend the scope of policy measures

Aim: Several NGOs asked frequently to broaden the scope of technologies and applications addressed in this study, despite that manufacturers and their association insisted in keeping the focus in e-mobility first. Hereafter we discuss briefly the possibilities and considerations based in the lessons learned from Tasks 2-6.

Potential options to consider are:

- Lithium e-mobility batteries below 2 kWh that are proposed to be exempted, e.g. those for electric bicycles, garden tools, cordless power tools, cordless home appliances, etc.
- Stationary batteries suitable for residential grid energy storage systems other than Lithium chemistries with high energy density; examples include: high temperature sodium-based batteries and lithium-sulphur batteries.
- Stationary batteries suitable for residential grid energy storage systems other than lithium chemistries with low energy density; examples include: Sodium batteries, nickel metal hydride and lead acid batteries.

Opportunities and challenges to consider a scope extension are:

Opportunities:

- In principle often, a scope extension can close loopholes in regulation because with the scope proposed batteries can still be brought on the market declared for use in other applications. Nevertheless, for vehicles due to their type approval process such a risk for a loophole in the regulation is likely non existing.
- A broader scope could create a level of playing field with other competing battery technology, e.g. sodium batteries.
- Finally, Task 2 clearly identified the proposed scope of vehicles by far as the largest in volume and thus impact. Off course, by extending the scope an additional environmental impact is reached. The main rationale for the proposed scope was the large total EU volume in tonnes of material expected on the market for e-mobility (see Task 2). Other applications and their technologies were not expected to have similar impact despite that they often exceed the threshold of 200.000 items sold per year because the capacity of these batteries is low per application (e.g. < 2 kWh).

Challenges:

- The standards on which the policy proposals rely are for LiB vehicle and grid energy storage applications. For other applications they are mostly missing. It would be better to develop them before considering the policy, this is a time-consuming process that should be outweighed compared to the impact.

- Impact on Small and Medium-sized Enterprises (SMEs) and innovation: The advent of low-cost lithium batteries will likely trigger new application. Much policy measures proposed will bring extra work and administration to SMEs and will jeopardize innovation in Europe because it will be more attractive to develop and market the products first elsewhere without this additional work and requirements.
- Creation of administrative overhead for niche battery applications: see previous argumentations, this also applies to large companies selling products for niche applications.
- Other policy tools that target ‘industrial installations’ instead of ‘consumer products’ might sometimes be more suitable. For example, large grid scale energy storage systems with redox-flow batteries can be constructed onsite whereby parts of the battery system, such as pumps and controllers, can be procured from different suppliers. The battery system is herein not a priori sold or brought on the market as a product but it is an installed system under the direct responsibility of the owner. In this case the Machinery Directive (2006/42/EC) might be a policy tool to consider, despite that it has currently a different scope (e.g. safety).
- Small battery packs (< 2 kWh) in cordless power tools or bicycles are already repaired for replacement in small workshops and their batteries are collected under the WEEE Directive. This market could likely more benefit from policy supporting (affordable) training and a quality label.
- Lack of data and evidence: For carbon footprint of some new or niche battery technologies the LCI data and/or PEFCR are not yet sufficiently available.
- Delay of policy measures:
    - Looking to all other potential applications at the level of detail done in Tasks 3-6 including modelling the use phase will be magnitudes more work and take several more years. For example, a vacuum cleaner can have such a battery as well and it will require to model properly the load cycle in Task 3 which can already become a point of discussion on itself[31].
    - Related to the previous concern, any life cycle analysis requires a well-defined and agreed functional unit (see Task 1). As already mentioned in Task 1 UPS applications have a different functional unit meaning that the whore approach from Task 3 to 6 will differ, moreover there are several UPS that have safety requirements, e.g. in a nuclear power plant. Also, when considering for example portable cordless power tools (PCT), their main requirement to substitute the nuisance of a power cord without excessive weight and cost to the product which is completely different.
    - Extending the scope will involve a larger set of stakeholders and therefore complicate reaching a agreement (if possible at all) and likely postpone taking policy measures.

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[31] https://uk.reuters.com/article/uk-eu-dyson-court-energy/dyson-wins-fight-against-eu-energy-labelling-rules-idUKKCN1ND1NM

  - The proposed policy is new in its kind and it might be wiser to learn first from some key applications and consider extending it to other applications in a second tier.

Conclusion:

We do not recommend to extend or review the scope relative to the proposal in Task 1 apart from:

- Considering other battery chemistries that can be used for residential energy storage where high energy density is not a driver and other chemistries can be found on the market that could provide unfair competition to batteries in the proposed scope if not included.
- Considering smaller e-mobility applications such as scooters etc., where the market may increase more than expected.

Note: a complementary study has been launched among others to investigate this scope extension, it will also look to other applications and chemistries.

7.1.4. Summary of stakeholder positions

Objective:

This section contains an overview and summary of the stakeholder positions.

Overview of stakeholder positions:

General remarks on the scope of a regulation:

Several stakeholders commented that any future regulation should be cross-checked for overlaps/consistency/conflict with:

- The Battery Directive (2006/66/EC) for what matters recycling, and which is currently under review. In addition, it is mentioned that guidelines are developed on setting modular fees in the context of Extended Producer Responsibility (EPR) largely based on circular economy principles.
- The end-of-life vehicles (ELV) Directive 2000/53/EC and its implementation, for what matters recycling of vehicles.
- The UNECE Regulations[32], for what matters performance of electric vehicles.
- The European Conflict Minerals Regulation that will start on 1 January 2021 (Regulation (EU) 2017/821).

All position papers and/or related comments received are included in separate 'Annex on stakeholder positions' hereafter is a summary.

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[32] https://ec.europa.eu/growth/sectors/automotive/legislation/unece_en

Positions related to minimum battery pack/system lifetime requirements:

The Danish Energy Agency suggested to consider a labelling type requirement to foster competition on warranty extent. There is an overall welcome to such requirements from the European Consumer Organisations (ANEC/BEUC), other comments received are of technical nature and to avoid overlap/conflict with upcoming UNECE Regulation for vehicles.

RECHARGE opposes to warranty as being not part of ecodesign.

The Danish Energy Agency utters doubts on the usefulness of IEC 61427-2. It has already developed more realistic and workable tests – in particular for residential systems.

Positions related to maximum auxiliary power consumption of the battery system:

Danish Energy Agency suggested to leave out requirements for auxiliary power requirements for automotive applications, because vehicles have already other incentives and it is redundant with WLTP tests. This is also supported by ECOS, an NGO on environmental standards, because vehicle manufacturers have already a strong incentive to improve the overall vehicle efficiency. Also, no technical information has been provided, meaning that setting a requirement would be difficult.

Positions related to requirements for battery management systems:

There is an overall welcome to such requirements from the European Consumer Organisations (ANEC/BEUC), other comments received are of technical nature. Also, ECOS very much support these requirements regarding the availability of data.

ECOS and RECHARGE ask for a single SOH value.

ACEA mentions that even with a lot of data battery ageing cannot be correctly derived. Too much information, especially about humidity, was prescribed.

The Danish Energy Agency expresses a concern in a possible manipulation of lifetime related information registered in a BMS.

Positions related to requirements for battery information:

There is an overall welcome to such requirements from the European Consumer Organisations (ANEC/BEUC), other comments received are of technical nature.

ACEA, the car manufacturers association, noted that sustainable sourcing is already part of OEMs sourcing strategy, see https://drivesustainability.org/.

Positions related to specific requirements for carbon footprint information and considering the option for a threshold

There is an overall welcome to such requirements from the European Consumer Organisations.

In February 2019 RECHARGE, the European Advanced Rechargeable and Lithium Batteries association, stated in their position paper that CO_2eq content of finished e-mobility batteries should be used as a criterion to discriminate across products placed on the EU market.

Both RECHARGE, battery manufacturers, and ACEA, car manufacturers, do not support using the existing PEFCR for calculating the carbon footprint. RECHARGE experienced that the PEF today faces some issues and limitations, especially when it comes to reliable, meaningful and auditable data. ACEA prefers the use of ISO 14040&14044 standards on LCA analysis to guarantee a global level playing field.

ECOS provided useful technical inputs also suggesting that the PEFCR needs to be reviewed for the purpose. Amongst others they argue that the metric used for the carbon footprint standard should be based on gram CO_2eq/cap(kWh) and not gram CO_2eq/FU(kWh) as in the PEFCR. This will better reflect the carbon footprint when they are brought on the market and focus on the production step only and will also eliminate the geographical and temporal uncertainty on the carbon intensity of the electricity used during the use phase.

ECOS welcomes the proposed Recyclability index and wants to broaden it to second life application possibilities.

Positions related to other minimum battery pack design and construction requirements to support reusability/recyclability/recoverability:

ACEA, the car manufacturers association, noted that recyclability as part of the ELV directive is already common practice and recycling information is sourced through the broadly used International Dismantling Information System, see https://www.idis2.com/.

The European Portable Battery Association, EPBA, stated that circular economy principles concerning discussions concerning reusability, reparability and recyclability proposed in this study would not apply to portable primary and rechargeable batteries. The application of these circular economy principles can differ subject to the battery type, what can work for a large industrial rechargeable battery does not necessarily work for a small consumer battery.

ECOS asked to rename the proposed recyclability index to reflect more the wider scope, i.e. reuse, repair, repurposing and recycling. This is implemented by naming it R-R-R-R index.

Positions related to recommendations on opportunities to extend the scope of policy measures:

The European Portable Battery Association, EPBA, states that any inclusion of portable primary and/or rechargeable batteries would require a separate discussion.

APPlia, the association of home appliances, strongly advised not the extend neither to review the scope relative to Task 1. They argue that that portable batteries below 2 kWh are already subject to regulation under the WEEE Directive (e.g. collection), they often have already their own Eco-design product regulation and there are no standards to underpin policy measures.

The Recharge battery manufacturers association agreed that there is no need to extend the scope and suggest to wait for output of this exercise before considering extending the scope.

ANEC/BEUC consumer organizations encourage investigating a scope extension.

Helmholtz Institute of Ulm (HIU) and the Institute for Technology Assessment and System Analysis (ITAS); both research organizations, asked to study much more applications and battery chemistries.

Note that the EC has launched an open public consultation on a potential regulatory intervention related to this study, see:

https://ec.europa.eu/info/law/better-regulation/initiatives/ares-2018-5951053/public-consultation_en

Hence for the latest state of play consult the EC website on related policy:

https://ec.europa.eu/info/law/better-regulation/initiatives/ares-2018-5951053_en

7.2. Scenario Analysis (unit stock/sale & environmental)

Aim of Task 7.2:

Subtask 7.2 establishes the scenarios according to the design options described in Task 6 and the policy measures described in subtask 7.1, so far this is possible. To this end, the analyses on the previous tasks have been extended to the defined scenarios in comparison with the Business-as-Usual (BAU) Scenario and the Best Available Technology (BAT) Scenario.

7.2.1. Introduction to Scenario Analysis

Different scenarios have been drawn up to illustrate quantitatively the improvements mainly in terms of sustainability that can be achieved at the EU level by 2045 with suitable Ecodesign policy actions against the Business-as-Usual scenario. Taking into account the time needed to elaborate and implement any regulation, the regulation is assumed to enter into force in 2022 under the scenario.

The reference case and main technical improvement option scenarios based on the findings of Task 6 are defined as follows:

- **BAU scenario**: no additional EU regulation. The products placed on the EU market have the same level of performance as the Base Case defined in Task 4
- **Reduction of materials (RedMat):** From year 2022, new batteries placed on the market are batteries with less passive and active materials than in the BAU scenario (see Task 6 assumptions)
- **Extended lifetime (ExtLifeTime):** From year 2022, new batteries placed on the market are batteries, which are used longer (if applicable), according to Task 6 assumptions
- **Combination of reduction of materials and extended lifetime (RedMat_ExtLifetime):** From year 2022, new batteries placed on the market are batteries which have less materials and are used longer (if applicable), based on Task 6 assumptions
- **RedMat_ExtLifeTime_GHG_Info**: same as RedMat_ExtLifetime, but in addition, information on carbon footprint is required. In this scenario, it is assumed, that the EU market will be driven by batteries with low carbon footprint in the production phase and that in total, 30% of the customers will buy the battery for the lowest GHG emissions.[33] Accordingly, in this scenario, the electricity mix in the production phase corresponds to 70% of the EU average electricity mix and 30% of the most decarbonised electricity mix.[34]
- **RedMat_ExtLifeTime_GHG_Low**: same as RedMat_ExtLifetime, but in addition, the GHG emissions related to electricity consumption during the production phase are the lowest and correspond to the low GHG emission scenario (see Table 7-8). The scenario highlights the contribution of the decarbonisation of the production phase of batteries to the overall GHG emissions during the whole lifecycle of a battery.
- **RedMat_ExtLifeTime_Recycling**: same as RedMat_ExtLifetime, but in addition, the recycling of CRM is improved.
- **BAT:** reflects a combination of all quantifiable improvement options: reduction of passive and active materials, extended lifetime, reduced GHG footprint with the most

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[33] this is a rough estimate

[34] see "low" and "medium" scenarios in Table 7-8

decarbonised electricity mix during the battery production phase as well as improved recycling at EoL.

Table 7-6 presents an overview of the scenarios covered in this task as well as the associated policies. In some cases, the impact of the policies cannot be quantified, due to a lack of data or a lack of concrete requirements.

Table 7-6: Overview of the scenarios and associated policies

Policy Measures	**General comment**	**Extended lifetime**	**Reduction of material**	**RedMax_ExtLifetime**	**RedMat_ExtLifeTime _GHG_Info**	**RedMat_ExtLifeTime _GHG_Low**	**RedMat_ExtLifeTime _Recycling**	**BAT**
Performance policy requirements								
Minimum battery pack/system lifetime requirements	quantifiable	XX		XX	XX	XX	XX	XX
Maximum auxiliary power consumption of the battery system	Not quantified	-	-	-	-	-	-	(X)
Policy measures on sustainability								
Requirements for battery management	Impact difficult to quantify	X	-	X	X	X	X	X
Requirements for battery information	Improve recycling and lifetime	X		X	X	X	XX	X
Specific requirements for carbon footprint information and considering the option for a threshold	Quantifiable	-	X	-	X	XX	-	XX
Other minimum battery pack design and construction requirements to support reusability/recyclability/recoverability	Quantifiable	-	--		-	-	XX	XX

XX: strong and large impact, X: moderate impact, (X): some impact, - : no / very small impact

Table 7-7 provides an overview of the main assumptions of new products placed on the market from 2022 for each product Base Case and scenario. The figures are derived from the results of Tasks 4, 5 and 6 and cover following parameters of a battery system:

- nominal capacity in kWh
- service lifetime in year
- total weight of a battery system in kg
- purchase costs in € / kWh capacity
- CAPEX for decommissioning in € / battery system
- OPEX for replacement in € / service
- weight of CRM, in kg / battery system. Cobalt, Graphite, Nickel, Manganese and Lithium were taken into account here
- weight of CRM recycled, in kg / battery system. This figure is negative, since the demand for CRM decreases due to recycling
- electricity consumption, in kWh/battery system, for each life stage of a battery system: raw material / production / transport, use and EoL. For the use phase, the electricity consumption is also calculated on a yearly basis.

Table 7-7: Main assumptions on the battery systems, according to Base Case and Design Option

					Cost			CRM - Weight / battery system					Recycling CRM - Weight / battery system					Electricity consumption			
		Nominal Capacity	Service Lifetime	Total weight of a battery system	Cost	CAPEX for decomissioning	OPEX replace battery	Cobalt	Graphite	Nickel	Manganese	Lithium	Cobalt	Graphite	Nickel	Manganese	Lithium	For raw materials, transport and production	Use stage	Use stage / year (=yearly losses)	EoL
Base Case	Tech Level	[kWh]	[year]	[kg]	[EURO/kWh]	[EUR/unit]	[EURO/service]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kWh]	[kWh]	[kWh/a]	[kWh]
1	BAU	80	14	609	206	1 200	700	9.56	87.28	35.92	17.11	14.44	- 1.53	-	- 5.75	-	-	9 640	9 756	697	- 197
1	RedMat	80	14	521	140	1 200	700	5.32	79.21	43.66	11.85	13.94	- 0.85	-	- 6.99	-	-	8 403	9 756	697	- 203
1	ExtLifeTime	80	18	609	206	1 200	840	9.56	87.28	35.92	17.11	14.44	- 1.53	-	- 5.75	-	-	9 640	11 178	621	- 197
1	RedMat_ExtLifeTime	80	18	521	140	1 200	840	5.32	79.21	43.66	11.85	13.94	- 0.85	-	- 6.99	-	-	8 403	11 178	621	- 203
1	RedMat_ExtLifeTime_Footprint	80	18	521	140	1 200	840	5.32	79.21	43.66	11.85	13.94	- 0.85	-	- 6.99	-	-	8 403	11 178	621	- 203
1	RedMat_ExtLifeTime_Recycling	80	18	521	140	1 200	840	5.32	79.21	43.66	11.85	13.94	- 4.48	-	- 36.00	- 9.97	- 11.14	8 403	11 178	621	- 203
1	BAT	80	18	521	140	1 200	840	5.32	79.21	43.66	11.85	13.94	- 4.48	-	- 36.00	- 9.97	- 11.14	8 403	11 178	621	- 203
2	BAU	40	13	304	206	600	700	4.78	43.64	17.96	8.56	7.22	- 0.76	-	- 2.87	-	-	4 820	5 720	440	- 99
2	RedMat	40	13	261	140	600	700	2.66	39.61	21.83	5.93	6.97	- 0.43	-	- 3.49	-	-	4 201	5 720	440	- 101
2	ExtLifeTime	40	17	304	206	600	840	4.78	43.64	17.96	8.56	7.22	- 0.76	-	- 2.87	-	-	4 820	6 554	386	- 99
2	RedMat_ExtLifeTime	40	17	261	140	600	840	2.66	39.61	21.83	5.93	6.97	- 0.43	-	- 3.49	-	-	4 201	6 554	386	- 101
2	RedMat_ExtLifeTime_Footprint	40	17	261	140	600	840	2.66	39.61	21.83	5.93	7.22	- 0.43	-	- 3.49	-	-	4 201	6 554	386	- 101
2	RedMat_ExtLifeTime_Recycling	40	17	261	140	600	840	2.66	39.61	21.83	5.93	7.22	- 2.24	-	- 18.00	- 4.99	- 5.77	4 201	6 554	386	- 101
2	BAT	40	17	261	140	600	840	2.66	39.61	21.83	5.93	7.22	- 2.24	-	- 18.00	- 4.99	- 5.77	4 201	6 554	386	- 101
3	BAU	12	11	126	254	180	700	1.25	15.89	3.41	2.59	2.01	- 0.20	-	- 0.55	-	-	2 120	3 252	296	- 117
3	RedMat	12	11	98	185	180	700	0.85	12.54	3.83	3.55	1.67	- 0.14	-	- 0.61	-	-	1 653	3 252	296	- 91
3	ExtLifeTime	12	11	126	254	180	840	1.25	15.89	3.41	2.59	2.01	- 0.20	-	- 0.55	-	-	2 120	3 252	296	- 117
3	RedMat_ExtLifeTime	12	11	98	185	180	840	0.85	12.54	3.83	3.55	1.67	- 0.14	-	- 0.61	-	-	1 653	3 252	296	- 91
3	RedMat_ExtLifeTime_Footprint	12	11	98	185	180	840	0.85	12.54	3.83	3.55	1.67	- 0.14	-	- 0.61	-	-	1 653	3 252	296	- 91
3	RedMat_ExtLifeTime_Recycling	12	11	98	185	180	840	0.85	12.54	3.83	3.55	1.67	- 0.71	-	- 3.15	- 2.99	- 1.33	1 653	3 252	296	- 91
3	BAT	12	11	98	185	180	840	0.85	12.54	3.83	3.55	1.67	- 0.71	-	- 3.15	- 2.99	- 1.33	1 653	3 252	296	- 91
4	BAU	30	8	256	220	450	400	2.77	36.45	9.99	1.89	4.70	- 0.44	-	- 1.60	-	-	3 883	7 571	946	- 69
4	RedMat	30	8	221	129	450	400	1.23	31.08	12.10	6.54	4.45	- 0.20	-	- 1.94	-	-	3 395	7 571	946	- 68
4	ExtLifeTime	30	10	256	220	450	480	2.77	36.45	9.99	1.89	4.70	- 0.44	-	- 1.60	-	-	3 883	8 118	812	- 69
4	RedMat_ExtLifeTime	30	10	221	129	450	480	1.23	31.08	12.10	6.54	4.45	- 0.20	-	- 1.94	-	-	3 395	8 118	812	- 68
4	RedMat_ExtLifeTime_Footprint	30	10	221	129	450	480	1.23	31.08	12.10	6.54	4.45	- 0.20	-	- 1.94	-	-	3 395	8 118	812	- 68
4	RedMat_ExtLifeTime_Recycling	30	10	221	129	450	480	1.23	31.08	12.10	6.54	4.45	- 1.04	-	- 9.98	- 5.50	- 3.56	3 395	8 118	812	- 68
4	BAT	30	10	221	129	450	480	1.23	31.08	12.10	6.54	4.45	- 1.04	-	- 9.98	- 5.50	- 3.56	3 395	8 118	812	- 68
5	BAU	20	5	210	212	300	400	2.09	26.49	5.69	4.31	3.36	- 0.33	-	- 0.91	-	-	3 534	8 976	1 795	- 195
5	RedMat	20	5	163	185	300	400	1.42	20.90	6.38	5.92	2.78	- 0.23	-	- 1.02	-	-	2 754	8 976	1 795	- 152
5	ExtLifeTime	20	5	210	212	300	480	2.09	26.49	5.69	4.31	3.36	- 0.33	-	- 0.91	-	-	3 534	8 976	1 795	- 195
5	RedMat_ExtLifeTime	20	5	163	185	300	480	1.42	20.90	6.38	5.92	2.78	- 0.23	-	- 1.02	-	-	2 754	8 976	1 795	- 152
5	RedMat_ExtLifeTime_Footprint	20	5	163	185	300	480	1.42	20.90	6.38	5.92	2.78	- 0.23	-	- 1.02	-	-	2 754	8 976	1 795	- 152
5	RedMat_ExtLifeTime_Recycling	20	5	163	185	300	480	1.42	20.90	6.38	5.92	2.78	- 1.19	-	- 5.26	- 4.98	- 2.22	2 754	8 976	1 795	- 152
5	BAT	20	5	163	185	300	480	1.42	20.90	6.38	5.92	2.78	- 1.19	-	- 5.26	- 4.98	- 2.22	2 754	8 976	1 795	- 152
6	BAU	10	17	128	683	150	100	0.29	14.48	1.16	0.16	1.16	- 0.05	-	- 0.19	-	-	1 855	3 497	206	- 25
6	RedMat	10	17	101	499	150	100	0.12	11.05	1.35	3.81	1.05	- 0.02	-	- 0.22	-	-	1 481	3 497	206	- 20
6	ExtLifeTime	10	17	128	683	150	120	0.29	14.48	1.16	0.16	1.16	- 0.05	-	- 0.19	-	-	1 855	3 497	206	- 25
6	RedMat_ExtLifeTime	10	17	101	499	150	120	0.12	11.05	1.35	3.81	1.05	- 0.02	-	- 0.22	-	-	1 481	3 497	206	- 20
6	RedMat_ExtLifeTime_Footprint	10	17	101	499	150	120	0.12	11.05	1.35	3.81	1.05	- 0.02	-	- 0.22	-	-	1 481	3 497	206	- 20
6	RedMat_ExtLifeTime_Recycling	10	17	101	499	150	120	0.12	11.05	1.35	3.81	1.05	- 0.10	-	- 1.11	- 3.21	- 0.84	1 481	3 497	206	- 20
6	BAT	10	17	101	499	150	120	0.12	11.05	1.35	3.81	1.05	- 0.10	-	- 1.11	- 3.21	- 0.84	1 481	3 497	206	- 20
7	BAU	10	17	128	683	150	100	0.29	14.48	1.16	0.16	1.16	- 0.05	-	- 0.19	-	-	1 855	4 371	257	- 25
7	RedMat	10	17	101	499	150	100	0.12	11.05	1.35	3.81	1.05	- 0.02	-	- 0.22	-	-	1 481	4 371	257	- 20
7	ExtLifeTime	10	17	128	683	150	120	0.29	14.48	1.16	0.16	1.16	- 0.05	-	- 0.19	-	-	1 855	4 371	257	- 25
7	RedMat_ExtLifeTime	10	17	101	499	150	120	0.12	11.05	1.35	3.81	1.05	- 0.02	-	- 0.22	-	-	1 481	4 371	257	- 20
7	RedMat_ExtLifeTime_Footprint	10	17	101	499	150	120	0.12	11.05	1.35	3.81	1.05	- 0.02	-	- 0.22	-	-	1 481	4 371	257	- 20
7	RedMat_ExtLifeTime_Recycling	10	17	101	499	150	120	0.12	11.05	1.35	3.81	1.05	- 0.10	-	- 1.11	- 3.21	- 0.84	1 481	4 371	257	- 20
7	BAT	10	17	101	499	150	120	0.12	11.05	1.35	3.81	1.05	- 0.10	-	- 1.11	- 3.21	- 0.84	1 481	4 371	257	- 20

7.2.2. Policy scenarios

7.2.2.1. Approach

For the purpose of producing the quantified scenario impact analyses under subtask 7.2, an Excel based stock-model was developed for the battery system product group. The structure of the model is shown in Figure 7-3.

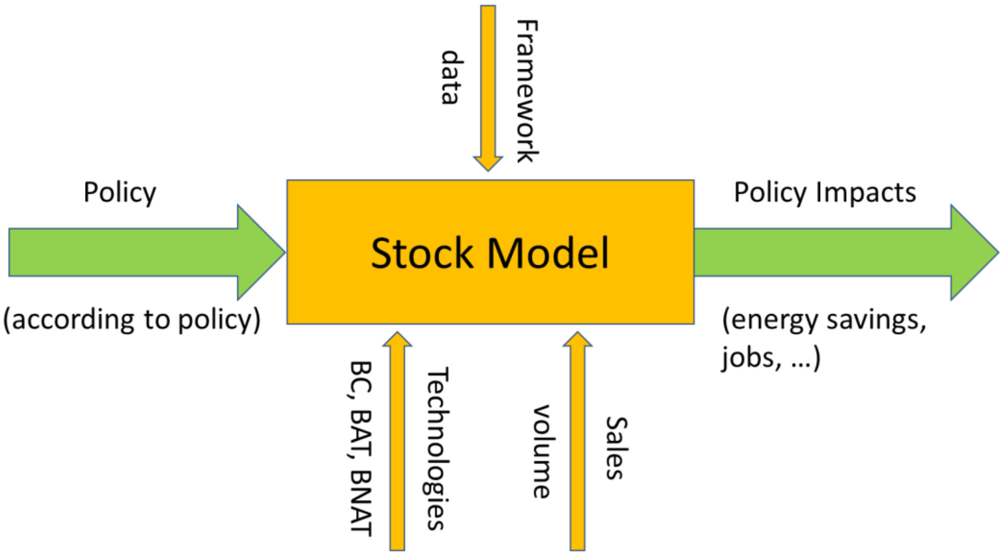

Figure 7-3: Simplified overview of the model (Source: Fraunhofer ISI)

With:

- Technologies and policies: an overview of the main data for each Base Case according to the level of technology considered was provided in Table 7-7.
- Figures related to GHG emissions of electricity (see Table 7-8): based on PRIMES[35] for the medium scenario, it applies for the use phase and the EoL.
  With regard to the production phase, the GHG emission factor applicable to a battery system that will be placed on the EU market depends on the manufacturers' electricity supplier along the value chain. Therefore, a range between a low-carbon electricity mix and a high-carbon electricity mix has been considered here.[36] The average assumption corresponds to the EU average (see PRIMES).

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[35] reference scenario for the EU electricity mix in EU

[36] To determine this range, the GWP impact of the available high voltage electricity generating technologies within the ecoinvent LCI database (version 3.4) were calculated within SimaPro (version 8.52). The power generator with the highest GWP impact is electricity production from lignite and the one with the lowest is run-of-river hydroelectricity. The impact was increased with 5% in order to include the losses when transforming high voltage electricity to medium voltage electricity.

- Figures related to electricity prices (see Table 7-9): based on PRIMES[37] for the medium scenario. For a sensitivity analysis, +50% and -50% are applied.
- Socio-economical figures from the battery sector (see Table 7-10).

Table 7-8: GHG emissions related to electricity

Parameter	Scenario	Unit	2020	2025	2030	2035	2040	2045
GHG Emission	Low[38]	[kgCO$_{2eq}$/kWh]	0.00	0.00	0.00	0.00	0.00	0.00
GHG Emission	Medium	[kgCO$_{2eq}$/kWh]	0.38	0.36	0.34	0.32	0.30	0.28
GHG Emission	High[39]	[kgCO$_{2eq}$/kWh]	1.28	1.28	1.28	1.28	1.28	1.28

Important remark: the figures in Table 7-8 do not match to those presented in Task 5 report. This is due to the fact, that Task 5 report uses figures from the EcoReport 2014 tool.

Table 7-9: Electricity prices

Parameter	Scenario	Unit	2020	2025	2030	2035	2040	2045
Price	Low[40]	[c€/MWh]	7.80	8.05	8.20	8.45	8.40	8.35
Price	Medium[41]	[c€/MWh]	15.60	16.10	16.40	16.90	16.80	16.70
Price	High[42]	[c€/MWh]	23.40	24.15	24.60	25.35	25.20	25.05

Table 7-10: Socio-economical figures from the battery sector

Variable name and unit	Value	Source
Jobs direct [full time equ./GWh]	125	Based on Task 2
Jobs Indirect [full time equ./GWh]	300	Based on Task 2

In addition, several recycling rates have been considered for the CRM during the EOL phase (see Table 7-11, taken from Task 4 report, see section 4.2.4.3, table 13 for the different sources of the recycling rates).

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[37] reference scenario for the EU electricity mix in EU

[38] only used in the production phase

[39] only used in the production phase

[40] -50% compared to the medium scenario

[41] based on PRIMES (reference year: 2015) as average of electricity prices for households and industry, see also Task 5

[42] +50% compared to the medium scenario

Table 7-11: EOL recycling rates [%] (EV battery specific data)

Scenario	Cobalt	Graphite	Nickel	Mangan-ese	Lithium
BAU	16.00	0.00	16.00	0.00	0.00
Improved: 65% collection rate + combination of pyrometallurgical & hydrometallurgical processes	61.10	0.00	61.75	0.00	37.05
Ambitious: 85% collection rate + purely hydrometallurgical process	84.15	0.00	82.45	84.15	79.90

- Sales and stock:

The model is a simplified stock model, wherein:

Equation 1

$$stock_{BC_i,y} = \sum_{j=y-lifetime_i+1}^{y} sales_{BC_i,j}$$

Equation 2

$$stock_{batteries,y} = \sum_{i=1}^{7} stock_{BC_i,y}$$

Where:

- Y = year
- lifetime = lifetime of the BC
- BC = Base Case
- i = index of the BC

Also, sales figures can be calculated based on stock figures:

Equation 3

$$sales_{BC_i,y} = stock_{BC_i,y} - stock_{BCi,y-1} + sales_{BC_i,y-litetime+1}$$

The market volume consists in the stock increase and in the replacement of old products, which have reached the technical lifetime.

Due to the long technical lifetime of the products considered (around 20 years for some battery systems), it is important to run the model and to analyse the results over a long period. Since policy options discussed in this task will address the sales market (new products) and not the stock, the effect of such new policy options will not be perceptible from the first year and thus requires the scenario analysis to cover the time window of 2019-2045.

The Task 7 stock figures are the same as in Task 2. In addition, the historical data had to be estimated by back casting the sales for the period prior 2010, considering the commercial lifetime of a battery. An overview of the stock figures is provided in Table 7-12 and Figure 7-4. Table 7-13 shows the stock figures expressed in number of battery systems.[43]

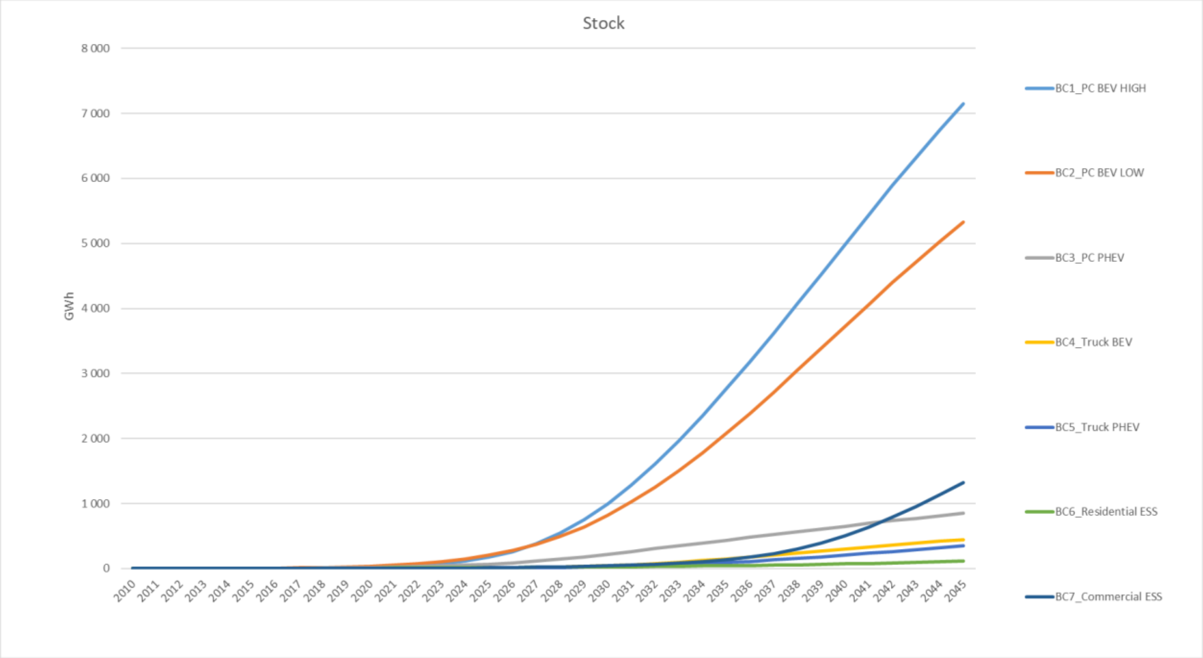

Figure 7-4: Forecast battery capacity stock for the EU market (medium sales scenario)

Table 7-12: Forecast battery capacity stock for the EU market (medium sales scenario)

Stock [GWh]	2010	2015	2020	2025	2030	2035	2040	2045
BC1_PC BEV HIGH	0	1	18	173	996	2 760	4 983	7 150
BC2_PC BEV LOW	0	6	39	207	818	2 078	3 723	5 327
BC3_PC PHEV	3	5	17	70	221	438	653	850
BC4_Truck BEV	0	0	1	8	45	149	301	443
BC5_Truck PHEV	0	0	1	7	30	92	207	350
BC6_Residential ESS	1	4	9	16	26	45	72	113
BC7_Commercial ESS	0	1	4	12	40	141	504	1 324
Total mobile application	4	12	76	464	2 110	5 518	9 867	14 120
Total stationary application	1	5	12	27	67	185	576	1 437
Total all application	5	18	89	491	2 177	5 703	10 443	15 557

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[43] Not in number of applications. For Basecase 7 (commercial ESS), there are 30 000 battery systems with 10 kWh nominal capacity.

Table 7-13: Forecast battery stock for the EU market (medium sales scenario) expressed in number of battery systems

Stock [1,000 battery systems]	2010	2015	2020	2025	2030	2035	2040	2045
BC1_PC BEV HIGH	1	16	227	2 160	12 450	34 503	62 292	89 372
BC2_PC BEV LOW	7	143	974	5 164	20 440	51 959	93 070	133 171
BC3_PC PHEV	250	417	1 439	5 795	18 454	36 515	54 382	70 873
BC4_Truck BEV	7	7	32	268	1 494	4 965	10 048	14 761
BC5_Truck PHEV	8	8	46	354	1 492	4 595	10 341	17 521
BC6_Residential ESS	108	435	886	1 566	2 644	4 454	7 228	11 316
BC7_Commercial ESS	30	112	361	1 163	4 045	14 069	50 355	132 385
Total mobile application	272	591	2 719	13 740	54 330	132 536	230 133	325 698
Total stationary application	138	547	1 247	2 729	6 689	18 523	57 583	143 701
Total all application	411	1 137	3 966	16 470	61 019	151 059	287 716	469 399

Figure 7-5 and Table 7-14 provide an overview of the evolution of the sales over time (based on the findings from the Task 2 report). Please note that due to the simplified approach of the Task 7 stock model (see Equation 3), the sales in Task 7 cannot match to the figures provided in Task 2. Table 7-15 shows the sales figures expressed in number of battery systems.

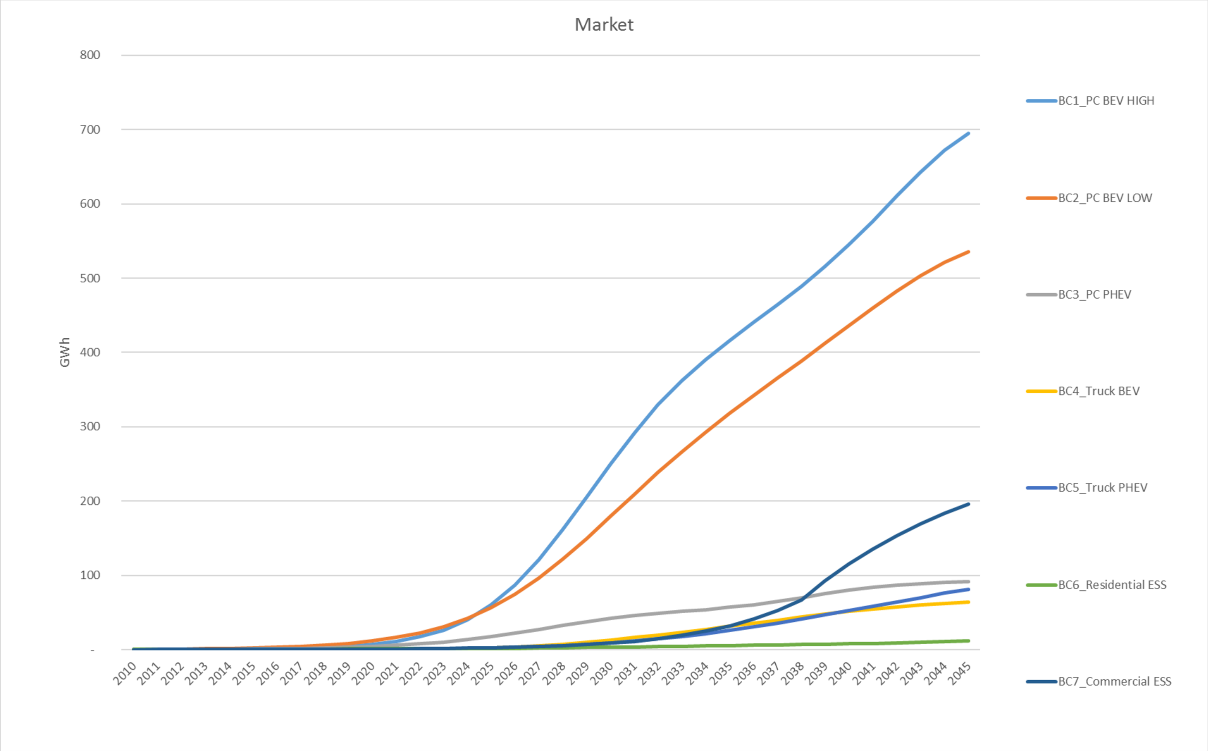

Figure 7-5: Forecast battery capacity sales for the EU market (medium sales scenario)

Table 7-14: Forecast battery capacity sales for the EU market (medium sales scenario)

Sales [GWh]	2010	2015	2020	2025	2030	2035	2040	2045
BC1_PC BEV HIGH	0	1	7	60	250	416	545	695
BC2_PC BEV LOW	0	2	12	57	179	318	436	536
BC3_PC PHEV	0	1	4	17	43	57	80	91
BC4_Truck BEV	0	0	0	3	13	32	52	64
BC5_Truck PHEV	0	0	0	2	9	26	53	82
BC6_Residential ESS	0	1	1	2	3	5	8	12
BC7_Commercial ESS	0	0	1	3	9	32	115	196
Total mobile application	0	4	24	139	495	849	1 166	1 468
Total stationary application	0	1	2	4	12	37	123	208
Total all application	0	5	26	143	507	886	1 289	1 676

Table 7-15: Forecast battery sales for the EU market (medium sales scenario) expressed in number of battery systems

Sales [1,000 battery systems]	2010	2015	2020	2025	2030	2035	2040	2045
BC1_PC BEV HIGH	0	8	87	749	3 129	5 206	6 809	8 688
BC2_PC BEV LOW	1	52	293	1 418	4 487	7 950	10 912	13 395
BC3_PC PHEV	23	90	369	1 445	3 560	4 750	6 687	7 618
BC4_Truck BEV	1	1	16	86	430	1 054	1 722	2 130
BC5_Truck PHEV	2	2	24	125	469	1 303	2 631	4 076
BC6_Residential ESS	6	79	113	165	338	527	786	1 222
BC7_Commercial ESS	2	25	74	261	874	3 203	11 513	19 576
Total mobile application	26	153	790	3 821	12 076	20 263	28 761	35 907
Total stationary application	8	104	187	426	1 212	3 730	12 299	20 798
Total all application	34	257	976	4 248	13 288	23 993	41 060	56 705

At the end of this task report, a sensitivity analysis is carried out. It covers low / high sales scenarios (see 7.3.1) as well as low / high energy price scenarios (see 7.3.2).

7.2.1. Environmental impacts

For most of the products covered by an Ecodesign preparatory study, the energy consumption during the use phase of the product is the most important environmental impacting life cycle stage. Task 5 and Task 6 showed for battery systems a more complex situation. Therefore, beside the electricity consumption and the GHG emissions, the demand of CRM will be analysed here. Furthermore, for most of the environmental impacts, figures are presented according to the three main phases of the product:

- Production: raw materials use and manufacturing
- Use phase
- EoL: End of Life

7.2.1.1. Electricity consumption

Figure 7-6[44] shows the electricity consumption of the battery systems in the production phase[45]. The best improvement potential is seen in the RedMat_ExtLifeTime scenarios as well as in the BAT scenario. All achieve a reduction of the energy consumption by 29.3% (159 656 GWh/year) in 2045, compared to the BAU scenario (225 721 GWh/year).

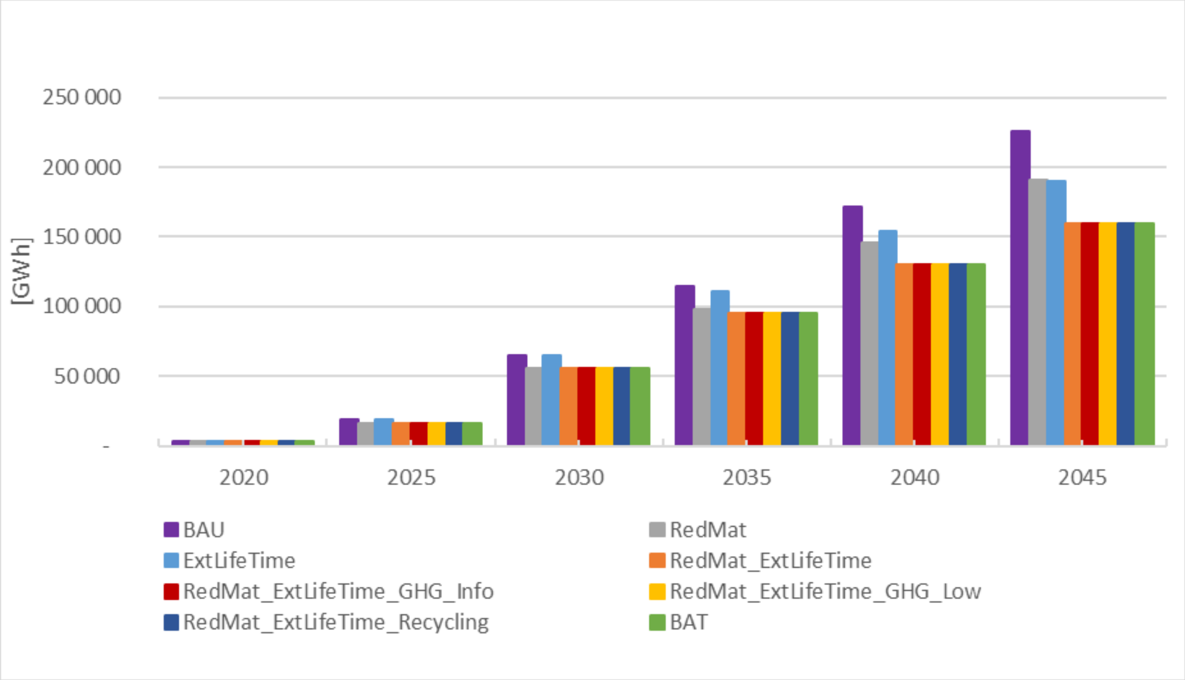

Figure 7-6: Electricity consumption in GWh/year for the production phase (EU-28 battery system stock)

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[44] see also Table 7-28 in Annex

[45] Within the EcoReport tool there are two primary energy related environmental indicators: the Gross Energy Requirement (GER, in MJ) and the part of the GER that is used in form of electricity (also in MJ). The environmental impact of primary energy depends on the energy source. As mentioned in the MEErP 2011 methodological report part 1 (p. 94): the electricity use is an auxiliary parameter which “should not be perceived as a form of energy that in itself would have a higher or lower reduction priority that the GER. However, it is an important auxiliary parameter, as it not only creates the link with efficiency of power generation but also with a host of other parameters (emissions, waste, water use) that are relevant”. Within the production of li-ion batteries, large amounts of electricity is used e.g. to prepare cathode active materials (when precursors are added to the lithium source) and for the electrode, cell forming and battery assembly (see table 8 and 10 of Task 5 report). In the EcoReport, the electricity part of the GER is given for the 55 common materials. For the added extra materials the study team has made rough estimates on the electricity part of the GER as good as possible, despite the limitations within LCA software to extract the amount of electricity in primary energy along the complete production chain. Considering all this, the study team found it important to include to electricity consumption in the production stage.

Electricity consumption in the use phase is illustrated in Figure 7-7. As visible in this figure, the electricity losses in all battery systems will exceed 200 000 GWh/a in 2045 This is in a similar range as the electricity consumption required for the production of the batteries.

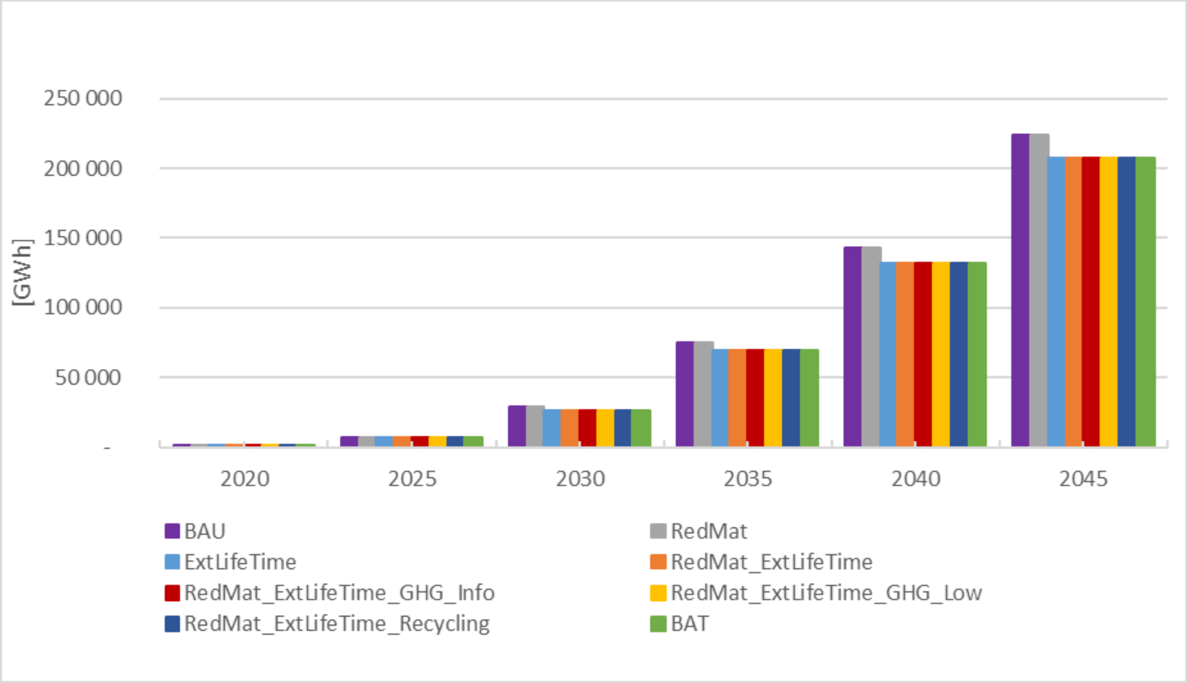

Figure 7-7: Electricity consumption in GWh/year for the use phase (EU-28 battery system stock)

The evolution of electricity consumption is also analysed for the EOL phase and the results are shown in Figure 7-8[46]. Until 2027, the electricity consumption in all scenarios is the same, since only batteries placed on the market after 2022 will be affected by the EOL measures when their technical lifetime will be reached.[47] In 2045, the BAU scenario will have the best impact, decreasing the electricity consumptions in the EOL phase by 2 724 GWh.

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[46] see also Table 7-29 in Annex

[47] Basecase 5 has the shortest technical lifetime: 5 years.

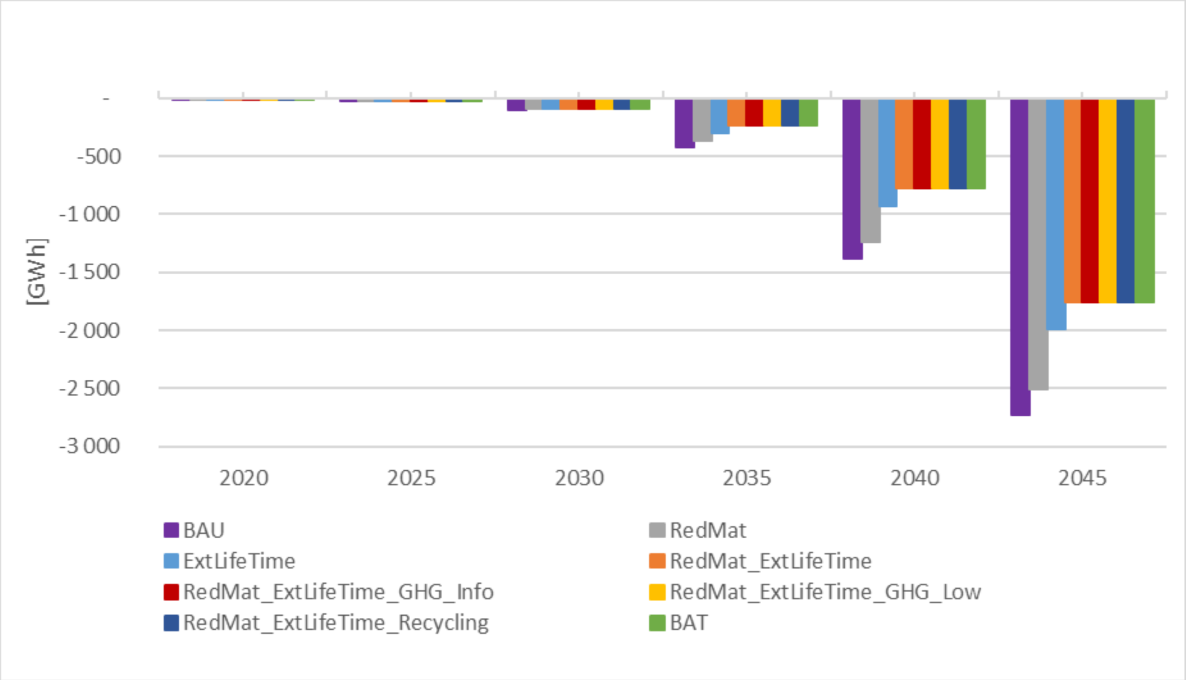

Figure 7-8: Electricity consumption in GWh/year for the EOL phase (EU-28 battery system stock)[48]

As summary, Figure 7-9[49] shows the electricity consumptions of the battery systems on the EU market in year 2045, considering all phases of the products. In general, the scenarios combining an extended lifetime and the reduction of material have the same impact on the electricity consumption: they have the potential to reduce it by 18.2% in year 2045 compared to the BAU scenario. Based on the previous tables and figures, the electricity consumption in the production and the use phase are similar, while the contribution in the EOL phase is negligible.

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[48] The MEErP EcoReport tool considers incineration and landfilling as impacting processes during EOL and recycling, reuse and energy recovery as beneficial processes. The benefits of recycling, reuse and energy recovery are calculated as a (fixed) percentage of the impacts from production, i.e. 40 %, 75 %, and 30 % respectively. For instance: if the production impact of a certain plastic material is 1 MJ electricity of primary energy and the (MEErP default) recycling, reuse and energy recovery rate are 29 %, 1 % and 15 % respectively, than the benefits due to recycling, reuse and energy recovery during EOL = (0.4 * 0.29 + 0.75 * 0.01 + 0.3 * 0.15) * 1 = 0.91 MJ. In case the impact from electricity used at the incineration and landfilling of the remaining fraction of that plastic material is smaller than 0.91 MJ, than it would result in a negative value (i.e. benefit) for the EOL phase. If it is bigger than 0.91 MJ than it would result in a positive value, i.e. an impact.

[49] see also Table 7-30 in Annex

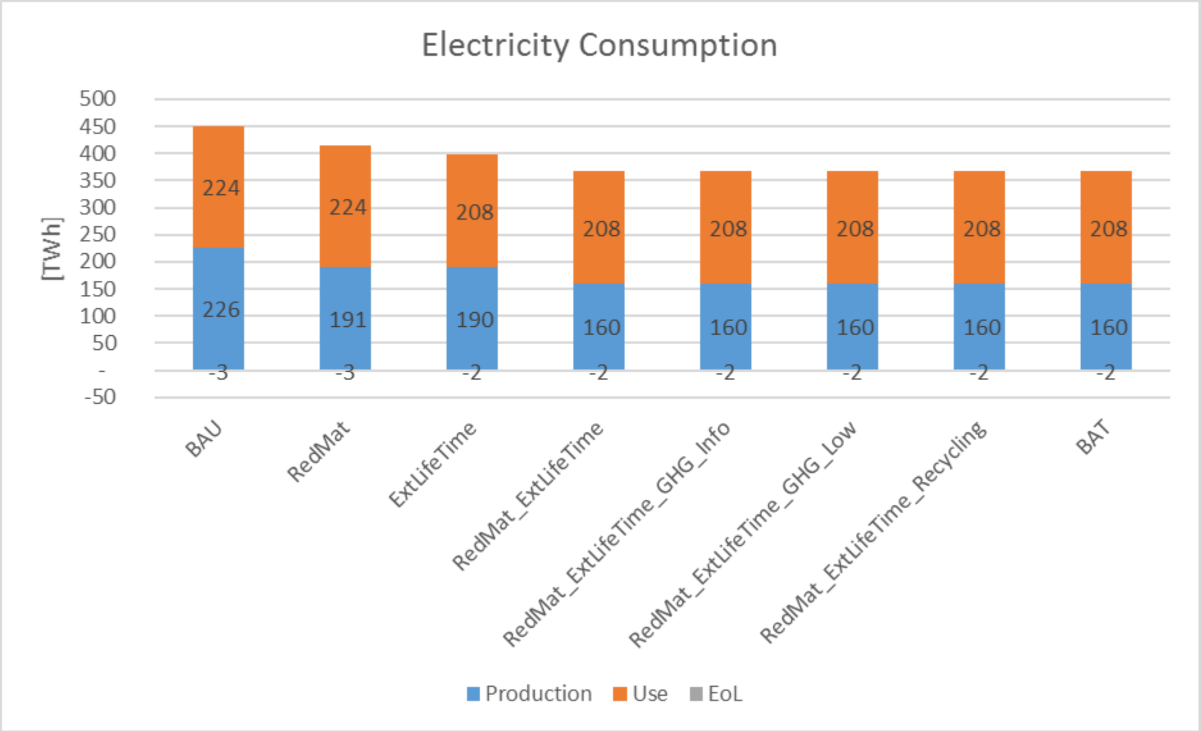

Figure 7-9: Electricity consumption in TWh/year for all phases in 2045 (EU-28 battery system stock)

7.2.1.2. GHG emissions

The results of the GHG emissions analysis in different phases of the battery systems are presented in this section.

Looking at the production phase (see Figure 7-10)[50], the best way to reduce the GHG emissions related to the electricity consumptions is through the electricity mix. The best scenarios are RedMat_ExtLifeTime_GHG_Low and BAT, emitting only 1 $MtCO_2$/year in 2045, which is 98.9% below the BAU level. RedMat_ExtLifeTime_GHG_Info is the next best scenario, with 50% reduction compared to the BAU scenario.

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[50] see also Table 7-31 in Annex

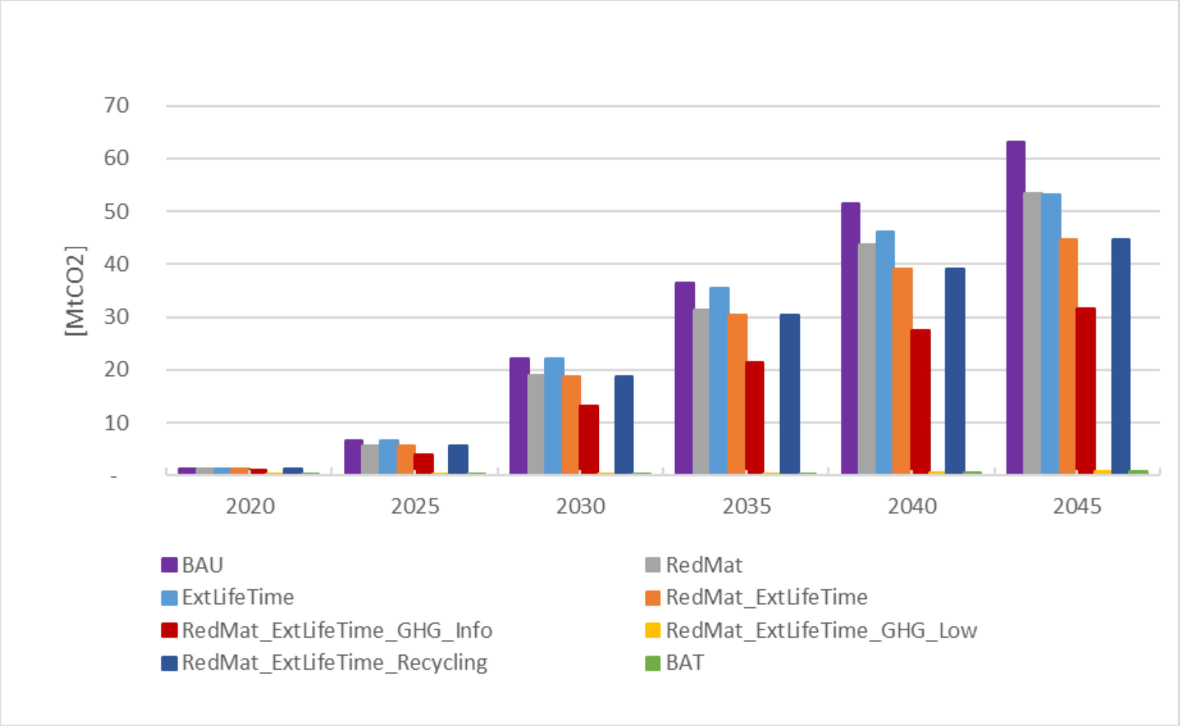

Figure 7-10: GHG emission (of the electricity consumption) in MtCO$_2$/year for the production phase (EU-28 battery system stock)

However, in the use phase (see Figure 7-11), where the same electricity mix (EU average) is assumed for all scenarios, the ranking of the scenarios is the same as for GHG emissions in the use phase (see Figure 7-7).

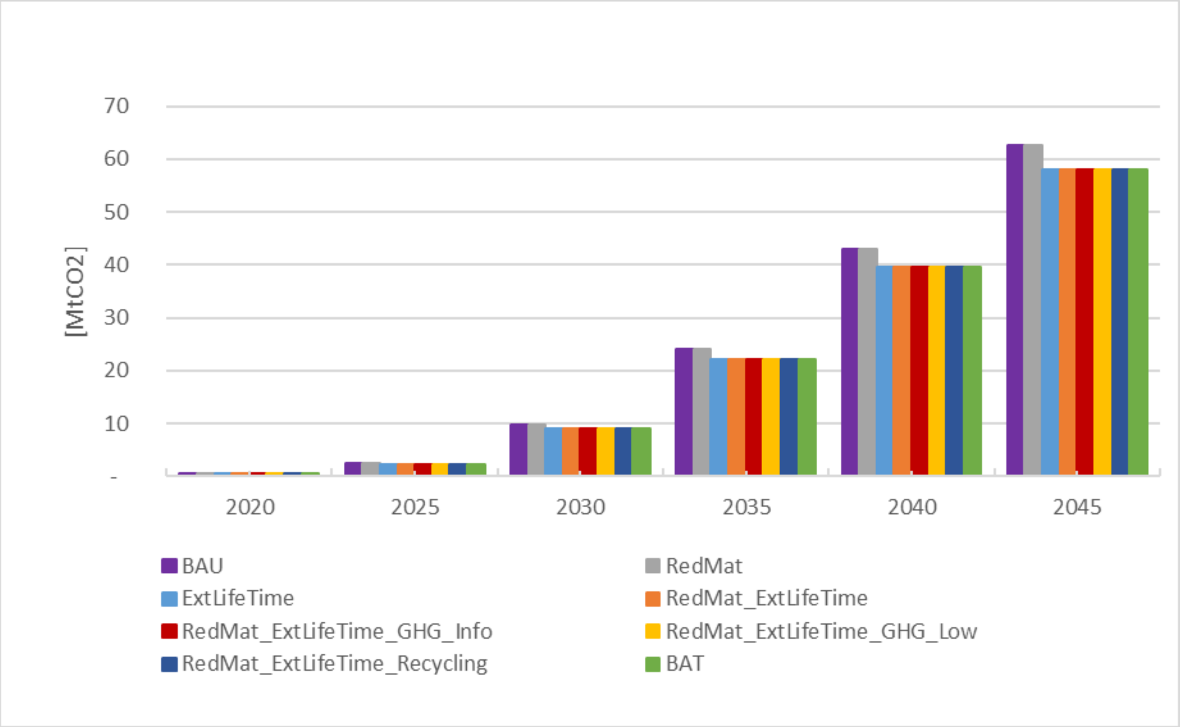

Figure 7-11: GHG emission (of the electricity consumption) in MtCO$_2$/year for the use phase (EU-28 battery system stock)

The evolution in terms of GHG Emissions is also compared for the EOL phase, see Figure 7-12[51]. The GHG figures are calculated on the basis of GHG emissions of an average kWh electricity in the EU and on the electricity consumptions (see Figure 7-8).

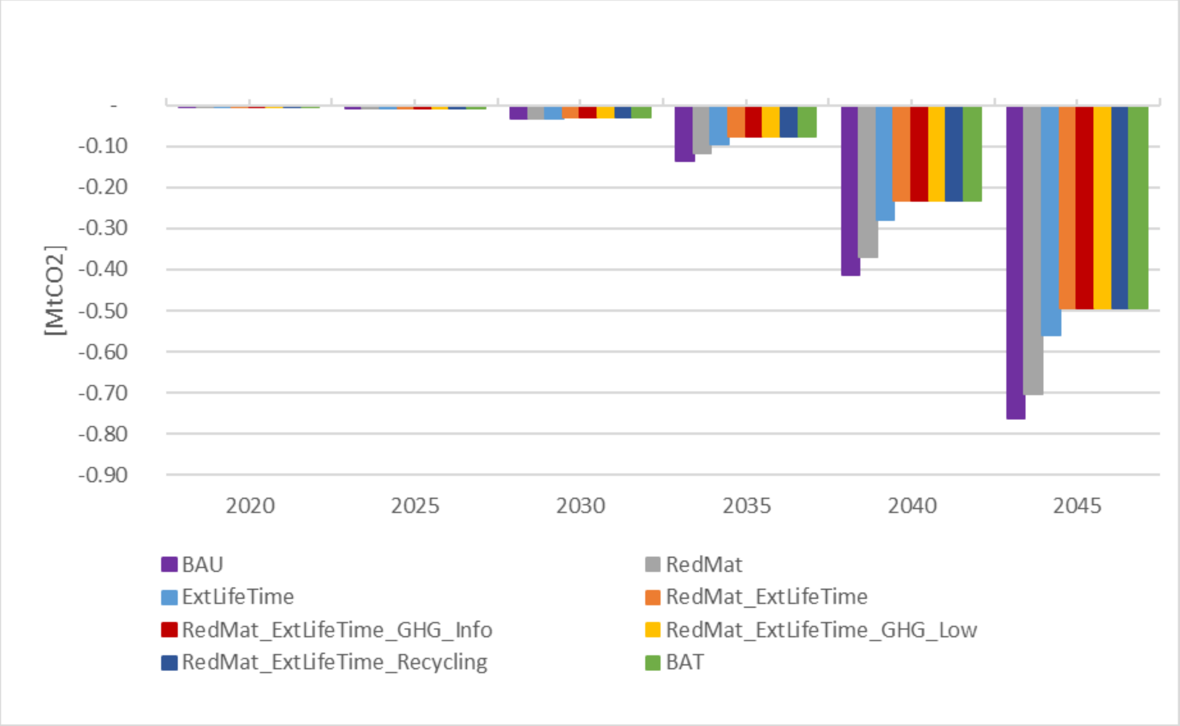

Figure 7-12: GHG emission (of the electricity consumption) in MtCO$_2$/year for the EOL phase (EU-28 battery system stock)

Figure 7-13[52] shows the GHG emissions for all phases and for battery systems in the EU in 2045. In the BAU scenario, the overall GHG emissions *are expected to* increase up to 125 MtCO$_{2eq}$/a, by 2045 assuming the average EU electricity mix for all phases of a battery system. The GHG emissions can be reduced by 53.3% in RedMat_ExtLifeTime scenarios[53] using low carbon electricity mix during the production phase.

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[51] see also Table 7-32 in Annex

[52] see also Table 7-33 in Annex

[53] RedMat_ExtLifeTime_GHG_Low and BAT

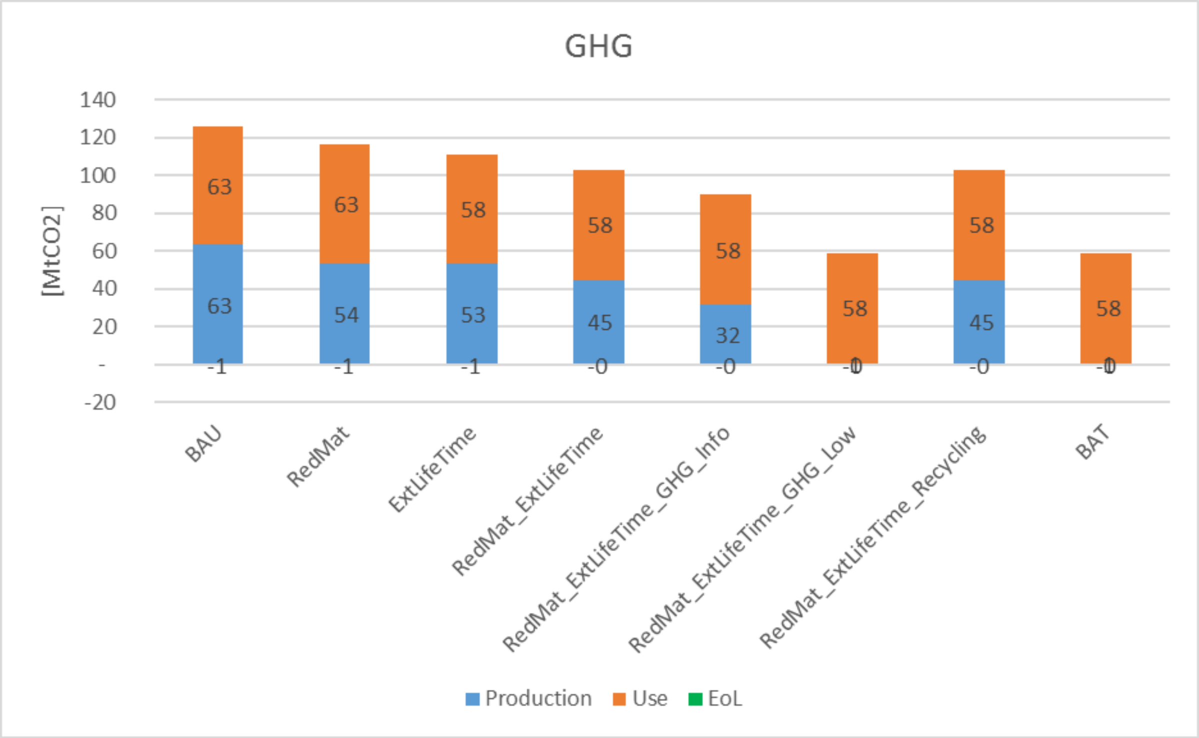

Figure 7-13: GHG emission (of the electricity consumption) in $MtCO_2$/year for all phases in 2045 (EU-28 battery system stock)

7.2.1.3. Cobalt demand

Figure 7-14[54] shows the Cobalt demand in the production phase of the battery systems. In the BAU scenario, the yearly Cobalt demand will rise up to 177 kt/a for the EU market in 2045. This demand could be reduced by 55% in the RedMat_ExtLifeTime scenarios as well as in the BAT scenario. A similar analysis for all phases shows the highest potential reduction in the Cobalt demand for RedMat_ExtLifeTime_Recycling and BAT scenarios (see Figure 7-15[55]).

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[54] see also Table 7-34 in Annex

[55] see also Table 7-35 in Annex

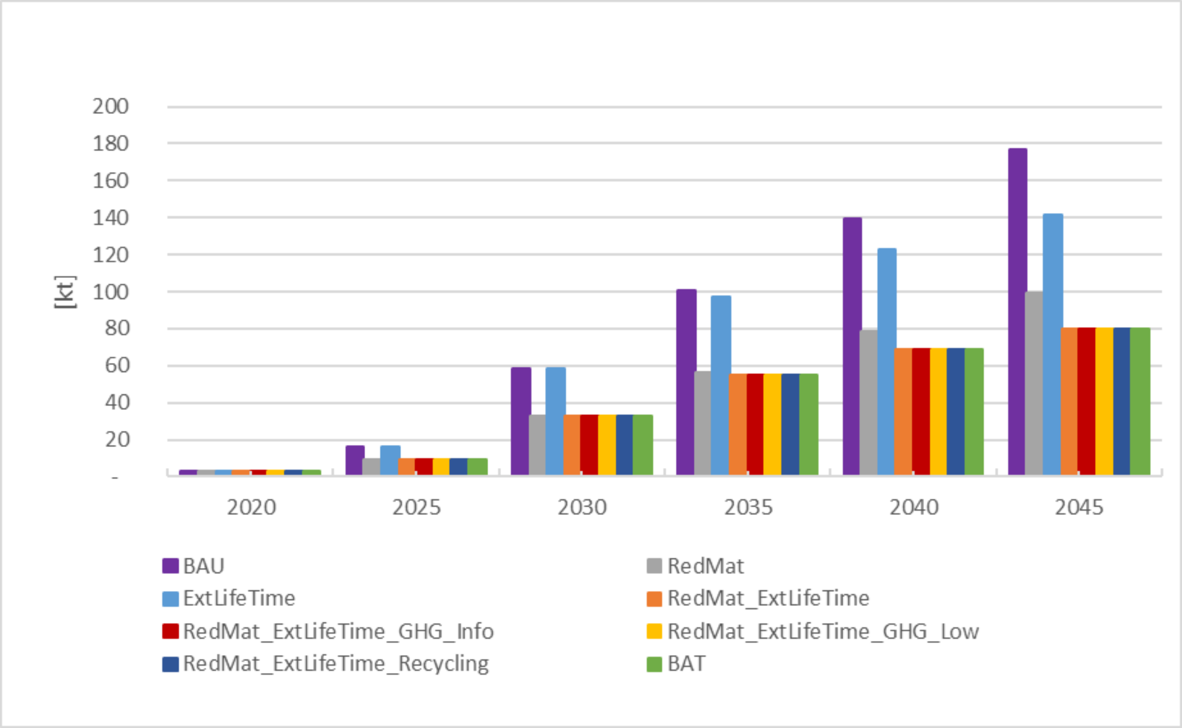

Figure 7-14: Cobalt demand in kt/year for the production phase (EU-28 battery system stock)

The following figure *(*Figure 7-15*)* shows the amount of cobalt used in batteries by product phase:

- *Production*: quantity required for the manufacture of new batteries.
- *U*se: total quantity used by all batteries in service on the market
- *EoL*: quantity recovered at the end of a battery's life. This quantity depends on the demand for the production (when the batteries have been put on the market) and the recycling rate. The figure is negative, since the amount of recycled cobalt decreases the

The sum indicates year by year the amount of cobalt mobilised for all batteries on the EU market.

For comparison, in 2016 global cobalt production was 126 kt with the largest supply (55%) coming from the Democratic Republic of the Congo. In turn, the EU production of cobalt was estimated at 2,3 kt sourced from Finland[56]. As a conclusion, significant more cobalt mining will be needed to satisfy the forecasted demand in this study and it will be essential to recycle all possible cobalt. Today most cobalt is obtained as a co- and by-product of copper (46 %) and nickel (39 %) mining, which is beneficial to reduce the environmental impact per kt due to synergies in production. An increased demand might however change this in future.

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[56] JRC (2018) Technical Report: ‘Cobalt: demand-supply balances in the transition to electric mobility’, ISBN 978-92-79-94311-9

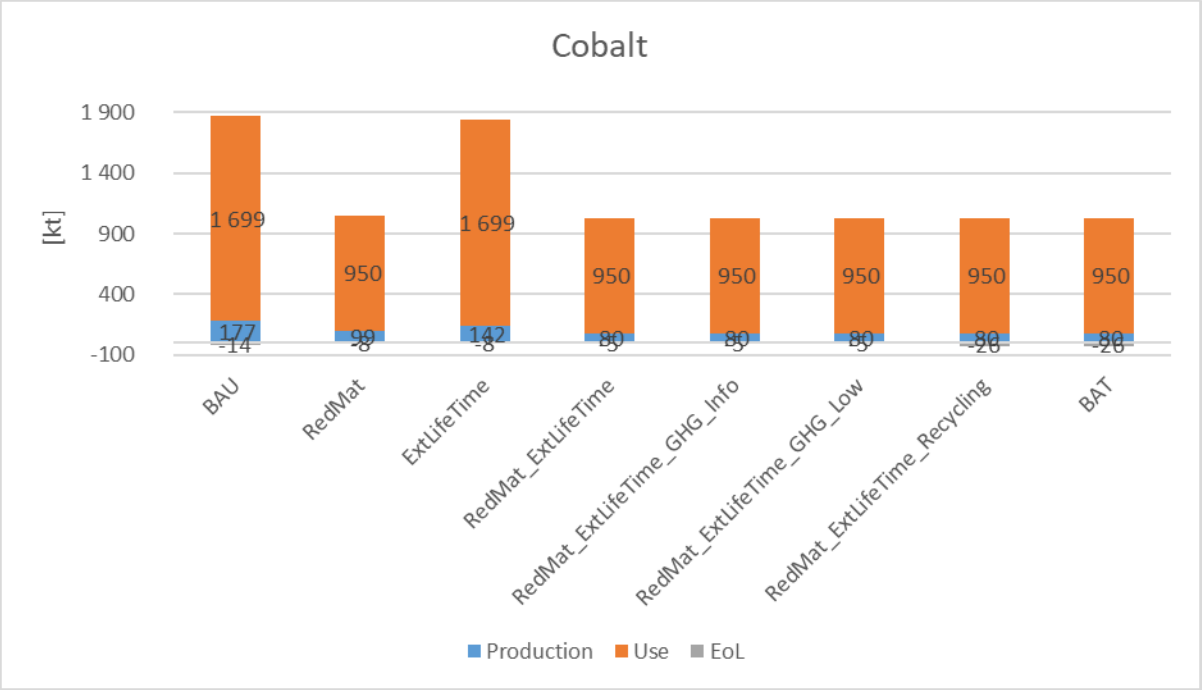

Figure 7-15: Cobalt demand in kt/year for all phases in 2045 (EU-28 battery system stock)

7.2.1.4. Graphite demand

The evolution of the Graphite demand for the battery systems over time is shown for the production phase in Figure 7-16[57] and for all phases in Figure 7-17.

The demand for Graphite is expected to rise up to 1 951 kt/y in 2045 in the BAU scenario. The RedMat_ExtLifeTime scenarios as well as the BAT scenario will reduce the demand by 28.3% in 2045.

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[57] see also Table 7-36 in Annex

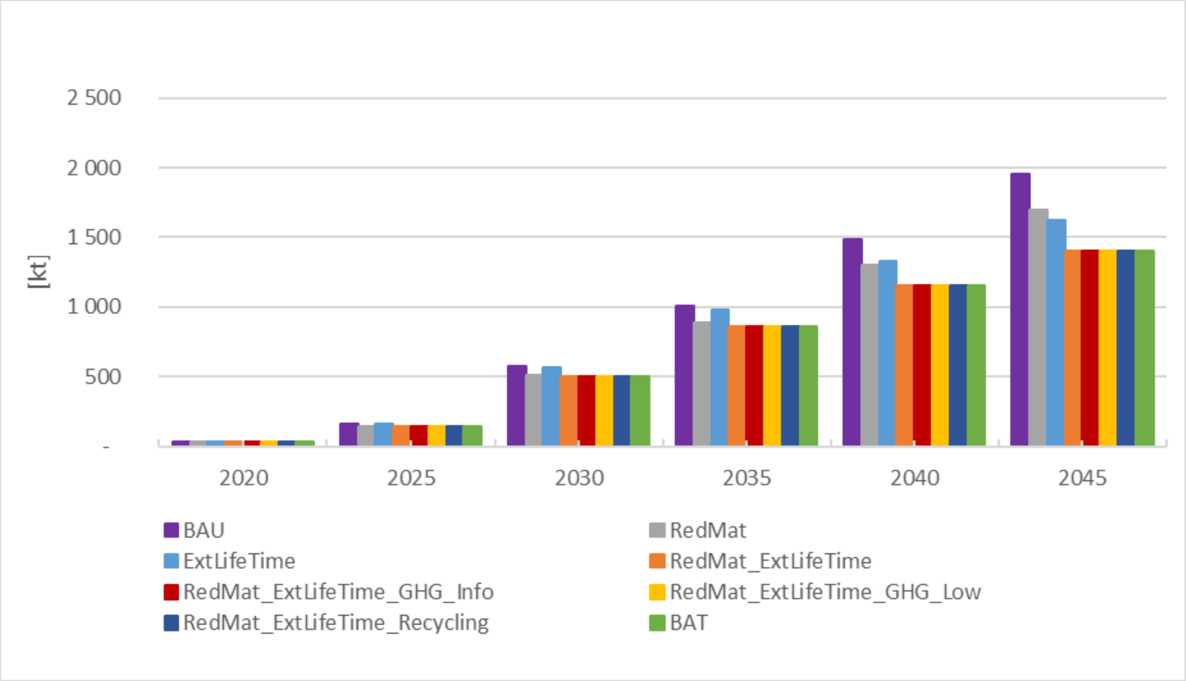

Figure 7-16: Graphite demand in kt/year for the production phase (EU-28 battery system stock)

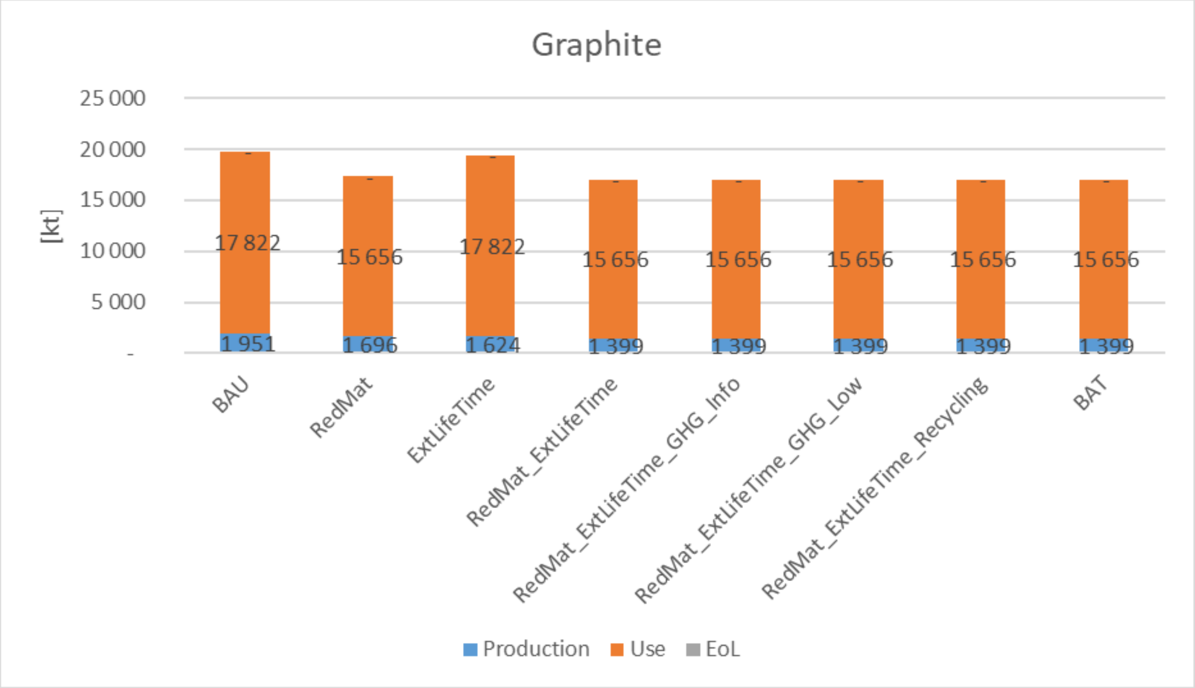

Figure 7-17: Graphite demand in kt/year for all phases (EU-28 battery system stock)

7.2.1.5. Nickel demand

Figure 7-18[58] illustrates the nickel demand in the battery systems for the production phase. Here, the nickel demand in the ExtLifeTime scenario is expected to be the lowest (514 kt/a) compared to the BAU scenario (647 kt/a) in 2045. An increase of 20.6% of the nickel demand is expected in the RedMat scenario. The other scenarios have a similar level of nickel demand as in the BAU scenario.

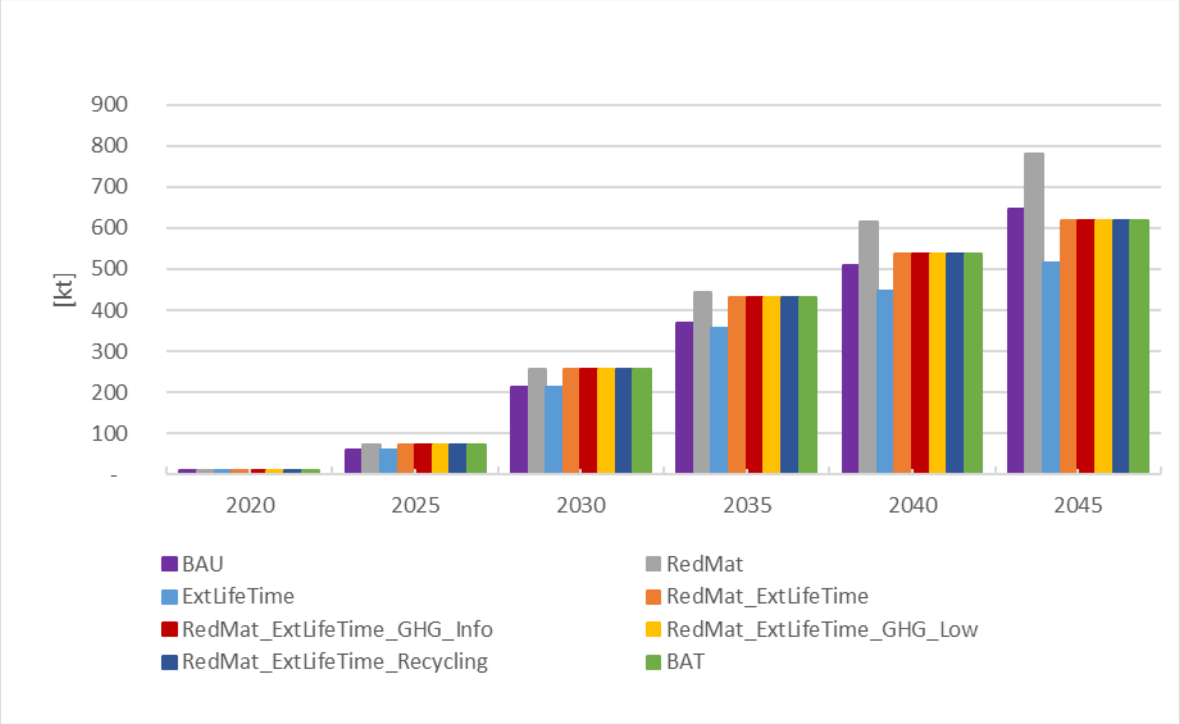

Figure 7-18: Nickel demand in kt/year for the production phase (EU-28 battery system stock)

An overview of the results, taking into account all phases of the battery systems, is provided in Figure 7-19[59].

For comparison, in 2018 global primary nickel demand was 2 293 kt mainly used in stainless steel alloys while supply was 2 193 kt[60].Clearly significant more nickel mining and/or recycling

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[58] see also Table 7-38 in Annex

[59] see also Table 7-39 in Annex

[60] Glencore (2017) report:'Nickel: State of the market November 2017', https://www.glencore.com/dam/jcr:ac289c69-acb9-48c5-8224-de4ce48c2627/2017-11-MB-Ferroalloy-conference.pdf

will be needed to satisfy this forecasted demand. In the EU the largest operational Nickel mines are located in Finland, Greece and Spain[61].

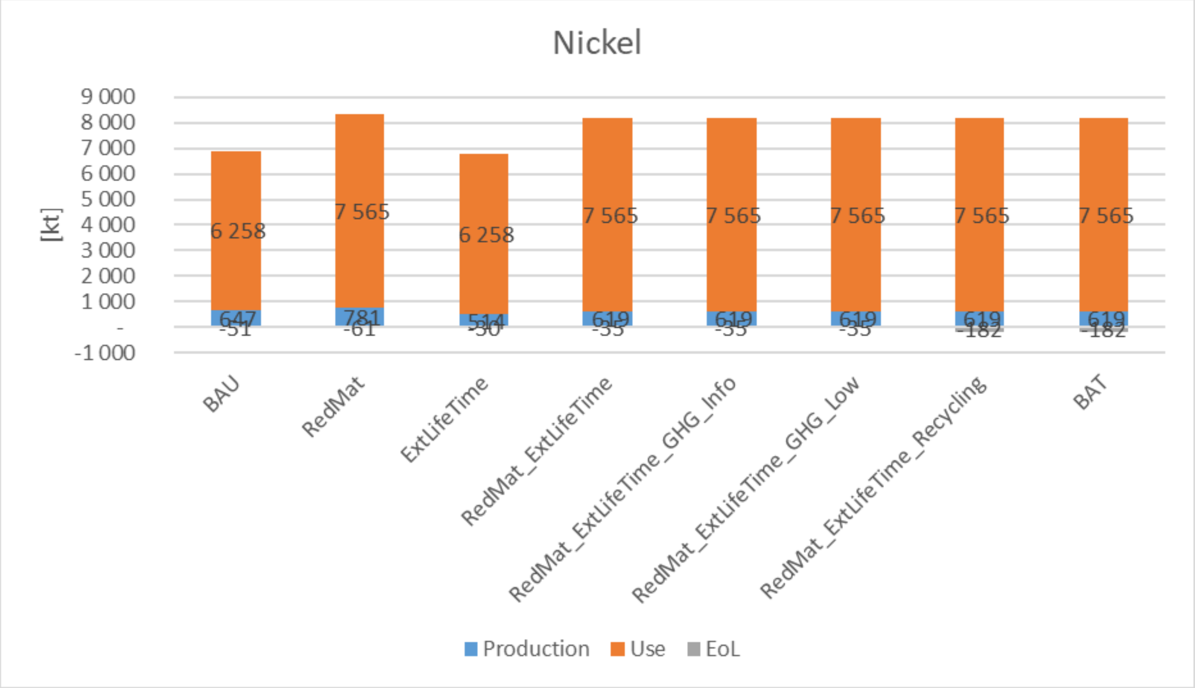

Figure 7-19: Nickel demand in kt/year for all phases (EU-28 battery system stock)

7.2.1.6. Manganese demand

Figure 7-20 and Figure 7-21 respectively illustrate the manganese demand in the production phase and all phases of the battery systems. The details of the results are shown in Table 7-40 and in Table 7-41 (see Annex).

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[61] http://www.euromines.org/mining-europe/production-mineral#Nickel

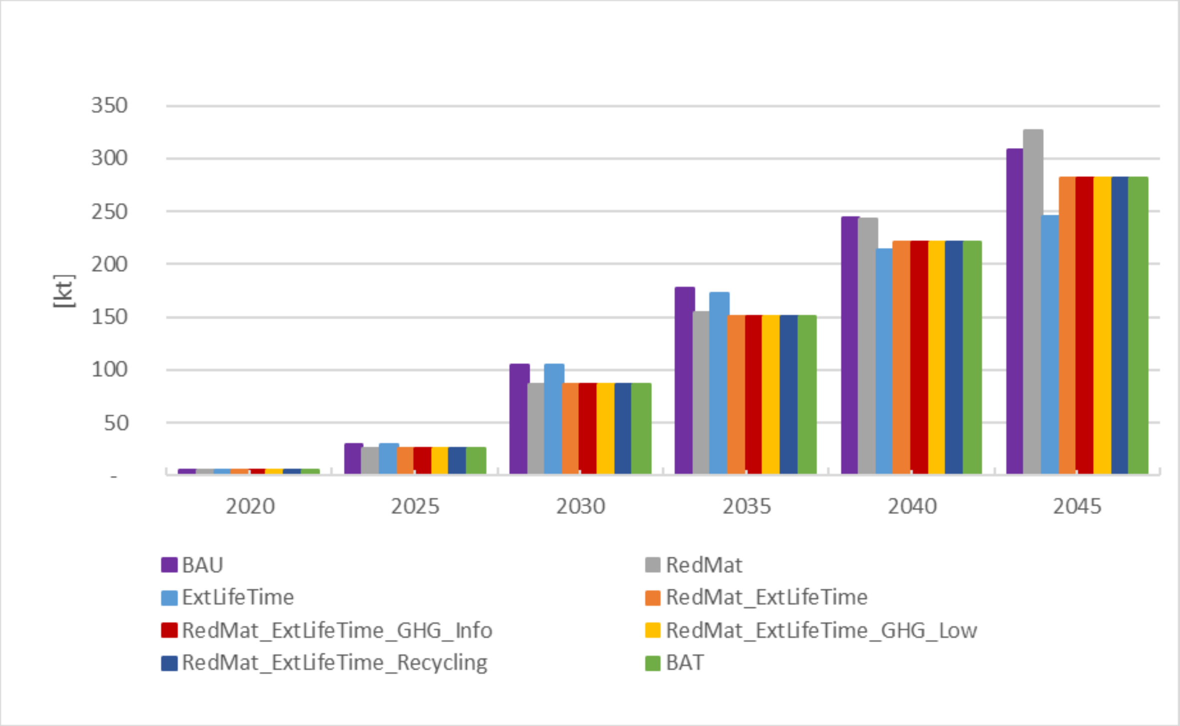

Figure 7-20: Manganese demand in kt/year for the production phase (EU-28 battery system stock)

By 2045, the ResdMat_ExtLifeTime_Recycling and BAT scenarios will reduced the total amount of Manganese by 7%, compared to BAU.

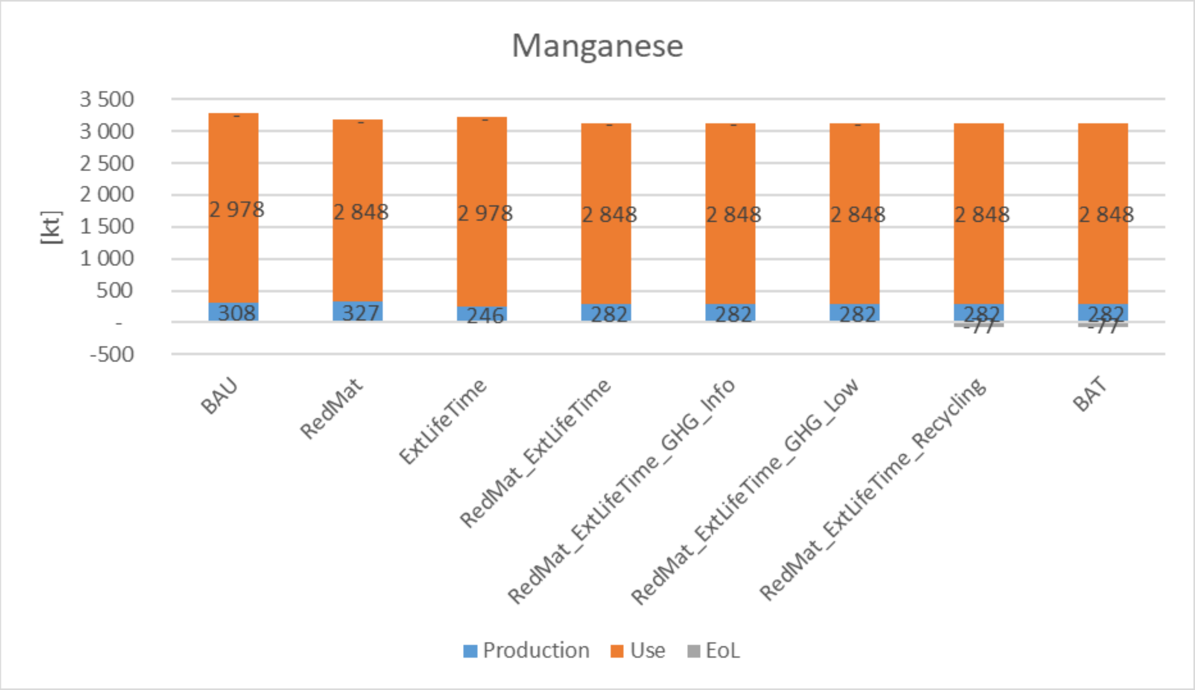

Figure 7-21: Manganese demand in kt/year for all phases in 2045 (EU-28 battery system stock)

The largest European mine for manganese is located in Bulgaria which produced 12 kT in 2016[62].

7.2.1.7. Lithium demand

As shown in Figure 7-22, the lithium demand in the production phase of the battery systems is expected to grow over the next decades, reaching 285 kt/a by 2045 in the BAU scenario. In the RedMat scenario, the demand will decrease by only 5.5% compared to the BAU scenario. However, the lithium demand is at its lowest level in the RedMat_ExtLifeTime, RedMat_ExtLifeTime_GHG_Info and RedMat_ExtLifeTime_GHG_Low scenarios, with a 23.6% decrease compared to the BAU scenario.[63]

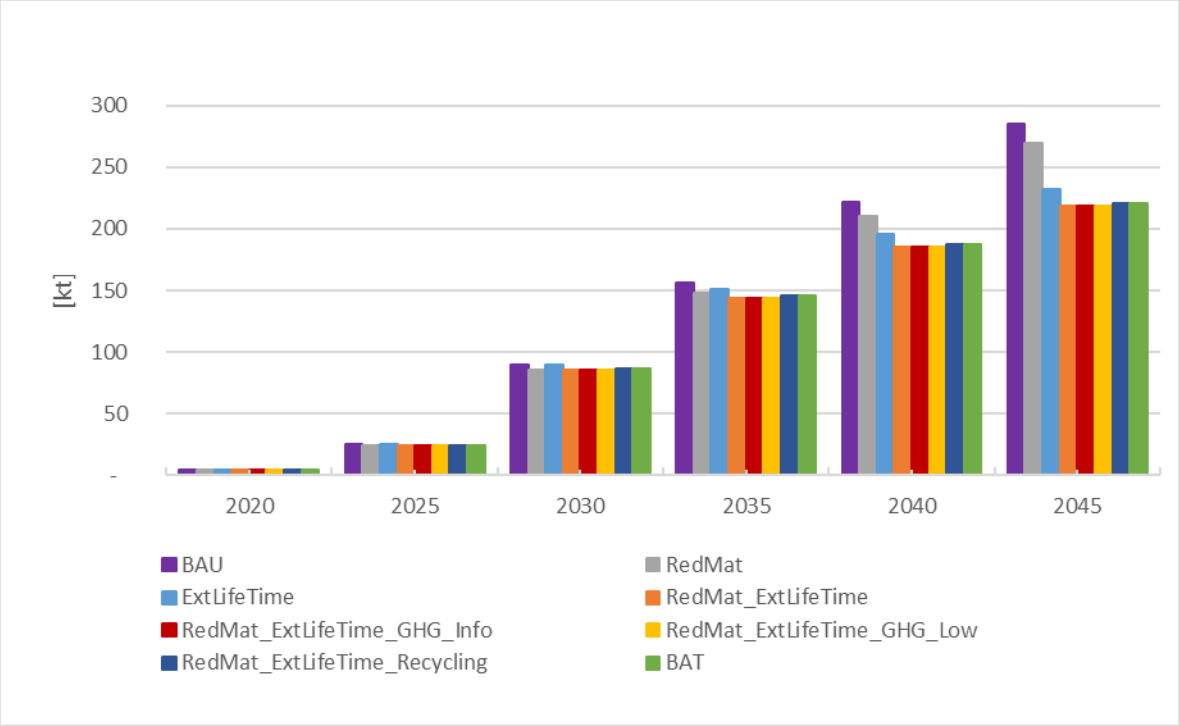

Figure 7-22: Lithium demand in kt/year for the production phase (EU-28 battery system stock)

The lithium demand has been also estimated for all phases and the results are presented in Figure 7-23.[64]

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[62] http://www.euromines.org/mining-europe/production-mineral#Manganese

[63] see also Table 7-42 in Annex

[64] see also Table 7-43 in Annex

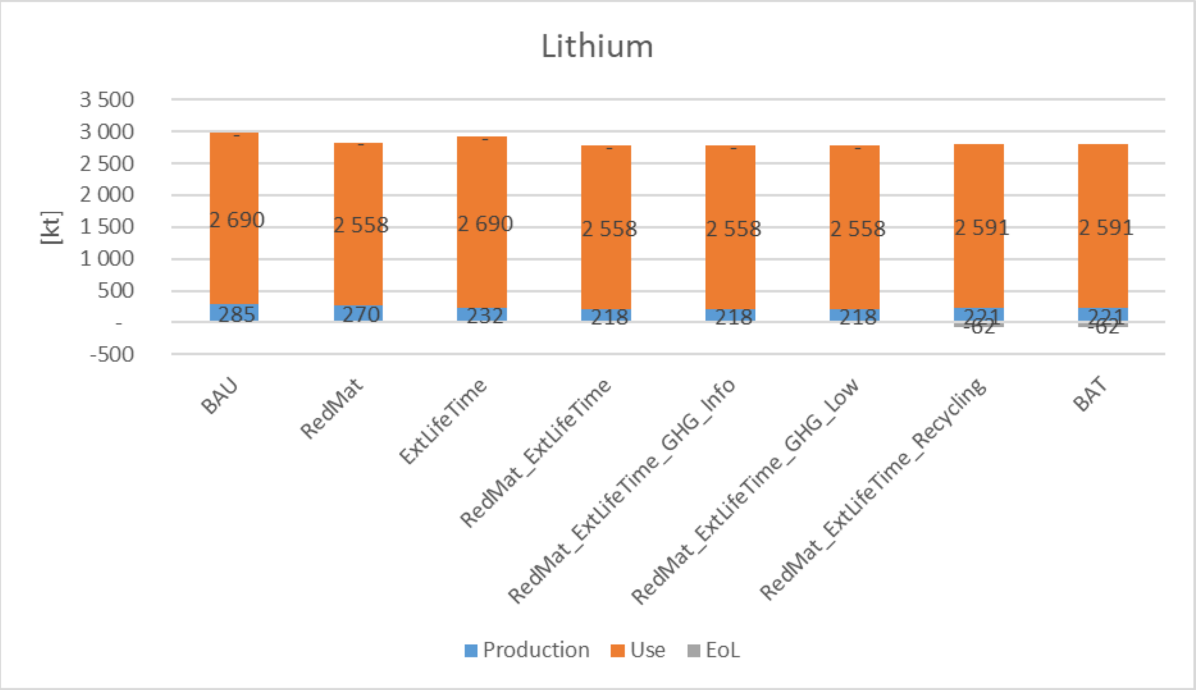

Figure 7-23: Lithium demand in kt/year for all phases in 2045 (EU-28 battery system stock)

7.2.2. Socio-economic impacts

In this section, socio-economic impacts are analysed according to the scenarios. The total expenditures include:

- the purchase costs: they are driven by the market sales and the purchase price of the battery systems.
- the running costs. In the model, only the electricity costs in the use phase were considered. They are expressed on a yearly basis until the technical lifetime of the battery system is reached.
- the EOL costs: including the replacement costs and the decommissioning costs.

The total expenditures in € bln./year are shown in Figure 7-24 and Figure 7-25. According to the figures, the expenditure for the BAU increases to 512 € bln. by 2045. The RedMat_ExtLifeTime scenarios and the BAT scenario however are expected to reduce the total expenditures by 36.2% in 2045, making them the cheapest scenarios. Furthermore, Figure 7-26, Figure 7-27 and Figure 7-28 show the details of the costs positions according to the scenarios until 2045.

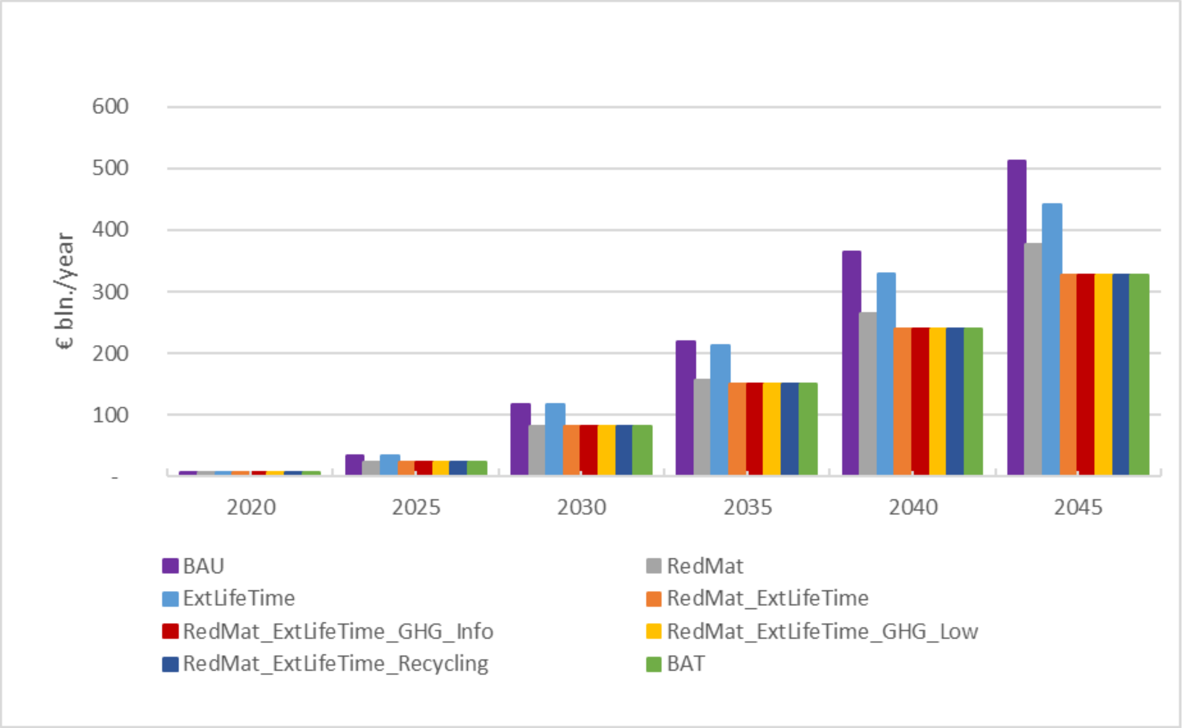

Figure 7-24: Total expenditure in € bln. /year (EU-28 battery system stock)

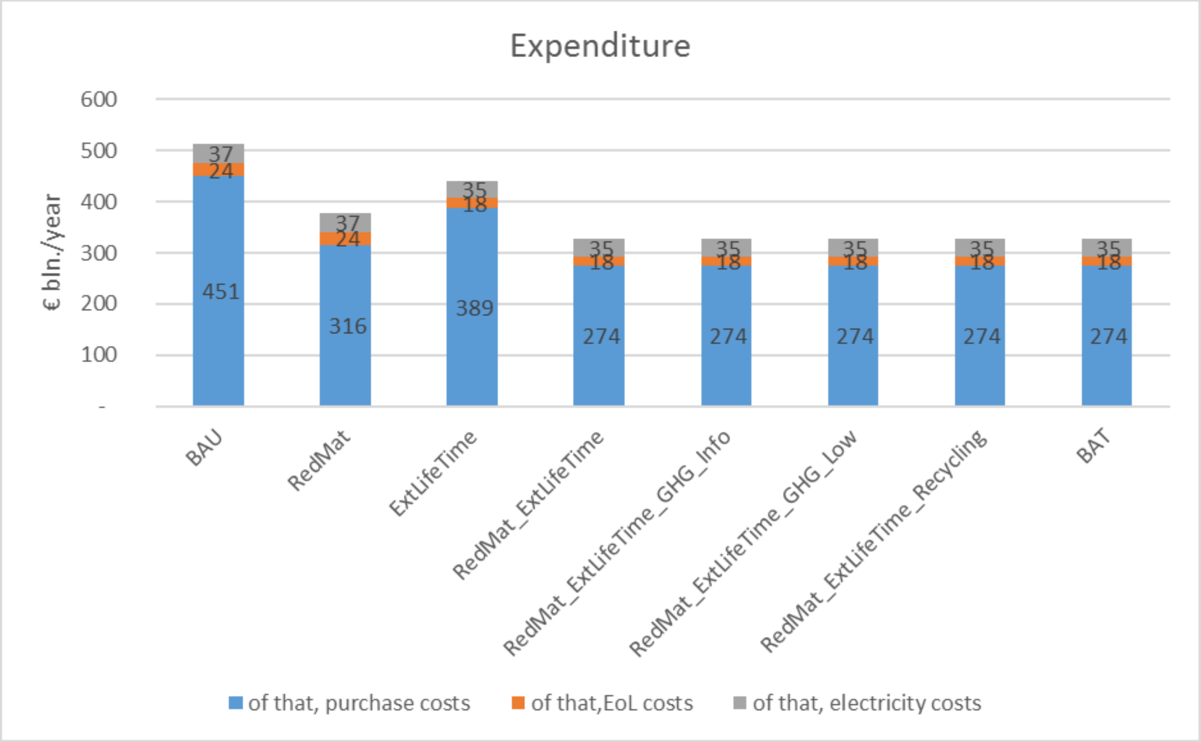

Figure 7-25: Total expenditure in € bln. /year in 2045 (EU-28 battery system stock)

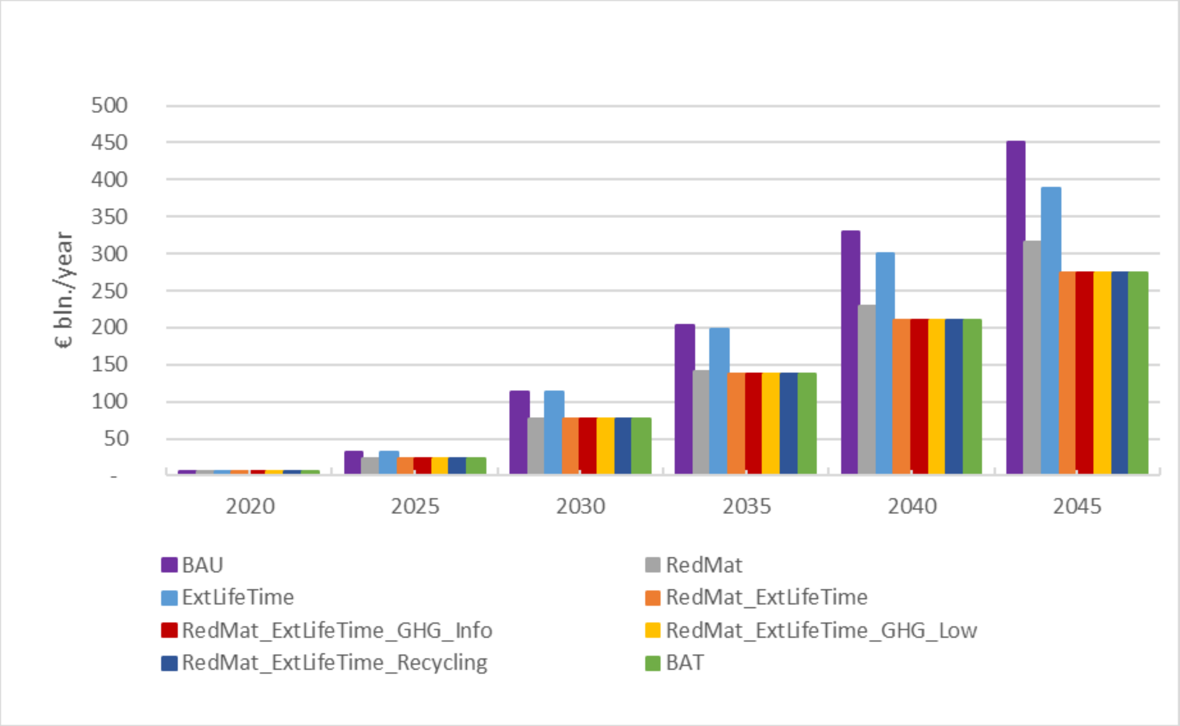

Figure 7-26: Purchase costs in € bln. /year (EU-28 battery system stock)

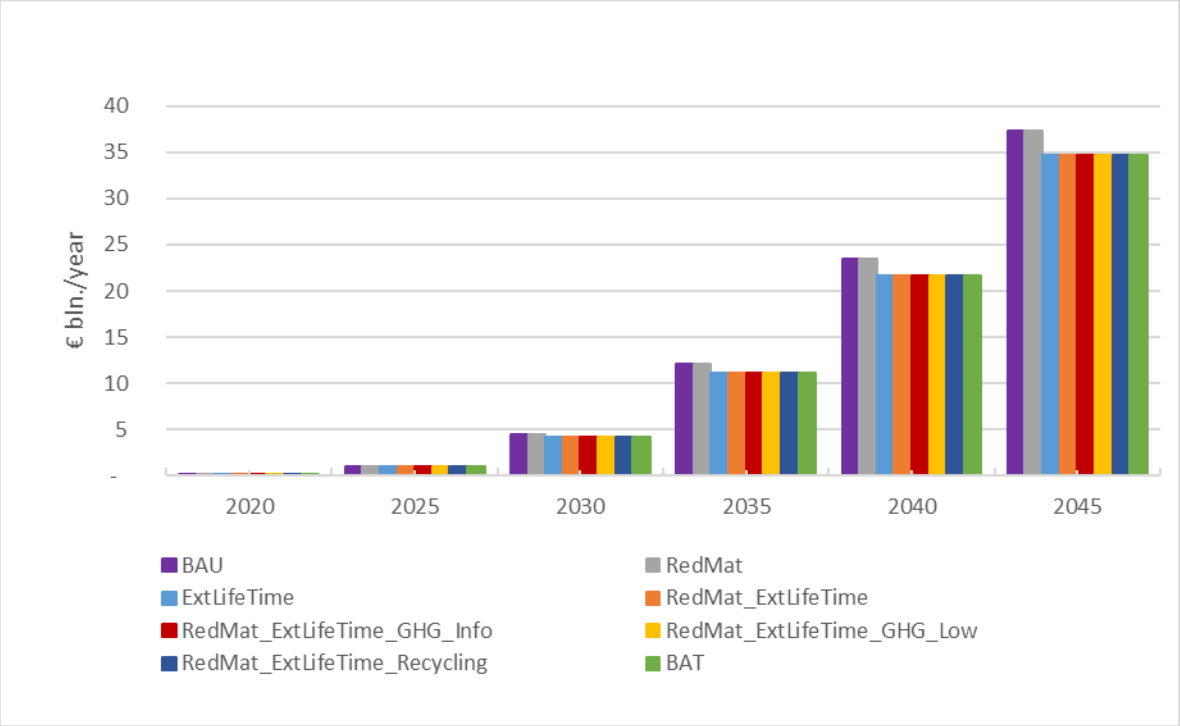

Figure 7-27: Electricity costs (use phase only) in € bln. /year (EU-28 battery system stock)

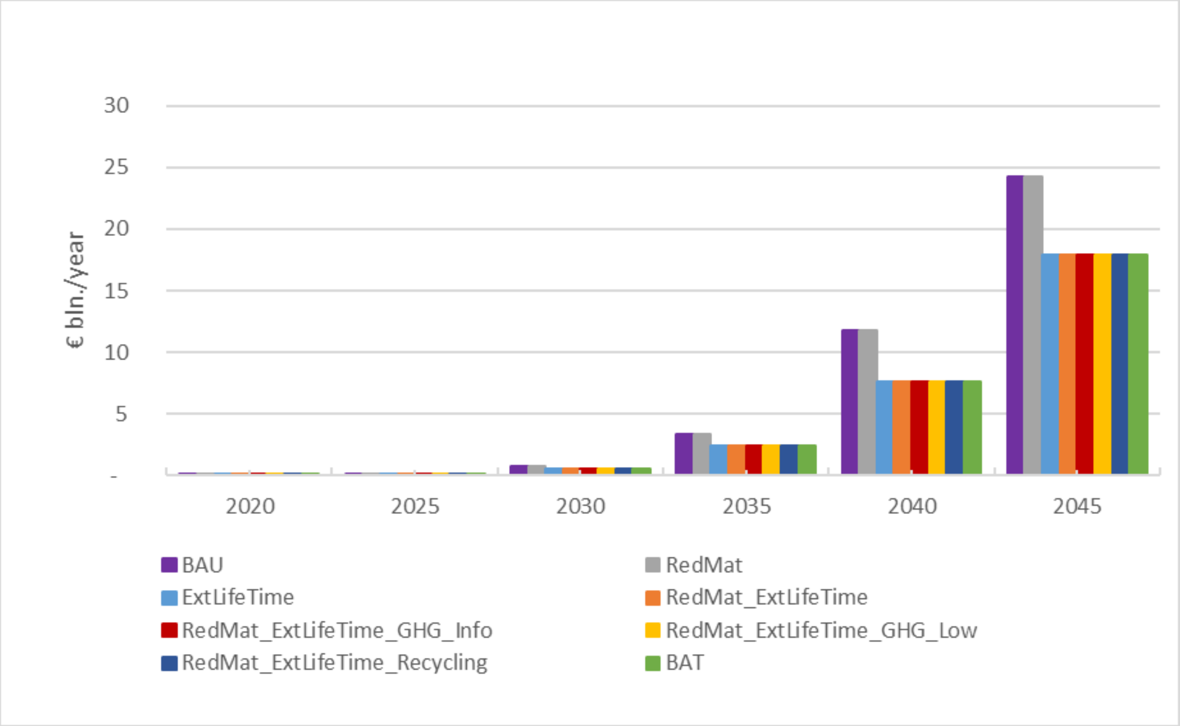

Figure 7-28: EOL costs in € bln. /year (EU-28 battery system stock)

7.2.3. Overview

A summary of the main impacts of the different scenarios is presented in Table 7-16, showing the figures for 2045.

Table 7-16: Overview of the main impacts in 2045 (EU-28 battery system stock)

			1	2	3	4	5	6	7	8
			BAU	RedMat	ExtLifeTime	RedMat_ExtLife Time	RedMat_ExtLife Time_GHG_Info	RedMat_ExtLife Time_GHG_Low	RedMat_ExtLife Time_Recycling	BAT
ENVIRONMENT										
	Electricity Consumption	[GWh]	446 616	412 233	395 234	365 498	365 498	365 498	365 498	365 498
	GHG	[MtCO2]	125	115	111	102	89	58	102	58
RESSOURCE										
	Cobalt	[kt]	1 685	942	1 690	946	946	946	925	925
	Graphite	[kt]	17 822	15 656	17 822	15 656	15 656	15 656	15 656	15 656
	Nickel	[kt]	6 208	7 504	6 229	7 529	7 529	7 529	7 383	7 383
	Manganese	[kt]	2 978	2 848	2 978	2 848	2 848	2 848	2 771	2 771
	Lithium	[kt]	2 690	2 558	2 690	2 558	2 558	2 558	2 529	2 529
CONSUMER										
EU totals	Expenditure	€ bln./year	512	378	441	327	327	327	327	327
	of that, purchase costs	€ bln./year	451	316	389	274	274	274	274	274
	of that,EoL costs	€ bln./year	24	24	18	18	18	18	18	18
	of that, electricity costs	€ bln./year	37	37	35	35	35	35	35	35
Per product sold	Sales (regulated)	000 000	57	57	51	51	51	51	51	51
	Product price	€	7 948	5 575	7 583	5 352	5 352	5 352	5 352	5 352
BUSINESS										
EU turnover	Manufacturers	€ bln./year	450.70	316.14	388.89	274.48	274.48	274.48	274.48	274.48
	Maintenance and EoL	€ bln./year	24.21	24.21	17.90	17.90	17.90	17.90	17.90	17.90
	Electricity Companies	€ bln./year	37.34	37.34	34.67	34.67	34.67	34.67	34.67	34.67
EMPLOYMENT										
Employment (jobs)	Manufacturers (direct jobs)	000	209.46	209.46	172.12	172.12	172.12	172.12	172.12	172.12
	Manufacturers (indirect jobs)	000	502.70	502.70	413.08	413.08	413.08	413.08	413.08	413.08
	TOTAL	000	712.16	712.16	585.20	585.20	585.20	585.20	585.20	585.20

7.3. Sensitivity analysis

Aim of Task 7.3:

The aim of the analysis in this section is to investigate the sensitivity of the main outcomes for changes in the main calculation parameters. The sensitivity analysis on the stock volumes (section 7.3.1) and electricity prices (section 7.3.2) is performed at scenario level.

This sensitivity analysis should also serve to compensate for weaknesses in the robustness of the reference scenarios and policy options due to uncertainties in the underlying data and assumptions.

The sensitivity analysis on the battery system service life (section 7.3.3) is done for the BAU on application level to complement the base case calculations of Task 5 and to see its effect on the life cycle impact of an application.

7.3.1. Stock volumes

In this section, the battery sales for the EU market for low and high sales scenarios are considered and the assumptions[65] are presented in Table 7-17 to Table 7-20.

Table 7-17: Forecast of battery systems stock for the EU market (low sales scenario), in capacity and in 1000' units

Stock [GWh]	2010	2015	2020	2025	2030	2035	2040	2045
BC1_PC BEV HIGH	0	1	18	146	755	2 099	3 854	5 612
BC2_PC BEV LOW	0	6	39	158	539	1 361	2 556	3 852
BC3_PC PHEV	3	5	17	60	180	404	714	1 090
BC4_Truck BEV	0	0	1	3	17	64	158	265
BC5_Truck PHEV	0	0	1	6	19	46	96	172
BC6_Residential ESS	1	4	9	14	20	30	44	61
BC7_Commercial ESS	0	1	4	12	27	50	111	253
Total mobile application	4	12	76	372	1 510	3 975	7 377	10 990
Total stationary application	1	5	12	25	47	79	155	314
Total all application	5	18	89	398	1 557	4 054	7 532	11 305
Stock [1,000 battery systems]	2010	2015	2020	2025	2030	2035	2040	2045
BC1_PC BEV HIGH	1	16	227	1 825	9 433	26 237	48 180	70 146
BC2_PC BEV LOW	7	143	974	3 946	13 478	34 030	63 896	96 305
BC3_PC PHEV	250	417	1 439	4 981	15 040	33 686	59 460	90 806
BC4_Truck BEV	7	7	32	105	572	2 145	5 258	8 827
BC5_Truck PHEV	8	8	46	284	928	2 307	4 783	8 604
BC6_Residential ESS	108	435	886	1 383	2 014	2 987	4 356	6 129
BC7_Commercial ESS	30	112	361	1 159	2 708	4 953	11 137	25 297
Total mobile application	272	591	2 719	11 141	39 451	98 406	181 577	274 688
Total stationary application	138	547	1 247	2 543	4 722	7 941	15 493	31 427
Total all application	411	1 137	3 966	13 684	44 173	106 346	197 069	306 115

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[65] Based on the stock scenarios (low and high) elaborated in Task 2

Table 7-18: Forecast of battery systems sales for the EU market (low sales scenario), in capacity and in 1000' units

Sales [GWh]	2010	2015	2020	2025	2030	2035	2040	2045
BC1_PC BEV HIGH	0	1	7	47	184	326	431	549
BC2_PC BEV LOW	0	2	12	39	112	213	319	407
BC3_PC PHEV	0	1	4	14	36	63	99	136
BC4_Truck BEV	0	0	0	1	4	16	30	41
BC5_Truck PHEV	0	0	0	2	5	12	24	42
BC6_Residential ESS	0	1	1	1	2	3	4	6
BC7_Commercial ESS	0	0	1	2	3	7	19	40
Total mobile application	0	4	24	103	342	630	902	1 176
Total stationary application	0	1	2	4	5	10	23	46
Total all application	0	5	26	106	347	641	925	1 222
Sales [1,000 battery systems]	2010	2015	2020	2025	2030	2035	2040	2045
BC1_PC BEV HIGH	0	8	87	591	2 306	4 073	5 388	6 865
BC2_PC BEV LOW	1	52	293	963	2 809	5 325	7 969	10 169
BC3_PC PHEV	23	90	369	1 168	2 981	5 284	8 210	11 367
BC4_Truck BEV	1	1	16	35	129	520	986	1 383
BC5_Truck PHEV	2	2	24	95	272	624	1 225	2 089
BC6_Residential ESS	6	79	113	115	221	322	416	573
BC7_Commercial ESS	2	25	74	238	303	698	1 884	4 050
Total mobile application	26	153	790	2 852	8 498	15 827	23 779	31 872
Total stationary application	8	104	187	352	524	1 019	2 300	4 622
Total all application	34	257	976	3 204	9 022	16 846	26 078	36 494

Table 7-19: Forecast of battery stock for the EU market (high sales scenario), in capacity and in 1000' units

Stock [GWh]	2010	2015	2020	2025	2030	2035	2040	2045
BC1_PC BEV HIGH	0	1	18	200	1 237	3 421	6 112	8 688
BC2_PC BEV LOW	0	6	39	255	1 096	2 796	4 890	6 801
BC3_PC PHEV	3	5	17	79	262	472	592	611
BC4_Truck BEV	0	0	1	13	73	234	445	621
BC5_Truck PHEV	0	0	1	8	41	138	318	529
BC6_Residential ESS	1	4	9	17	33	59	101	165
BC7_Commercial ESS	0	1	4	12	54	232	896	2 395
Total mobile application	4	12	76	556	2 710	7 060	12 357	17 250
Total stationary application	1	5	12	29	87	291	997	2 560
Total all application	5	18	89	585	2 796	7 351	13 354	19 810
Stock [1,000 battery systems]	2010	2015	2020	2025	2030	2035	2040	2045
BC1_PC BEV HIGH	1	16	227	2 495	15 468	42 768	76 404	108 598
BC2_PC BEV LOW	7	143	974	6 381	27 401	69 888	122 245	170 037
BC3_PC PHEV	250	417	1 439	6 609	21 867	39 343	49 304	50 941
BC4_Truck BEV	7	7	32	430	2 417	7 785	14 838	20 695
BC5_Truck PHEV	8	8	46	424	2 055	6 883	15 898	26 437
BC6_Residential ESS	108	435	886	1 749	3 274	5 921	10 101	16 503
BC7_Commercial ESS	30	112	361	1 167	5 382	23 185	89 573	239 473
Total mobile application	272	591	2 719	16 340	69 209	166 666	278 689	376 709
Total stationary application	138	547	1 247	2 916	8 656	29 105	99 674	255 975
Total all application	411	1 137	3 966	19 255	77 865	195 772	378 363	632 684

Table 7-20: Forecast battery systems sales for the EU market (high sales scenario), in capacity and in 1000' units

Sales [GWh]	2010	2015	2020	2025	2030	2035	2040	2045
BC1_PC BEV HIGH	0	1	7	73	316	507	658	841
BC2_PC BEV LOW	0	2	12	75	247	423	554	665
BC3_PC PHEV	0	1	4	21	50	51	62	46
BC4_Truck BEV	0	0	0	4	22	48	74	86
BC5_Truck PHEV	0	0	0	3	13	40	81	121
BC6_Residential ESS	0	1	1	2	5	7	12	19
BC7_Commercial ESS	0	0	1	3	14	57	211	351
Total mobile application	0	4	24	175	648	1 068	1 429	1 760
Total stationary application	0	1	2	5	19	64	223	370
Total all application	0	5	26	180	667	1 132	1 652	2 130
Sales [1,000 battery systems]	2010	2015	2020	2025	2030	2035	2040	2045
BC1_PC BEV HIGH	0	8	87	907	3 953	6 338	8 229	10 512
BC2_PC BEV LOW	1	52	293	1 873	6 164	10 576	13 855	16 622
BC3_PC PHEV	23	90	369	1 722	4 140	4 216	5 163	3 870
BC4_Truck BEV	1	1	16	136	730	1 587	2 458	2 877
BC5_Truck PHEV	2	2	24	154	666	1 981	4 038	6 062
BC6_Residential ESS	6	79	113	215	455	732	1 156	1 872
BC7_Commercial ESS	2	25	74	285	1 445	5 709	21 143	35 102
Total mobile application	26	153	790	4 791	15 654	24 699	33 744	39 943
Total stationary application	8	104	187	500	1 901	6 441	22 298	36 973
Total all application	34	257	976	5 291	17 554	31 140	56 042	76 917

Table 7-21 and Table 7-22 respectively present an overview of the main impacts of the low and high sales scenarios for battery systems in 2045.

Table 7-21: Overview of the main impacts in 2045 (EU-28 battery system stock) – low sales scenario

			1	2	3	4	5	6	7	8
			BAU	RedMat	ExtLifeTime	RedMat_ExtLife Time	RedMat_ExtLife Time_GHG_Info	RedMat_ExtLife Time_GHG_Low	RedMat_ExtLife Time_Recycling	BAT
ENVIRONMENT										
	Electricity Consumption	[GWh]	308 274	284 317	271 436	250 779	250 779	250 779	250 779	250 779
	GHG	[MtCO2]	86	80	76	70	61	39	70	39
RESSOURCE										
	Cobalt	[kt]	1 286	728	1 290	730	730	730	715	715
	Graphite	[kt]	12 773	11 311	12 773	11 311	11 311	11 311	11 311	11 311
	Nickel	[kt]	4 697	5 673	4 713	5 692	5 692	5 692	5 591	5 591
	Manganese	[kt]	2 318	1 953	2 318	1 953	1 953	1 953	1 899	1 899
	Lithium	[kt]	1 998	1 897	1 998	1 897	1 897	1 897	1 878	1 878
CONSUMER										
EU totals	Expenditure	€ bln./year	325	238	274	202	202	202	202	202
	of that, purchase costs	€ bln./year	282	195	238	165	165	165	165	165
	of that,EoL costs	€ bln./year	18	18	14	14	14	14	14	14
	of that, electricity costs	€ bln./year	25	25	23	23	23	23	23	23
Per product sold	Sales (regulated)	000 000	36	36	33	33	33	33	33	33
	Product price	€	7 715	5 344	7 263	5 056	5 056	5 056	5 056	5 056
BUSINESS										
EU turnover	Manufacturers	€ bln./year	281.56	195.02	237.67	165.43	165.43	165.43	165.43	165.43
	Maintenance and EoL	€ bln./year	18.04	18.04	13.52	13.52	13.52	13.52	13.52	13.52
	Electricity Companies	€ bln./year	24.99	24.99	23.03	23.03	23.03	23.03	23.03	23.03
EMPLOYMENT										
Employment (jobs)	Manufacturers (direct jobs)	000	152.73	152.73	126.21	126.21	126.21	126.21	126.21	126.21
	Manufacturers (indirect jobs)	000	366.54	366.54	302.90	302.90	302.90	302.90	302.90	302.90
	TOTAL	000	519.27	519.27	429.10	429.10	429.10	429.10	429.10	429.10

Table 7-22: Overview of the main impacts in 2045 (EU-28 battery system stock) – high sales scenario

			1	2	3	4	5	6	7	8
			BAU	RedMat	ExtLifeTime	RedMat_ExtLife Time	RedMat_ExtLife Time_GHG_Info	RedMat_ExtLife Time_GHG_Low	RedMat_ExtLife Time_Recycling	BAT
ENVIRONMENT										
	Electricity Consumption	[GWh]	584 957	540 149	519 031	480 217	480 217	480 217	480 217	480 217
	GHG	[MtCO2]	164	151	145	134	118	78	134	78
RESSOURCE										
	Cobalt	[kt]	2 083	1 157	2 090	1 161	1 161	1 161	1 134	1 134
	Graphite	[kt]	22 871	20 001	22 871	20 001	20 001	20 001	20 001	20 001
	Nickel	[kt]	7 718	9 334	7 744	9 366	9 366	9 366	9 174	9 174
	Manganese	[kt]	3 638	3 743	3 638	3 743	3 743	3 743	3 644	3 644
	Lithium	[kt]	3 382	3 218	3 382	3 218	3 218	3 218	3 180	3 180
CONSUMER										
EU totals	Expenditure	€ bln./year	700	517	609	452	452	452	452	452
	of that, purchase costs	€ bln./year	620	437	540	384	384	384	384	384
	of that,EoL costs	€ bln./year	30	30	22	22	22	22	22	22
	of that, electricity costs	€ bln./year	50	50	46	46	46	46	46	46
Per product sold	Sales (regulated)	000 000	77	77	70	70	70	70	70	70
	Product price	€	8 059	5 685	7 733	5 491	5 491	5 491	5 491	5 491
BUSINESS										
EU turnover	Manufacturers	€ bln./year	619.83	437.25	540.10	383.53	383.53	383.53	383.53	383.53
	Maintenance and EoL	€ bln./year	30.38	30.38	22.28	22.28	22.28	22.28	22.28	22.28
	Electricity Companies	€ bln./year	49.69	49.69	46.31	46.31	46.31	46.31	46.31	46.31
EMPLOYMENT										
Employment (jobs)	Manufacturers (direct jobs)	000	266.19	266.19	218.03	218.03	218.03	218.03	218.03	218.03
	Manufacturers (indirect jobs)	000	638.86	638.86	523.26	523.26	523.26	523.26	523.26	523.26
	TOTAL	000	905.05	905.05	741.29	741.29	741.29	741.29	741.29	741.29

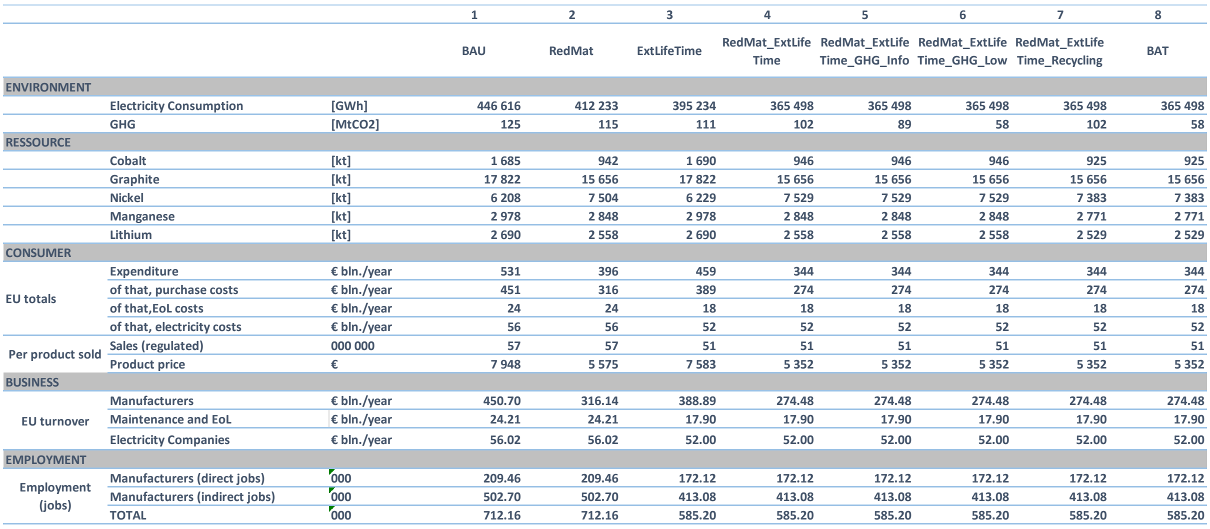
7.3.2. Electricity prices

In this section, electricity prices for the use phase are based on the low and high assumptions of Table 7-9. Using those assumptions, the scenarios are compared and presented in Table 7-23 (low electricity price) and Table 7-24 (high electricity price). Regarding the sales and stock volumes, the medium scenario was considered.

Table 7-23: Overview of the main impacts in 2045 (EU-28 battery system stock) **–** *low electricity price scenario*

			1	2	3	4	5	6	7	8
			BAU	RedMat	ExtLifeTime	RedMat_ExtLife Time	RedMat_ExtLife Time_GHG_Info	RedMat_ExtLife Time_GHG_Low	RedMat_ExtLife Time_Recycling	BAT
ENVIRONMENT										
	Electricity Consumption	[GWh]	446 616	412 233	395 234	365 498	365 498	365 498	365 498	365 498
	GHG	[MtCO2]	125	115	111	102	89	58	102	58
RESSOURCE										
	Cobalt	[kt]	1 685	942	1 690	946	946	946	925	925
	Graphite	[kt]	17 822	15 656	17 822	15 656	15 656	15 656	15 656	15 656
	Nickel	[kt]	6 208	7 504	6 229	7 529	7 529	7 529	7 383	7 383
	Manganese	[kt]	2 978	2 848	2 978	2 848	2 848	2 848	2 771	2 771
	Lithium	[kt]	2 690	2 558	2 690	2 558	2 558	2 558	2 529	2 529
CONSUMER										
EU totals	Expenditure	€ bln./year	494	359	424	310	310	310	310	310
	of that, purchase costs	€ bln./year	451	316	389	274	274	274	274	274
	of that,EoL costs	€ bln./year	24	24	18	18	18	18	18	18
	of that, electricity costs	€ bln./year	19	19	17	17	17	17	17	17
Per product sold	Sales (regulated)	000 000	57	57	51	51	51	51	51	51
	Product price	€	7 948	5 575	7 583	5 352	5 352	5 352	5 352	5 352
BUSINESS										
EU turnover	Manufacturers	€ bln./year	450.70	316.14	388.89	274.48	274.48	274.48	274.48	274.48
	Maintenance and EoL	€ bln./year	24.21	24.21	17.90	17.90	17.90	17.90	17.90	17.90
	Electricity Companies	€ bln./year	18.67	18.67	17.33	17.33	17.33	17.33	17.33	17.33
EMPLOYMENT										
Employment (jobs)	Manufacturers (direct jobs)	000	209.46	209.46	172.12	172.12	172.12	172.12	172.12	172.12
	Manufacturers (indirect jobs)	000	502.70	502.70	413.08	413.08	413.08	413.08	413.08	413.08
	TOTAL	000	712.16	712.16	585.20	585.20	585.20	585.20	585.20	585.20

Table 7-24: Overview of the main impacts in 2045 (EU-28 battery system stock) – high electricity price scenario



			1	2	3	4	5	6	7	8
			BAU	RedMat	ExtLifeTime	RedMat_ExtLife Time	RedMat_ExtLife Time_GHG_Info	RedMat_ExtLife Time_GHG_Low	RedMat_ExtLife Time_Recycling	BAT
ENVIRONMENT										
	Electricity Consumption	[GWh]	446 616	412 233	395 234	365 498	365 498	365 498	365 498	365 498
	GHG	[MtCO2]	125	115	111	102	89	58	102	58
RESSOURCE										
	Cobalt	[kt]	1 685	942	1 690	946	946	946	925	925
	Graphite	[kt]	17 822	15 656	17 822	15 656	15 656	15 656	15 656	15 656
	Nickel	[kt]	6 208	7 504	6 229	7 529	7 529	7 529	7 383	7 383
	Manganese	[kt]	2 978	2 848	2 978	2 848	2 848	2 848	2 771	2 771
	Lithium	[kt]	2 690	2 558	2 690	2 558	2 558	2 558	2 529	2 529
CONSUMER										
EU totals	Expenditure	€ bln./year	531	396	459	344	344	344	344	344
	of that, purchase costs	€ bln./year	451	316	389	274	274	274	274	274
	of that,EoL costs	€ bln./year	24	24	18	18	18	18	18	18
	of that, electricity costs	€ bln./year	56	56	52	52	52	52	52	52
Per product sold	Sales (regulated)	000 000	57	57	51	51	51	51	51	51
	Product price	€	7 948	5 575	7 583	5 352	5 352	5 352	5 352	5 352
BUSINESS										
EU turnover	Manufacturers	€ bln./year	450.70	316.14	388.89	274.48	274.48	274.48	274.48	274.48
	Maintenance and EoL	€ bln./year	24.21	24.21	17.90	17.90	17.90	17.90	17.90	17.90
	Electricity Companies	€ bln./year	56.02	56.02	52.00	52.00	52.00	52.00	52.00	52.00
EMPLOYMENT										
Employment (jobs)	Manufacturers (direct jobs)	000	209.46	209.46	172.12	172.12	172.12	172.12	172.12	172.12
	Manufacturers (indirect jobs)	000	502.70	502.70	413.08	413.08	413.08	413.08	413.08	413.08
	TOTAL	000	712.16	712.16	585.20	585.20	585.20	585.20	585.20	585.20

7.3.3. Service life of battery

In this section, the service lifetime of the battery (Tbat) [yr] is adjusted with -20 % and +20 % to represent the situation of a shorter and a longer battery lifetime. The formula that is used to calculate Tbat (see section 5.1.2.4 of Task 5 report) is an early approximation open to a significant margin of error depending on the specific Li-ion battery design. The parameters used to calculate Tbat were also under discussion by the stakeholders during the course of this preparatory study. Therefore, this sensitivity analysis considers Tbat as the variable parameter and not the underlying parameters nor the formula to show the effect of a shorter or longer battery lifetime, which will have an impact on the number of replacement battery application systems during the economic lifetime of the application.

Table 7-25: Overview of assumed Tbat

	BC1 PC BEV HIGH	BC2 PC BEV LOW	BC3 PC PHEV	BC4 Truck BEV	BC5 Truck PHEV	BC6 Resid. ESS	BC7 Comm. ESS
Economic lifetime of application (Tapp) [yr]	13	14	13	14	12	20	20
Service life of battery (Tbat) [yr] - BAU	14.40	13.43	10.67	8.04	5.33	17.02	17.02
Service life of battery (Tbat - 20 %) [yr] - BAU-20%	11.52	10.75	8.53	6.43	4.26	13.62	13.62
Service life of battery (Tbat + 20 %) [yr] - BAU+20%	17.28	16.12	12.80	9.65	6.40	20.43	20.43

Table 7-26: Overview of the effect of a shorter or longer battery service lifetime on GWP, functional EEI and capacity EEI

	GWP [kg CO2 eq/FU (kWh)]				GWP [kg CO2 eq/cap. (kWh)]	GWP [kg CO2 eq/kg product]	functional EEI [%] *FU [MJ]/GER [MJ]*	capacity EEI [ratio] *GER [MJ]/capacity [MJ]*
Base case	Prod. + distr.	Use	EOL	TOTAL	Prod. + distr.	Prod. + distr.	Prod. + distr.	Prod. + distr.
Business As Usual (Task 5)								
1 PC BEV-HIGH	0.197	0.094	-0.024	0.268	108	14.164	93.32	585
2 PC BEV-LOW	0.292	0.095	-0.036	0.351	216	14.171	63.15	1 171
3 PC PHEV	0.179	0.094	-0.026	0.247	293	13.957	98.84	1 657
4 Truck BEV	0.088	0.073	-0.011	0.149	2 750	13.442	205.04	15 295
5 Truck PHEV	0.079	0.074	-0.011	0.142	3 514	13.942	223.99	19 876
6 res. ESS	0.077	0.053	-0.010	0.121	309	12.089	224.71	1 780
7 comm. ESS	0.077	0.053	-0.010	0.121	927 761	12.089	224.71	5 340 154
Sensitivity analysis - shorter lifetime (Tbat -20%)								
1 PC BEV-HIGH	0.395	0.094	-0.048	0.441	215	14.164	46.66	1 170
2 PC BEV-LOW	0.292	0.095	-0.036	0.351	216	14.171	63.15	1 171
3 PC PHEV	0.179	0.094	-0.026	0.247	293	13.957	98.84	1 657
4 Truck BEV	0.132	0.073	-0.017	0.188	4 126	13.442	136.69	22 942
5 Truck PHEV	0.079	0.074	-0.011	0.142	3 514	13.942	223.99	19 876
6 res. ESS	0.077	0.053	-0.010	0.121	309	12.089	224.71	1 780
7 comm. ESS	0.077	0.053	-0.010	0.121	927 761	12.089	224.71	5 340 154
Sensitivity analysis - longer lifetime (Tbat +20%)								
1 PC BEV-HIGH	0.197	0.094	-0.024	0.268	108	14.164	93.32	585
2 PC BEV-LOW	0.146	0.095	-0.018	0.223	108	14.171	126.30	585
3 PC PHEV	0.179	0.094	-0.026	0.247	293	13.957	98.84	1 657
4 Truck BEV	0.088	0.073	-0.011	0.149	2 750	13.442	205.04	15 295
5 Truck PHEV	0.053	0.074	-0.008	0.119	2 343	13.942	335.99	13 251
6 res. ESS	0.039	0.053	-0.005	0.087	155	12.089	449.43	890
7 comm. ESS	0.039	0.053	-0.005	0.087	463 881	12.089	449.43	2 670 077

Based on the table above, we see that:

- Tbat of -20% or +20% has no effect on BC3, as with all three Tbat the same number of replacements during Tapp (i.e 1 replacement) is still needed. However it can be questioned whether in case of a Tbat of + 20% the replacement will still occur in practice seeing the small differences with Tapp.For BC1 and B4 a shorter battery lifetime would have a negative effect, as an additional replacement would be needed in comparison with the BAU Tbat. A longer Tbat has no effect on BC1 and B4.
- For BC2, BC5, BC6 and B7 a longer Tbat would a positive effect, as a replacement less would be needed in comparison with the BAU Tbat. A shorter Tbat gives no difference for the four base cases compared to BAU.

ANNEX A Battery requirements covered in current standards

Table 7-27: Battery requirements covered in current standards for the discerned base cases. Also industrial batteries are added for information.

Base case	Level	Reference	Refined application		Capacity	Energy	Power	Energy efficiency	Resistance	Cycle life test	Calendar life test	Auxiliary power need	Cooling & heating need	**Conclusion**
BC1 PC BEV high &	Cell	IEC 62660-1: 2010	Cells for the propulsion of BEV		x	x	x	x	x	x				Many tests covered
		DOE-INL/EXT-15-34184(2015)	U.S. DOE Battery Test Manual for EV		x	x	x		x	x	x			Many tests covered, including Calendar life
& BC2 PC BEV low	Module	DOE-INL/EXT-15-34184(2015)	U.S. DOE Battery Test Manual for EV		x	x	x		x	x	x			Many tests covered, including Calendar life
		SAE J1798:2008	Performance Rating of EV Battery Modules		x	x	x		x					Limited number of tests
	Pack	ISO 12405-4: 2018	BEV& PHEV packs and system	{a}	x	x	x	x	x					Parameters covered, not ageing tests
		DOE-INL/EXT-15-34184(2015)	U.S. DOE Battery Test Manual for EV		x	x	x		x	x	x			Many tests covered, including Calendar life
	Battery system	ISO 12405-4: 2018	BEV& PHEV packs and system	{b}	x	x	x	x	x	x {c}				Many tests covered
		DOE-INL/EXT-15-34184(2015)	U.S. DOE Battery Test Manual for EV		x	x	x		x	x	x			Many tests covered, including Calendar life
	Batt.appl.system													
BC3 PC PHEV	Cell	DOE-INL/EXT-07-12536 (2008)	Battery test manual for PHEV				x	x	x	x	x			Few parameters covered, but calendar life included in ageing test
	Module	DOE-INL/EXT-07-12536 (2008)	Battery test manual for PHEV				x	x	x	x	x			Few parameters covered, but calendar life included in ageing test
	Pack	ISO 12405-4: 2018	BEV& PHEV packs and system	{a}	x	x	x	x	x					Parameters covered, not ageing tests
		DOE-INL/EXT-07-12536 (2008)	Battery test manual for PHEV				x	x	x	x	x			Few parameters covered, but calendar life included in ageing test
	Battery system	ISO 12405-4: 2018	BEV& PHEV packs and system	{b}	x	x	x	x	x	x {c}				Many tests covered
		DOE-INL/EXT-07-12536 (2008)	Battery test manual for PHEV				x	x	x	x	x			Few parameters covered, but calendar life included in ageing test
	Batt.appl.system													
BC4 Truck BEV &	Cell													
& BC5 Truck PHEV	Module													
	Pack													
	Battery system													
	Batt.appl.system													
BC6 Residential ESS	Cell													
	Module													
	Pack													
	Battery system	IEC 61427-2	PV energy storage / time shift	{d}				x		x {e}				Limited use: cycle life only
	Batt.appl.system													
BC7 Grid ESS	Cell													
	Module													
	Pack													
	Battery system	IEC 61427-2	Frequency regulation service	{d}				x		x {e}				Limited use: cycle life only
			Load-following service	„				x		x {e}				Limited use: cycle life only
			Peak-power shaving service	„				x		x {e}				Limited use: cycle life only
	Batt.appl.system	IEC 62933-2-1	All grid-connected services	{f}		x	x	x		x {g}		x		Few tests covered
Industrial battery	Cell	IEC 62620	Energy (E; C/2)		x	x	x		x	x	x {h}			Many tests covered
			Medium rate discharge (M; <3.5C)		x	x	x		x	x	x {h}			„
			High rate discharge (H; >3.5C)		x	x	x		x	x	x {h}			„
	Module	„	„		„	„	„			„	„			„
	Pack	„	„		„	„	„			„	„			„
	Battery system	„	„		„	„	„			„	„			„
	Batt.appl.system													

{a} The standard discerns cells, packs and system. No module level. The pack has cell electronics but no BMS (called BCU).
{b} System included electronics like contacter and BMS, but also cooling device. The cooling device is not defined. Power electronics is excluded.
{c} Test profile is given but conditions like SOC window and test power are mainly left to the battery manufacturer. Only at system level with cooling applied.
{d} Includes battery support system such as cooling devices. Power electronics is excluded.
{e} Powers and periods are defined. Manufacturer can spread the power over a number of cells, modules or packs, to be defined by him.
{f} The services are divided in short duration (<1h), long duration (>1h; typically 24h) and back-up power. For the test topics in this table the test descriptions are identical.
{g} No test cycles are given in the standard. They are left to agreement between supplier and user. The manufacturer must show representative degradation data.
{h} Applicable for standby applications only.

ANNEX B Details of the scenarios

Table 7-28: Electricity consumption in GWh/year for the production phase (EU-28 battery system stock)

Electricity Consumption, in [GWh]

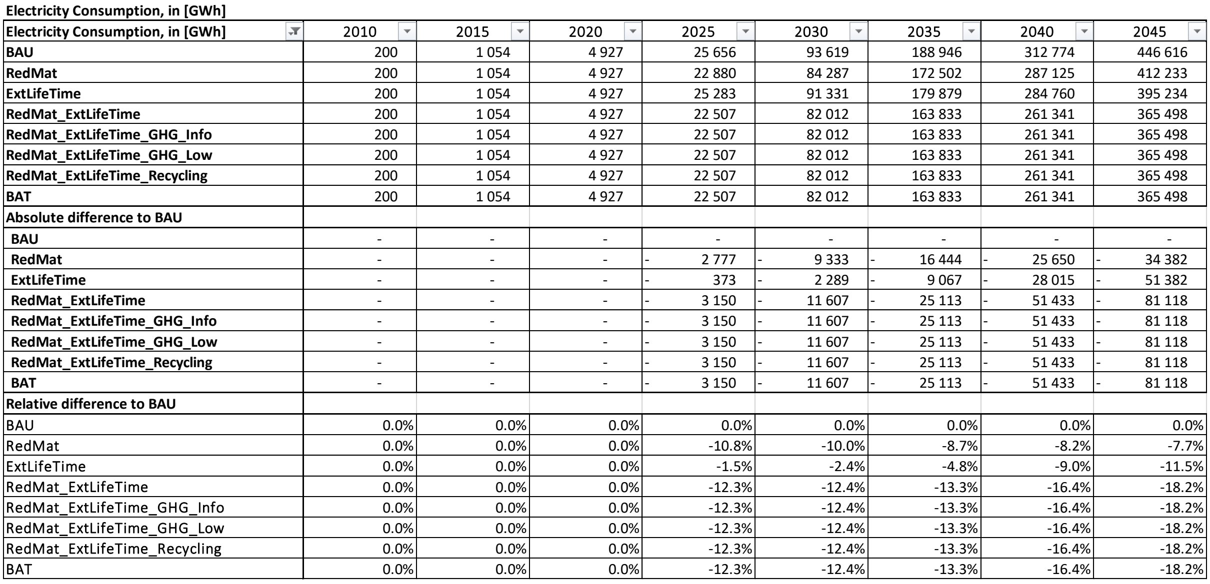
Electricity Consumption, in [GWh]	2010	2015	2020	2025	2030	2035	2040	2045
BAU	75	721	3 530	18 675	64 918	114 188	171 209	225 721
RedMat	75	721	3 530	15 899	55 578	97 684	145 415	191 123
ExtLifeTime	75	721	3 530	18 675	64 801	111 108	153 890	189 627
RedMat_ExtLifeTime	75	721	3 530	15 899	55 476	94 999	130 315	159 656
RedMat_ExtLifeTime_GHG_Info	75	721	3 530	15 899	55 476	94 999	130 315	159 656
RedMat_ExtLifeTime_GHG_Low	75	721	3 530	15 899	55 476	94 999	130 315	159 656
RedMat_ExtLifeTime_Recycling	75	721	3 530	15 899	55 476	94 999	130 315	159 656
BAT	75	721	3 530	15 899	55 476	94 999	130 315	159 656
Absolute difference to BAU								
BAU	-	-	-	-	-	-	-	-
RedMat	-	-	-	- 2 777	- 9 340	- 16 503	- 25 795	- 34 598
ExtLifeTime	-	-	-	-	- 116	- 3 079	- 17 319	- 36 094
RedMat_ExtLifeTime	-	-	-	- 2 777	- 9 441	- 19 189	- 40 894	- 66 065
RedMat_ExtLifeTime_GHG_Info	-	-	-	- 2 777	- 9 441	- 19 189	- 40 894	- 66 065
RedMat_ExtLifeTime_GHG_Low	-	-	-	- 2 777	- 9 441	- 19 189	- 40 894	- 66 065
RedMat_ExtLifeTime_Recycling	-	-	-	- 2 777	- 9 441	- 19 189	- 40 894	- 66 065
BAT	-	-	-	- 2 777	- 9 441	- 19 189	- 40 894	- 66 065
Relative difference to BAU								
BAU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat	0.0%	0.0%	0.0%	-14.9%	-14.4%	-14.5%	-15.1%	-15.3%
ExtLifeTime	0.0%	0.0%	0.0%	0.0%	-0.2%	-2.7%	-10.1%	-16.0%
RedMat_ExtLifeTime	0.0%	0.0%	0.0%	-14.9%	-14.5%	-16.8%	-23.9%	-29.3%
RedMat_ExtLifeTime_GHG_Info	0.0%	0.0%	0.0%	-14.9%	-14.5%	-16.8%	-23.9%	-29.3%
RedMat_ExtLifeTime_GHG_Low	0.0%	0.0%	0.0%	-14.9%	-14.5%	-16.8%	-23.9%	-29.3%
RedMat_ExtLifeTime_Recycling	0.0%	0.0%	0.0%	-14.9%	-14.5%	-16.8%	-23.9%	-29.3%
BAT	0.0%	0.0%	0.0%	-14.9%	-14.5%	-16.8%	-23.9%	-29.3%

Table 7-29: Electricity consumption in GWh/year for the EOL phase (EU-28 battery system stock)

Electricity Consumption, in [GWh]

Electricity Consumption, in [GWh]	2010	2015	2020	2025	2030	2035	2040	2045
BAU	- 3	- 3	- 3	- 20	- 100	- 424	- 1 379	- 2 724
RedMat	- 3	- 3	- 3	- 20	- 93	- 364	- 1 235	- 2 508
ExtLifeTime	- 3	- 3	- 3	- 20	- 97	- 297	- 930	- 1 995
RedMat_ExtLifeTime	- 3	- 3	- 3	- 20	- 90	- 234	- 774	- 1 760
RedMat_ExtLifeTime_GHG_Info	- 3	- 3	- 3	- 20	- 90	- 234	- 774	- 1 760
RedMat_ExtLifeTime_GHG_Low	- 3	- 3	- 3	- 20	- 90	- 234	- 774	- 1 760
RedMat_ExtLifeTime_Recycling	- 3	- 3	- 3	- 20	- 90	- 234	- 774	- 1 760
BAT	- 3	- 3	- 3	- 20	- 90	- 234	- 774	- 1 760
Absolute difference to BAU								
BAU	-	-	-	-	-	-	-	-
RedMat	-	-	-	-	7	60	145	216
ExtLifeTime	-	-	-	-	3	127	449	729
RedMat_ExtLifeTime	-	-	-	-	10	190	606	964
RedMat_ExtLifeTime_GHG_Info	-	-	-	-	10	190	606	964
RedMat_ExtLifeTime_GHG_Low	-	-	-	-	10	190	606	964
RedMat_ExtLifeTime_Recycling	-	-	-	-	10	190	606	964
BAT	-	-	-	-	10	190	606	964
Relative difference to BAU								
BAU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat	0.0%	0.0%	0.0%	0.0%	-7.2%	-14.1%	-10.5%	-7.9%
ExtLifeTime	0.0%	0.0%	0.0%	0.0%	-2.9%	-30.0%	-32.6%	-26.8%
RedMat_ExtLifeTime	0.0%	0.0%	0.0%	0.0%	-10.0%	-44.8%	-43.9%	-35.4%
RedMat_ExtLifeTime_GHG_Info	0.0%	0.0%	0.0%	0.0%	-10.0%	-44.8%	-43.9%	-35.4%
RedMat_ExtLifeTime_GHG_Low	0.0%	0.0%	0.0%	0.0%	-10.0%	-44.8%	-43.9%	-35.4%
RedMat_ExtLifeTime_Recycling	0.0%	0.0%	0.0%	0.0%	-10.0%	-44.8%	-43.9%	-35.4%
BAT	0.0%	0.0%	0.0%	0.0%	-10.0%	-44.8%	-43.9%	-35.4%

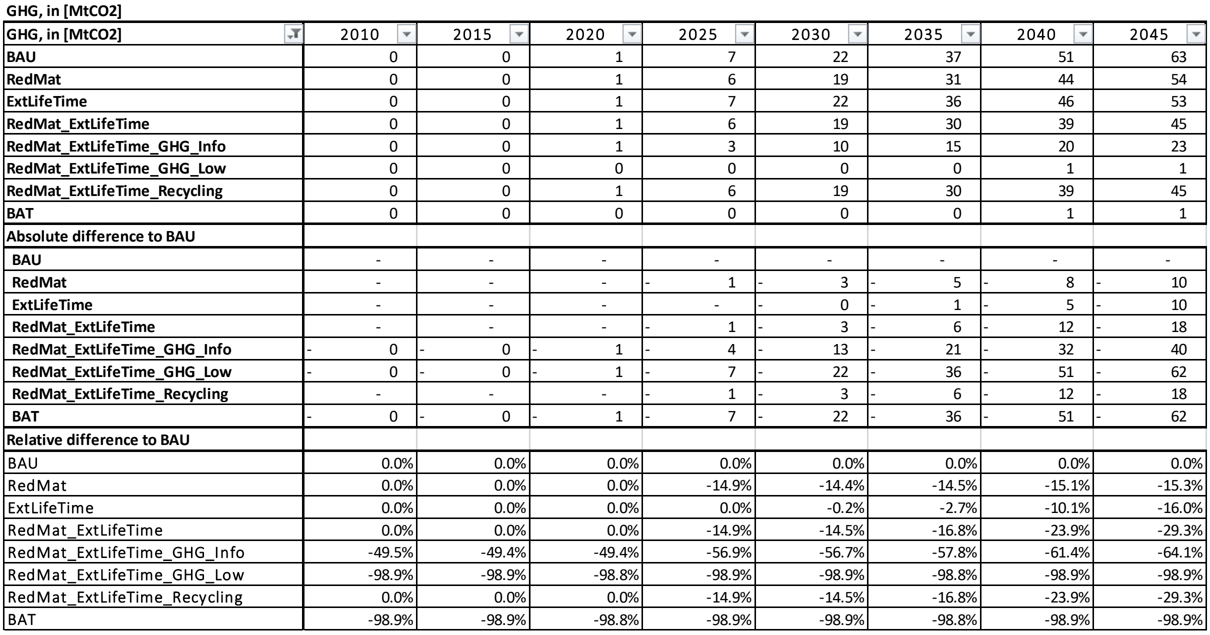
Table 7-30: Electricity consumption in GWh/year for all phases (EU-28 battery system stock)



Electricity Consumption, in [GWh]

Electricity Consumption, in [GWh]	2010	2015	2020	2025	2030	2035	2040	2045
BAU	200	1 054	4 927	25 656	93 619	188 946	312 774	446 616
RedMat	200	1 054	4 927	22 880	84 287	172 502	287 125	412 233
ExtLifeTime	200	1 054	4 927	25 283	91 331	179 879	284 760	395 234
RedMat_ExtLifeTime	200	1 054	4 927	22 507	82 012	163 833	261 341	365 498
RedMat_ExtLifeTime_GHG_Info	200	1 054	4 927	22 507	82 012	163 833	261 341	365 498
RedMat_ExtLifeTime_GHG_Low	200	1 054	4 927	22 507	82 012	163 833	261 341	365 498
RedMat_ExtLifeTime_Recycling	200	1 054	4 927	22 507	82 012	163 833	261 341	365 498
BAT	200	1 054	4 927	22 507	82 012	163 833	261 341	365 498
Absolute difference to BAU								
BAU	-	-	-	-	-	-	-	-
RedMat	-	-	-	- 2 777	- 9 333	- 16 444	- 25 650	- 34 382
ExtLifeTime	-	-	-	- 373	- 2 289	- 9 067	- 28 015	- 51 382
RedMat_ExtLifeTime	-	-	-	- 3 150	- 11 607	- 25 113	- 51 433	- 81 118
RedMat_ExtLifeTime_GHG_Info	-	-	-	- 3 150	- 11 607	- 25 113	- 51 433	- 81 118
RedMat_ExtLifeTime_GHG_Low	-	-	-	- 3 150	- 11 607	- 25 113	- 51 433	- 81 118
RedMat_ExtLifeTime_Recycling	-	-	-	- 3 150	- 11 607	- 25 113	- 51 433	- 81 118
BAT	-	-	-	- 3 150	- 11 607	- 25 113	- 51 433	- 81 118
Relative difference to BAU								
BAU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat	0.0%	0.0%	0.0%	-10.8%	-10.0%	-8.7%	-8.2%	-7.7%
ExtLifeTime	0.0%	0.0%	0.0%	-1.5%	-2.4%	-4.8%	-9.0%	-11.5%
RedMat_ExtLifeTime	0.0%	0.0%	0.0%	-12.3%	-12.4%	-13.3%	-16.4%	-18.2%
RedMat_ExtLifeTime_GHG_Info	0.0%	0.0%	0.0%	-12.3%	-12.4%	-13.3%	-16.4%	-18.2%
RedMat_ExtLifeTime_GHG_Low	0.0%	0.0%	0.0%	-12.3%	-12.4%	-13.3%	-16.4%	-18.2%
RedMat_ExtLifeTime_Recycling	0.0%	0.0%	0.0%	-12.3%	-12.4%	-13.3%	-16.4%	-18.2%
BAT	0.0%	0.0%	0.0%	-12.3%	-12.4%	-13.3%	-16.4%	-18.2%

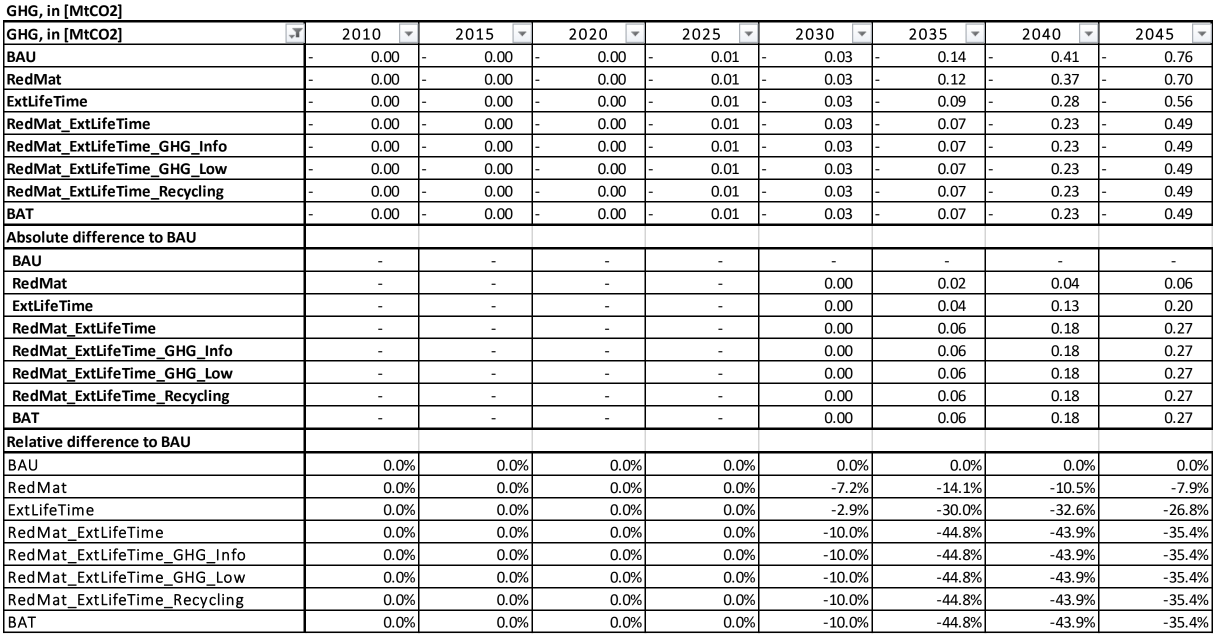
Table 7-31: GHG emission (of the electricity consumption) in MtCO$_2$/year for the production phase (EU-28 battery system stock)



GHG, in [MtCO2]

GHG, in [MtCO2]	2010	2015	2020	2025	2030	2035	2040	2045
BAU	0	0	1	7	22	37	51	63
RedMat	0	0	1	6	19	31	44	54
ExtLifeTime	0	0	1	7	22	36	46	53
RedMat_ExtLifeTime	0	0	1	6	19	30	39	45
RedMat_ExtLifeTime_GHG_Info	0	0	1	3	10	15	20	23
RedMat_ExtLifeTime_GHG_Low	0	0	0	0	0	0	1	1
RedMat_ExtLifeTime_Recycling	0	0	1	6	19	30	39	45
BAT	0	0	0	0	0	0	1	1
Absolute difference to BAU								
BAU	-	-	-	-	-	-	-	-
RedMat	-	-	-	- 1	- 3	- 5	- 8	- 10
ExtLifeTime	-	-	-	-	- 0	- 1	- 5	- 10
RedMat_ExtLifeTime	-	-	-	- 1	- 3	- 6	- 12	- 18
RedMat_ExtLifeTime_GHG_Info	- 0	- 0	- 1	- 4	- 13	- 21	- 32	- 40
RedMat_ExtLifeTime_GHG_Low	- 0	- 0	- 1	- 7	- 22	- 36	- 51	- 62
RedMat_ExtLifeTime_Recycling	-	-	-	- 1	- 3	- 6	- 12	- 18
BAT	- 0	- 0	- 1	- 7	- 22	- 36	- 51	- 62
Relative difference to BAU								
BAU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat	0.0%	0.0%	0.0%	-14.9%	-14.4%	-14.5%	-15.1%	-15.3%
ExtLifeTime	0.0%	0.0%	0.0%	0.0%	-0.2%	-2.7%	-10.1%	-16.0%
RedMat_ExtLifeTime	0.0%	0.0%	0.0%	-14.9%	-14.5%	-16.8%	-23.9%	-29.3%
RedMat_ExtLifeTime_GHG_Info	-49.5%	-49.4%	-49.4%	-56.9%	-56.7%	-57.8%	-61.4%	-64.1%
RedMat_ExtLifeTime_GHG_Low	-98.9%	-98.9%	-98.8%	-98.9%	-98.9%	-98.8%	-98.9%	-98.9%
RedMat_ExtLifeTime_Recycling	0.0%	0.0%	0.0%	-14.9%	-14.5%	-16.8%	-23.9%	-29.3%
BAT	-98.9%	-98.9%	-98.8%	-98.9%	-98.9%	-98.8%	-98.9%	-98.9%

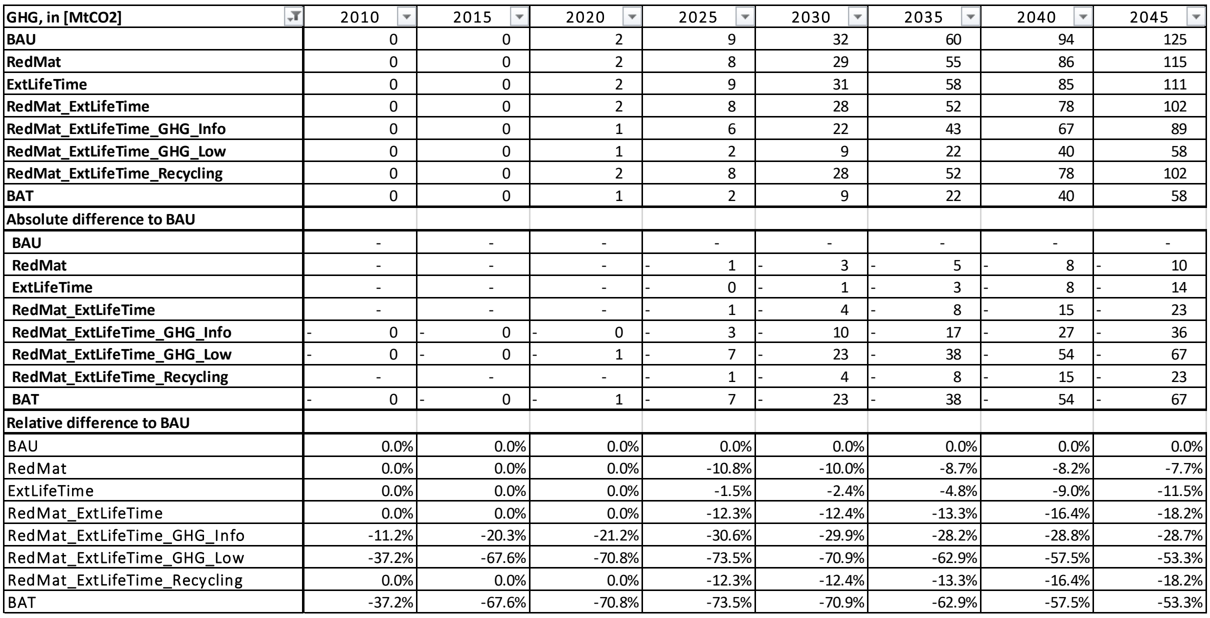
Table 7-32: GHG emission (of the electricity consumption) in MtCO$_2$/year for the EOL phase (EU-28 battery system stock)



GHG, in [MtCO2]

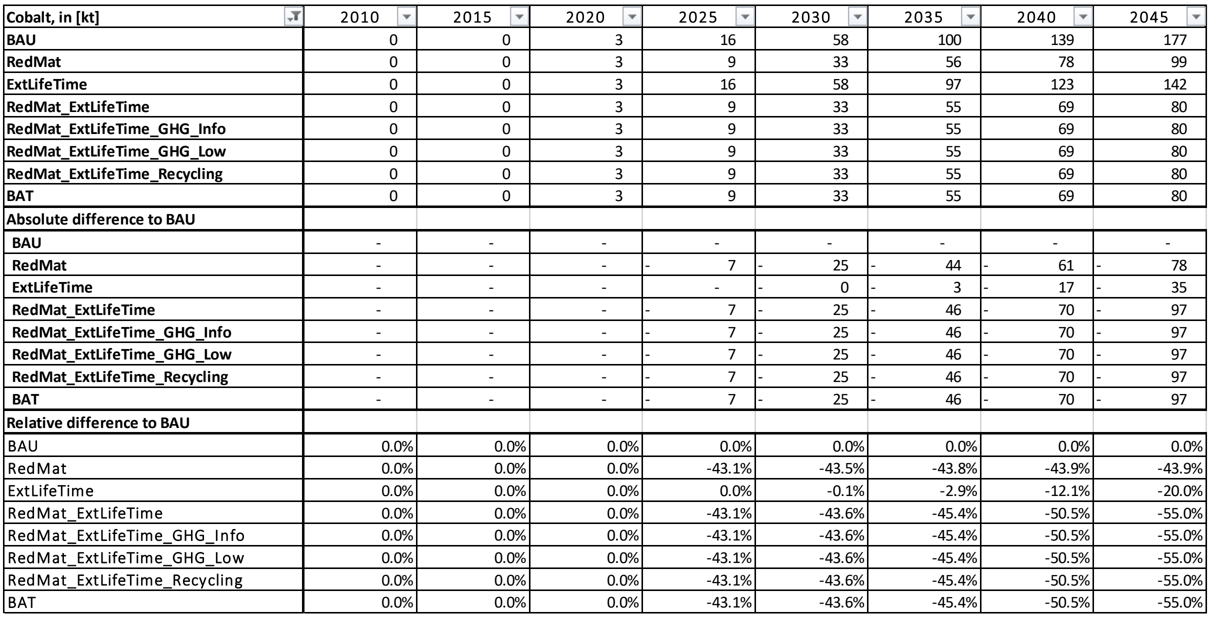
GHG, in [MtCO2]	2010	2015	2020	2025	2030	2035	2040	2045
BAU	- 0.00	- 0.00	- 0.00	- 0.01	- 0.03	- 0.14	- 0.41	- 0.76
RedMat	- 0.00	- 0.00	- 0.00	- 0.01	- 0.03	- 0.12	- 0.37	- 0.70
ExtLifeTime	- 0.00	- 0.00	- 0.00	- 0.01	- 0.03	- 0.09	- 0.28	- 0.56
RedMat_ExtLifeTime	- 0.00	- 0.00	- 0.00	- 0.01	- 0.03	- 0.07	- 0.23	- 0.49
RedMat_ExtLifeTime_GHG_Info	- 0.00	- 0.00	- 0.00	- 0.01	- 0.03	- 0.07	- 0.23	- 0.49
RedMat_ExtLifeTime_GHG_Low	- 0.00	- 0.00	- 0.00	- 0.01	- 0.03	- 0.07	- 0.23	- 0.49
RedMat_ExtLifeTime_Recycling	- 0.00	- 0.00	- 0.00	- 0.01	- 0.03	- 0.07	- 0.23	- 0.49
BAT	- 0.00	- 0.00	- 0.00	- 0.01	- 0.03	- 0.07	- 0.23	- 0.49
Absolute difference to BAU								
BAU	-	-	-	-	-	-	-	-
RedMat	-	-	-	-	0.00	0.02	0.04	0.06
ExtLifeTime	-	-	-	-	0.00	0.04	0.13	0.20
RedMat_ExtLifeTime	-	-	-	-	0.00	0.06	0.18	0.27
RedMat_ExtLifeTime_GHG_Info	-	-	-	-	0.00	0.06	0.18	0.27
RedMat_ExtLifeTime_GHG_Low	-	-	-	-	0.00	0.06	0.18	0.27
RedMat_ExtLifeTime_Recycling	-	-	-	-	0.00	0.06	0.18	0.27
BAT	-	-	-	-	0.00	0.06	0.18	0.27
Relative difference to BAU								
BAU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat	0.0%	0.0%	0.0%	0.0%	-7.2%	-14.1%	-10.5%	-7.9%
ExtLifeTime	0.0%	0.0%	0.0%	0.0%	-2.9%	-30.0%	-32.6%	-26.8%
RedMat_ExtLifeTime	0.0%	0.0%	0.0%	0.0%	-10.0%	-44.8%	-43.9%	-35.4%
RedMat_ExtLifeTime_GHG_Info	0.0%	0.0%	0.0%	0.0%	-10.0%	-44.8%	-43.9%	-35.4%
RedMat_ExtLifeTime_GHG_Low	0.0%	0.0%	0.0%	0.0%	-10.0%	-44.8%	-43.9%	-35.4%
RedMat_ExtLifeTime_Recycling	0.0%	0.0%	0.0%	0.0%	-10.0%	-44.8%	-43.9%	-35.4%
BAT	0.0%	0.0%	0.0%	0.0%	-10.0%	-44.8%	-43.9%	-35.4%

Table 7-33: GHG emission (of the electricity consumption) in MtCO$_2$/year for all phases (EU-28 battery system stock)



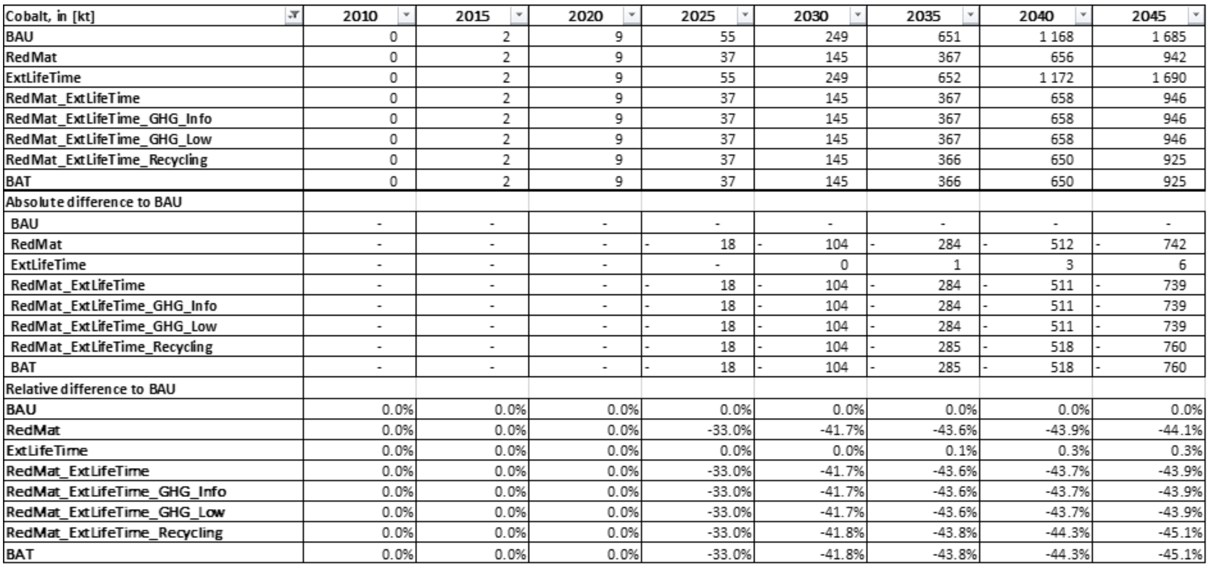
GHG, in [MtCO2]	2010	2015	2020	2025	2030	2035	2040	2045
BAU	0	0	2	9	32	60	94	125
RedMat	0	0	2	8	29	55	86	115
ExtLifeTime	0	0	2	9	31	58	85	111
RedMat_ExtLifeTime	0	0	2	8	28	52	78	102
RedMat_ExtLifeTime_GHG_Info	0	0	1	6	22	43	67	89
RedMat_ExtLifeTime_GHG_Low	0	0	1	2	9	22	40	58
RedMat_ExtLifeTime_Recycling	0	0	2	8	28	52	78	102
BAT	0	0	1	2	9	22	40	58
Absolute difference to BAU								
BAU	-	-	-	-	-	-	-	-
RedMat	-	-	-	- 1	- 3	- 5	- 8	- 10
ExtLifeTime	-	-	-	- 0	- 1	- 3	- 8	- 14
RedMat_ExtLifeTime	-	-	-	- 1	- 4	- 8	- 15	- 23
RedMat_ExtLifeTime_GHG_Info	- 0	- 0	- 0	- 3	- 10	- 17	- 27	- 36
RedMat_ExtLifeTime_GHG_Low	- 0	- 0	- 1	- 7	- 23	- 38	- 54	- 67
RedMat_ExtLifeTime_Recycling	-	-	-	- 1	- 4	- 8	- 15	- 23
BAT	- 0	- 0	- 1	- 7	- 23	- 38	- 54	- 67
Relative difference to BAU								
BAU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat	0.0%	0.0%	0.0%	-10.8%	-10.0%	-8.7%	-8.2%	-7.7%
ExtLifeTime	0.0%	0.0%	0.0%	-1.5%	-2.4%	-4.8%	-9.0%	-11.5%
RedMat_ExtLifeTime	0.0%	0.0%	0.0%	-12.3%	-12.4%	-13.3%	-16.4%	-18.2%
RedMat_ExtLifeTime_GHG_Info	-11.2%	-20.3%	-21.2%	-30.6%	-29.9%	-28.2%	-28.8%	-28.7%
RedMat_ExtLifeTime_GHG_Low	-37.2%	-67.6%	-70.8%	-73.5%	-70.9%	-62.9%	-57.5%	-53.3%
RedMat_ExtLifeTime_Recycling	0.0%	0.0%	0.0%	-12.3%	-12.4%	-13.3%	-16.4%	-18.2%
BAT	-37.2%	-67.6%	-70.8%	-73.5%	-70.9%	-62.9%	-57.5%	-53.3%

Table 7-34: Cobalt demand in kt/year for the production phase (EU-28 battery system stock)



Cobalt, in [kt]	2010	2015	2020	2025	2030	2035	2040	2045
BAU	0	0	3	16	58	100	139	177
RedMat	0	0	3	9	33	56	78	99
ExtLifeTime	0	0	3	16	58	97	123	142
RedMat_ExtLifeTime	0	0	3	9	33	55	69	80
RedMat_ExtLifeTime_GHG_Info	0	0	3	9	33	55	69	80
RedMat_ExtLifeTime_GHG_Low	0	0	3	9	33	55	69	80
RedMat_ExtLifeTime_Recycling	0	0	3	9	33	55	69	80
BAT	0	0	3	9	33	55	69	80
Absolute difference to BAU								
BAU	-	-	-	-	-	-	-	-
RedMat	-	-	-	- 7	- 25	- 44	- 61	- 78
ExtLifeTime	-	-	-	-	- 0	- 3	- 17	- 35
RedMat_ExtLifeTime	-	-	-	- 7	- 25	- 46	- 70	- 97
RedMat_ExtLifeTime_GHG_Info	-	-	-	- 7	- 25	- 46	- 70	- 97
RedMat_ExtLifeTime_GHG_Low	-	-	-	- 7	- 25	- 46	- 70	- 97
RedMat_ExtLifeTime_Recycling	-	-	-	- 7	- 25	- 46	- 70	- 97
BAT	-	-	-	- 7	- 25	- 46	- 70	- 97
Relative difference to BAU								
BAU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat	0.0%	0.0%	0.0%	-43.1%	-43.5%	-43.8%	-43.9%	-43.9%
ExtLifeTime	0.0%	0.0%	0.0%	0.0%	-0.1%	-2.9%	-12.1%	-20.0%
RedMat_ExtLifeTime	0.0%	0.0%	0.0%	-43.1%	-43.6%	-45.4%	-50.5%	-55.0%
RedMat_ExtLifeTime_GHG_Info	0.0%	0.0%	0.0%	-43.1%	-43.6%	-45.4%	-50.5%	-55.0%
RedMat_ExtLifeTime_GHG_Low	0.0%	0.0%	0.0%	-43.1%	-43.6%	-45.4%	-50.5%	-55.0%
RedMat_ExtLifeTime_Recycling	0.0%	0.0%	0.0%	-43.1%	-43.6%	-45.4%	-50.5%	-55.0%
BAT	0.0%	0.0%	0.0%	-43.1%	-43.6%	-45.4%	-50.5%	-55.0%

Table 7-35: Cobalt demand in kt/year for all phases (EU-28 battery system stock)



Cobalt, in [kt]	2010	2015	2020	2025	2030	2035	2040	2045
BAU	0	2	9	55	249	651	1 168	1 685
RedMat	0	2	9	37	145	367	656	942
ExtLifeTime	0	2	9	55	249	652	1 172	1 690
RedMat_ExtLifeTime	0	2	9	37	145	367	658	946
RedMat_ExtLifeTime_GHG_Info	0	2	9	37	145	367	658	946
RedMat_ExtLifeTime_GHG_Low	0	2	9	37	145	367	658	946
RedMat_ExtLifeTime_Recycling	0	2	9	37	145	366	650	925
BAT	0	2	9	37	145	366	650	925
Absolute difference to BAU								
BAU	-	-	-	-	-	-	-	-
RedMat	-	-	-	- 18	- 104	- 284	- 512	- 742
ExtLifeTime	-	-	-	-	0	1	3	6
RedMat_ExtLifeTime	-	-	-	- 18	- 104	- 284	- 511	- 739
RedMat_ExtLifeTime_GHG_Info	-	-	-	- 18	- 104	- 284	- 511	- 739
RedMat_ExtLifeTime_GHG_Low	-	-	-	- 18	- 104	- 284	- 511	- 739
RedMat_ExtLifeTime_Recycling	-	-	-	- 18	- 104	- 285	- 518	- 760
BAT	-	-	-	- 18	- 104	- 285	- 518	- 760
Relative difference to BAU								
BAU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat	0.0%	0.0%	0.0%	-33.0%	-41.7%	-43.6%	-43.9%	-44.1%
ExtLifeTime	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%	0.3%
RedMat_ExtLifeTime	0.0%	0.0%	0.0%	-33.0%	-41.7%	-43.6%	-43.7%	-43.9%
RedMat_ExtLifeTime_GHG_Info	0.0%	0.0%	0.0%	-33.0%	-41.7%	-43.6%	-43.7%	-43.9%
RedMat_ExtLifeTime_GHG_Low	0.0%	0.0%	0.0%	-33.0%	-41.7%	-43.6%	-43.7%	-43.9%
RedMat_ExtLifeTime_Recycling	0.0%	0.0%	0.0%	-33.0%	-41.8%	-43.8%	-44.3%	-45.1%
BAT	0.0%	0.0%	0.0%	-33.0%	-41.8%	-43.8%	-44.3%	-45.1%

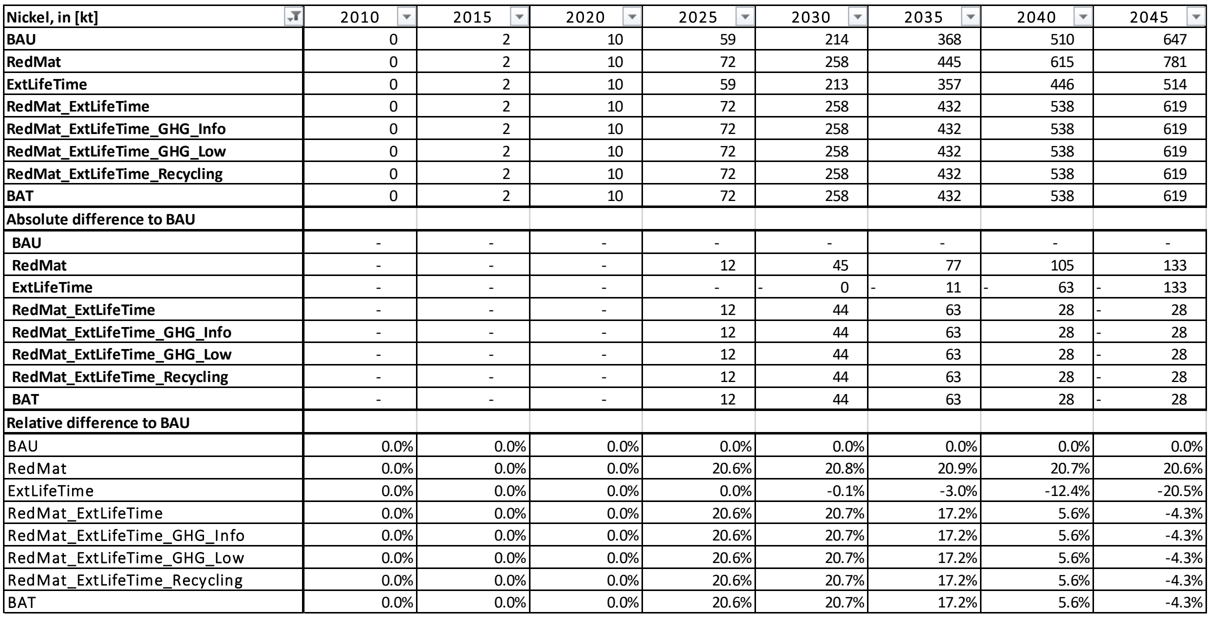
Table 7-36: Graphite demand in kt/year for the production phase (EU-28 battery system stock)

Graphite, in [kt]	2010	2015	2020	2025	2030	2035	2040	2045
BAU	1	6	30	163	571	1 004	1 487	1 951
RedMat	1	6	30	144	507	888	1 300	1 696
ExtLifeTime	1	6	30	163	570	976	1 330	1 624
RedMat_ExtLifeTime	1	6	30	144	506	863	1 158	1 399
RedMat_ExtLifeTime_GHG_Info	1	6	30	144	506	863	1 158	1 399
RedMat_ExtLifeTime_GHG_Low	1	6	30	144	506	863	1 158	1 399
RedMat_ExtLifeTime_Recycling	1	6	30	144	506	863	1 158	1 399
BAT	1	6	30	144	506	863	1 158	1 399
Absolute difference to BAU								
BAU	-	-	-	-	-	-	-	-
RedMat	-	-	-	- 19	- 64	- 116	- 188	- 255
ExtLifeTime	-	-	-	-	- 1	- 28	- 157	- 327
RedMat_ExtLifeTime	-	-	-	- 19	- 65	- 141	- 330	- 552
RedMat_ExtLifeTime_GHG_Info	-	-	-	- 19	- 65	- 141	- 330	- 552
RedMat_ExtLifeTime_GHG_Low	-	-	-	- 19	- 65	- 141	- 330	- 552
RedMat_ExtLifeTime_Recycling	-	-	-	- 19	- 65	- 141	- 330	- 552
BAT	-	-	-	- 19	- 65	- 141	- 330	- 552
Relative difference to BAU								
BAU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat	0.0%	0.0%	0.0%	-11.8%	-11.3%	-11.5%	-12.6%	-13.1%
ExtLifeTime	0.0%	0.0%	0.0%	0.0%	-0.2%	-2.8%	-10.6%	-16.8%
RedMat_ExtLifeTime	0.0%	0.0%	0.0%	-11.8%	-11.4%	-14.0%	-22.2%	-28.3%
RedMat_ExtLifeTime_GHG_Info	0.0%	0.0%	0.0%	-11.8%	-11.4%	-14.0%	-22.2%	-28.3%
RedMat_ExtLifeTime_GHG_Low	0.0%	0.0%	0.0%	-11.8%	-11.4%	-14.0%	-22.2%	-28.3%
RedMat_ExtLifeTime_Recycling	0.0%	0.0%	0.0%	-11.8%	-11.4%	-14.0%	-22.2%	-28.3%
BAT	0.0%	0.0%	0.0%	-11.8%	-11.4%	-14.0%	-22.2%	-28.3%

Table 7-37: Graphite demand in kt/year for all phases (EU-28 battery system stock)

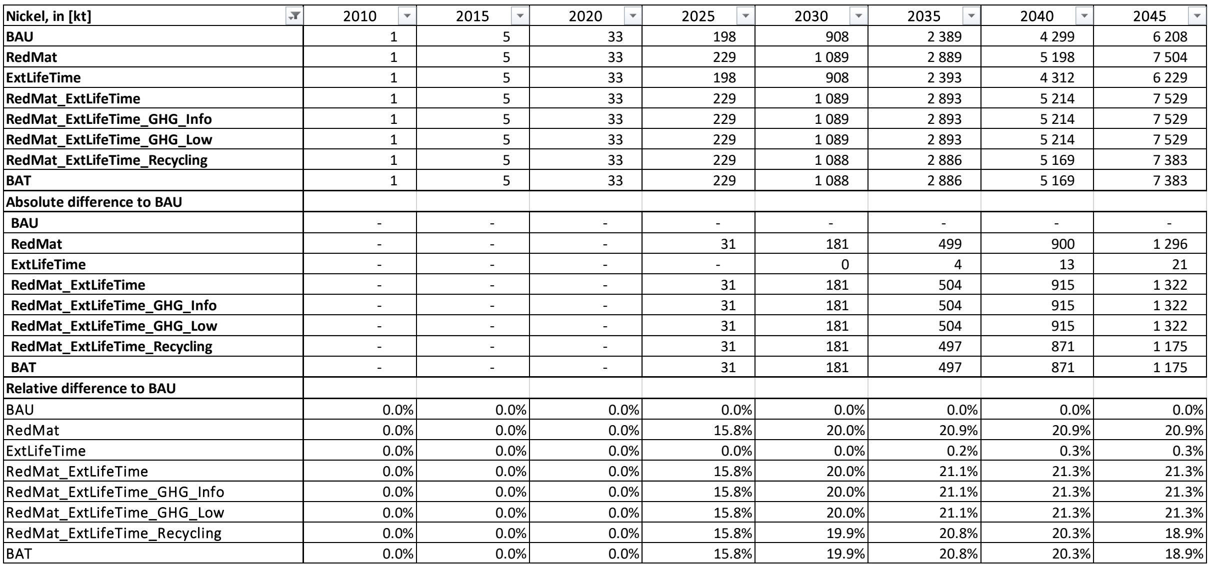
Graphite, in [kt]	2010	2015	2020	2025	2030	2035	2040	2045
BAU	7	23	106	565	2 463	6 430	11 837	17 822
RedMat	7	23	106	514	2 193	5 706	10 467	15 656
ExtLifeTime	7	23	106	565	2 463	6 430	11 837	17 822
RedMat_ExtLifeTime	7	23	106	514	2 193	5 706	10 467	15 656
RedMat_ExtLifeTime_GHG_Info	7	23	106	514	2 193	5 706	10 467	15 656
RedMat_ExtLifeTime_GHG_Low	7	23	106	514	2 193	5 706	10 467	15 656
RedMat_ExtLifeTime_Recycling	7	23	106	514	2 193	5 706	10 467	15 656
BAT	7	23	106	514	2 193	5 706	10 467	15 656
Absolute difference to BAU								
BAU	-	-	-	-	-	-	-	-
RedMat	-	-	-	- 51	- 270	- 724	- 1 370	- 2 166
ExtLifeTime	-	-	-	-	-	-	-	-
RedMat_ExtLifeTime	-	-	-	- 51	- 270	- 724	- 1 370	- 2 166
RedMat_ExtLifeTime_GHG_Info	-	-	-	- 51	- 270	- 724	- 1 370	- 2 166
RedMat_ExtLifeTime_GHG_Low	-	-	-	- 51	- 270	- 724	- 1 370	- 2 166
RedMat_ExtLifeTime_Recycling	-	-	-	- 51	- 270	- 724	- 1 370	- 2 166
BAT	-	-	-	- 51	- 270	- 724	- 1 370	- 2 166
Relative difference to BAU								
BAU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat	0.0%	0.0%	0.0%	-9.0%	-11.0%	-11.3%	-11.6%	-12.2%
ExtLifeTime	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat_ExtLifeTime	0.0%	0.0%	0.0%	-9.0%	-11.0%	-11.3%	-11.6%	-12.2%
RedMat_ExtLifeTime_GHG_Info	0.0%	0.0%	0.0%	-9.0%	-11.0%	-11.3%	-11.6%	-12.2%
RedMat_ExtLifeTime_GHG_Low	0.0%	0.0%	0.0%	-9.0%	-11.0%	-11.3%	-11.6%	-12.2%
RedMat_ExtLifeTime_Recycling	0.0%	0.0%	0.0%	-9.0%	-11.0%	-11.3%	-11.6%	-12.2%
BAT	0.0%	0.0%	0.0%	-9.0%	-11.0%	-11.3%	-11.6%	-12.2%

Table 7-38: Nickel demand in kt/year for the production phase (EU-28 battery system stock)



Nickel, in [kt]	2010	2015	2020	2025	2030	2035	2040	2045
BAU	0	2	10	59	214	368	510	647
RedMat	0	2	10	72	258	445	615	781
ExtLifeTime	0	2	10	59	213	357	446	514
RedMat_ExtLifeTime	0	2	10	72	258	432	538	619
RedMat_ExtLifeTime_GHG_Info	0	2	10	72	258	432	538	619
RedMat_ExtLifeTime_GHG_Low	0	2	10	72	258	432	538	619
RedMat_ExtLifeTime_Recycling	0	2	10	72	258	432	538	619
BAT	0	2	10	72	258	432	538	619
Absolute difference to BAU								
BAU	-	-	-	-	-	-	-	-
RedMat	-	-	-	12	45	77	105	133
ExtLifeTime	-	-	-	-	- 0	- 11	- 63	- 133
RedMat_ExtLifeTime	-	-	-	12	44	63	28	- 28
RedMat_ExtLifeTime_GHG_Info	-	-	-	12	44	63	28	- 28
RedMat_ExtLifeTime_GHG_Low	-	-	-	12	44	63	28	- 28
RedMat_ExtLifeTime_Recycling	-	-	-	12	44	63	28	- 28
BAT	-	-	-	12	44	63	28	- 28
Relative difference to BAU								
BAU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat	0.0%	0.0%	0.0%	20.6%	20.8%	20.9%	20.7%	20.6%
ExtLifeTime	0.0%	0.0%	0.0%	0.0%	-0.1%	-3.0%	-12.4%	-20.5%
RedMat_ExtLifeTime	0.0%	0.0%	0.0%	20.6%	20.7%	17.2%	5.6%	-4.3%
RedMat_ExtLifeTime_GHG_Info	0.0%	0.0%	0.0%	20.6%	20.7%	17.2%	5.6%	-4.3%
RedMat_ExtLifeTime_GHG_Low	0.0%	0.0%	0.0%	20.6%	20.7%	17.2%	5.6%	-4.3%
RedMat_ExtLifeTime_Recycling	0.0%	0.0%	0.0%	20.6%	20.7%	17.2%	5.6%	-4.3%
BAT	0.0%	0.0%	0.0%	20.6%	20.7%	17.2%	5.6%	-4.3%

Table 7-39: Nickel demand in kt/year for all phases (EU-28 battery system stock)



Nickel, in [kt]	2010	2015	2020	2025	2030	2035	2040	2045
BAU	1	5	33	198	908	2 389	4 299	6 208
RedMat	1	5	33	229	1 089	2 889	5 198	7 504
ExtLifeTime	1	5	33	198	908	2 393	4 312	6 229
RedMat_ExtLifeTime	1	5	33	229	1 089	2 893	5 214	7 529
RedMat_ExtLifeTime_GHG_Info	1	5	33	229	1 089	2 893	5 214	7 529
RedMat_ExtLifeTime_GHG_Low	1	5	33	229	1 089	2 893	5 214	7 529
RedMat_ExtLifeTime_Recycling	1	5	33	229	1 088	2 886	5 169	7 383
BAT	1	5	33	229	1 088	2 886	5 169	7 383
Absolute difference to BAU								
BAU	-	-	-	-	-	-	-	-
RedMat	-	-	-	31	181	499	900	1 296
ExtLifeTime	-	-	-	-	0	4	13	21
RedMat_ExtLifeTime	-	-	-	31	181	504	915	1 322
RedMat_ExtLifeTime_GHG_Info	-	-	-	31	181	504	915	1 322
RedMat_ExtLifeTime_GHG_Low	-	-	-	31	181	504	915	1 322
RedMat_ExtLifeTime_Recycling	-	-	-	31	181	497	871	1 175
BAT	-	-	-	31	181	497	871	1 175
Relative difference to BAU								
BAU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat	0.0%	0.0%	0.0%	15.8%	20.0%	20.9%	20.9%	20.9%
ExtLifeTime	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.3%	0.3%
RedMat_ExtLifeTime	0.0%	0.0%	0.0%	15.8%	20.0%	21.1%	21.3%	21.3%
RedMat_ExtLifeTime_GHG_Info	0.0%	0.0%	0.0%	15.8%	20.0%	21.1%	21.3%	21.3%
RedMat_ExtLifeTime_GHG_Low	0.0%	0.0%	0.0%	15.8%	20.0%	21.1%	21.3%	21.3%
RedMat_ExtLifeTime_Recycling	0.0%	0.0%	0.0%	15.8%	19.9%	20.8%	20.3%	18.9%
BAT	0.0%	0.0%	0.0%	15.8%	19.9%	20.8%	20.3%	18.9%

Table 7-40: Manganese demand in kt/year for the production phase (EU-28 battery system stock)

Manganese, in [kt]	2010	2015	2020	2025	2030	2035	2040	2045
BAU	0	1	5	29	104	178	244	308
RedMat	0	1	5	25	87	154	243	327
ExtLifeTime	0	1	5	29	104	173	214	246
RedMat_ExtLifeTime	0	1	5	25	86	151	221	282
RedMat_ExtLifeTime_GHG_Info	0	1	5	25	86	151	221	282
RedMat_ExtLifeTime_GHG_Low	0	1	5	25	86	151	221	282
RedMat_ExtLifeTime_Recycling	0	1	5	25	86	151	221	282
BAT	0	1	5	25	86	151	221	282
Absolute difference to BAU								
BAU	-	-	-	-	-	-	-	-
RedMat	-	-	-	- 4	- 18	- 23	- 1	19
ExtLifeTime	-	-	-	-	- 0	- 5	- 29	- 62
RedMat_ExtLifeTime	-	-	-	- 4	- 18	- 27	- 23	- 26
RedMat_ExtLifeTime_GHG_Info	-	-	-	- 4	- 18	- 27	- 23	- 26
RedMat_ExtLifeTime_GHG_Low	-	-	-	- 4	- 18	- 27	- 23	- 26
RedMat_ExtLifeTime_Recycling	-	-	-	- 4	- 18	- 27	- 23	- 26
BAT	-	-	-	- 4	- 18	- 27	- 23	- 26
Relative difference to BAU								
BAU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat	0.0%	0.0%	0.0%	-14.0%	-17.0%	-13.0%	-0.4%	6.1%
ExtLifeTime	0.0%	0.0%	0.0%	0.0%	-0.1%	-2.8%	-12.1%	-20.2%
RedMat_ExtLifeTime	0.0%	0.0%	0.0%	-14.0%	-17.1%	-15.2%	-9.3%	-8.5%
RedMat_ExtLifeTime_GHG_Info	0.0%	0.0%	0.0%	-14.0%	-17.1%	-15.2%	-9.3%	-8.5%
RedMat_ExtLifeTime_GHG_Low	0.0%	0.0%	0.0%	-14.0%	-17.1%	-15.2%	-9.3%	-8.5%
RedMat_ExtLifeTime_Recycling	0.0%	0.0%	0.0%	-14.0%	-17.1%	-15.2%	-9.3%	-8.5%
BAT	0.0%	0.0%	0.0%	-14.0%	-17.1%	-15.2%	-9.3%	-8.5%

Table 7-41: Manganese demand in kt/year for all phases (EU-28 battery system stock)

Manganese, in [kt]	2010	2015	2020	2025	2030	2035	2040	2045
BAU	1	3	16	99	446	1 162	2 076	2 978
RedMat	1	3	16	89	378	975	1 829	2 848
ExtLifeTime	1	3	16	99	446	1 162	2 076	2 978
RedMat_ExtLifeTime	1	3	16	89	378	975	1 829	2 848
RedMat_ExtLifeTime_GHG_Info	1	3	16	89	378	975	1 829	2 848
RedMat_ExtLifeTime_GHG_Low	1	3	16	89	378	975	1 829	2 848
RedMat_ExtLifeTime_Recycling	1	3	16	89	377	967	1 798	2 771
BAT	1	3	16	89	377	967	1 798	2 771
Absolute difference to BAU								
BAU	-	-	-	-	-	-	-	-
RedMat	-	-	-	- 9	- 68	- 187	- 246	- 130
ExtLifeTime	-	-	-	-	-	-	-	-
RedMat_ExtLifeTime	-	-	-	- 9	- 68	- 187	- 246	- 130
RedMat_ExtLifeTime_GHG_Info	-	-	-	- 9	- 68	- 187	- 246	- 130
RedMat_ExtLifeTime_GHG_Low	-	-	-	- 9	- 68	- 187	- 246	- 130
RedMat_ExtLifeTime_Recycling	-	-	-	- 9	- 69	- 195	- 277	- 207
BAT	-	-	-	- 9	- 69	- 195	- 277	- 207
Relative difference to BAU								
BAU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat	0.0%	0.0%	0.0%	-9.4%	-15.3%	-16.1%	-11.9%	-4.4%
ExtLifeTime	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat_ExtLifeTime	0.0%	0.0%	0.0%	-9.4%	-15.3%	-16.1%	-11.9%	-4.4%
RedMat_ExtLifeTime_GHG_Info	0.0%	0.0%	0.0%	-9.4%	-15.3%	-16.1%	-11.9%	-4.4%
RedMat_ExtLifeTime_GHG_Low	0.0%	0.0%	0.0%	-9.4%	-15.3%	-16.1%	-11.9%	-4.4%
RedMat_ExtLifeTime_Recycling	0.0%	0.0%	0.0%	-9.4%	-15.5%	-16.8%	-13.4%	-7.0%
BAT	0.0%	0.0%	0.0%	-9.4%	-15.5%	-16.8%	-13.4%	-7.0%

Table 7-42: Lithium demand in kt/year for the production phase (EU-28 battery system stock)

Lithium, in [kt]	2010	2015	2020	2025	2030	2035	2040	2045
BAU	0	1	4	25	90	156	222	285
RedMat	0	1	4	24	85	148	210	270
ExtLifeTime	0	1	4	25	90	151	196	232
RedMat_ExtLifeTime	0	1	4	24	85	144	185	218
RedMat_ExtLifeTime_GHG_Info	0	1	4	24	85	144	185	218
RedMat_ExtLifeTime_GHG_Low	0	1	4	24	85	144	185	218
RedMat_ExtLifeTime_Recycling	0	1	4	24	86	146	188	221
BAT	0	1	4	24	86	146	188	221
Absolute difference to BAU								
BAU	-	-	-	-	-	-	-	-
RedMat	-	-	-	- 1	- 4	- 8	- 12	- 16
ExtLifeTime	-	-	-	-	- 0	- 5	- 26	- 54
RedMat_ExtLifeTime	-	-	-	- 1	- 5	- 12	- 37	- 67
RedMat_ExtLifeTime_GHG_Info	-	-	-	- 1	- 5	- 12	- 37	- 67
RedMat_ExtLifeTime_GHG_Low	-	-	-	- 1	- 5	- 12	- 37	- 67
RedMat_ExtLifeTime_Recycling	-	-	-	- 1	- 3	- 10	- 34	- 65
BAT	-	-	-	- 1	- 3	- 10	- 34	- 65
Relative difference to BAU								
BAU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat	0.0%	0.0%	0.0%	-5.4%	-4.9%	-4.9%	-5.3%	-5.5%
ExtLifeTime	0.0%	0.0%	0.0%	0.0%	-0.2%	-2.9%	-11.6%	-18.8%
RedMat_ExtLifeTime	0.0%	0.0%	0.0%	-5.4%	-5.1%	-7.7%	-16.5%	-23.6%
RedMat_ExtLifeTime_GHG_Info	0.0%	0.0%	0.0%	-5.4%	-5.1%	-7.7%	-16.5%	-23.6%
RedMat_ExtLifeTime_GHG_Low	0.0%	0.0%	0.0%	-5.4%	-5.1%	-7.7%	-16.5%	-23.6%
RedMat_ExtLifeTime_Recycling	0.0%	0.0%	0.0%	-4.0%	-3.8%	-6.5%	-15.4%	-22.7%
BAT	0.0%	0.0%	0.0%	-4.0%	-3.8%	-6.5%	-15.4%	-22.7%

Table 7-43: Lithium demand in kt/year for all phases (EU-28 battery system stock)

Lithium, in [kt]	2010	2015	2020	2025	2030	2035	2040	2045
BAU	1	3	15	86	384	1 007	1 830	2 690
RedMat	1	3	15	82	365	958	1 742	2 558
ExtLifeTime	1	3	15	86	384	1 007	1 830	2 690
RedMat_ExtLifeTime	1	3	15	82	365	958	1 742	2 558
RedMat_ExtLifeTime_GHG_Info	1	3	15	82	365	958	1 742	2 558
RedMat_ExtLifeTime_GHG_Low	1	3	15	82	365	958	1 742	2 558
RedMat_ExtLifeTime_Recycling	1	3	15	83	370	968	1 745	2 529
BAT	1	3	15	83	370	968	1 745	2 529
Absolute difference to BAU								
BAU	-	-	-	-	-	-	-	-
RedMat	-	-	-	- 4	- 19	- 49	- 88	- 132
ExtLifeTime	-	-	-	-	-	-	-	-
RedMat_ExtLifeTime	-	-	-	- 4	- 19	- 49	- 88	- 132
RedMat_ExtLifeTime_GHG_Info	-	-	-	- 4	- 19	- 49	- 88	- 132
RedMat_ExtLifeTime_GHG_Low	-	-	-	- 4	- 19	- 49	- 88	- 132
RedMat_ExtLifeTime_Recycling	-	-	-	- 3	- 14	- 39	- 85	- 161
BAT	-	-	-	- 3	- 14	- 39	- 85	- 161
Relative difference to BAU								
BAU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat	0.0%	0.0%	0.0%	-4.3%	-4.9%	-4.8%	-4.8%	-4.9%
ExtLifeTime	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat_ExtLifeTime	0.0%	0.0%	0.0%	-4.3%	-4.9%	-4.8%	-4.8%	-4.9%
RedMat_ExtLifeTime_GHG_Info	0.0%	0.0%	0.0%	-4.3%	-4.9%	-4.8%	-4.8%	-4.9%
RedMat_ExtLifeTime_GHG_Low	0.0%	0.0%	0.0%	-4.3%	-4.9%	-4.8%	-4.8%	-4.9%
RedMat_ExtLifeTime_Recycling	0.0%	0.0%	0.0%	-3.2%	-3.7%	-3.9%	-4.6%	-6.0%
BAT	0.0%	0.0%	0.0%	-3.2%	-3.7%	-3.9%	-4.6%	-6.0%

Table 7-44: Total expenditure in € bln. /year (EU-28 battery system stock)

Expenditure, in € bln./year	2010	2015	2020	2025	2030	2035	2040	2045
BAU	0	2	7	34	118	220	365	512
RedMat	0	2	7	24	83	156	265	378
ExtLifeTime	0	2	7	34	117	212	329	441
RedMat_ExtLifeTime	0	2	7	24	82	151	239	327
RedMat_ExtLifeTime_GHG_Info	0	2	7	24	82	151	239	327
RedMat_ExtLifeTime_GHG_Low	0	2	7	24	82	151	239	327
RedMat_ExtLifeTime_Recycling	0	2	7	24	82	151	239	327
BAT	0	2	7	24	82	151	239	327
Absolute difference to BAU								
BAU	-	-	-	-	-	-	-	-
RedMat	-	-	-	- 10	- 35	- 63	- 100	- 135
ExtLifeTime	-	-	-	- 0	- 1	- 7	- 36	- 71
RedMat_ExtLifeTime	-	-	-	- 10	- 36	- 69	- 126	- 185
RedMat_ExtLifeTime_GHG_Info	-	-	-	- 10	- 36	- 69	- 126	- 185
RedMat_ExtLifeTime_GHG_Low	-	-	-	- 10	- 36	- 69	- 126	- 185
RedMat_ExtLifeTime_Recycling	-	-	-	- 10	- 36	- 69	- 126	- 185
BAT	-	-	-	- 10	- 36	- 69	- 126	- 185
Relative difference to BAU								
BAU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat	0.0%	0.0%	0.0%	-29.9%	-29.9%	-28.8%	-27.3%	-26.3%
ExtLifeTime	0.0%	0.0%	0.0%	-0.3%	-0.6%	-3.3%	-9.8%	-13.8%
RedMat_ExtLifeTime	0.0%	0.0%	0.0%	-30.1%	-30.4%	-31.3%	-34.4%	-36.2%
RedMat_ExtLifeTime_GHG_Info	0.0%	0.0%	0.0%	-30.1%	-30.4%	-31.3%	-34.4%	-36.2%
RedMat_ExtLifeTime_GHG_Low	0.0%	0.0%	0.0%	-30.1%	-30.4%	-31.3%	-34.4%	-36.2%
RedMat_ExtLifeTime_Recycling	0.0%	0.0%	0.0%	-30.1%	-30.4%	-31.3%	-34.4%	-36.2%
BAT	0.0%	0.0%	0.0%	-30.1%	-30.4%	-31.3%	-34.4%	-36.2%

Table 7-45: Purchase costs in € bln. /year (EU-28 battery system stock)

of that, purchase costs, in € bln./year	2010	2015	2020	2025	2030	2035	2040	2045
BAU	0	2	6	32	113	204	329	451
RedMat	0	2	6	22	77	141	230	316
ExtLifeTime	0	2	6	32	112	199	300	389
RedMat_ExtLifeTime	0	2	6	22	77	137	210	274
RedMat_ExtLifeTime_GHG_Info	0	2	6	22	77	137	210	274
RedMat_ExtLifeTime_GHG_Low	0	2	6	22	77	137	210	274
RedMat_ExtLifeTime_Recycling	0	2	6	22	77	137	210	274
BAT	0	2	6	22	77	137	210	274
Absolute difference to BAU								
BAU	-	-	-	-	-	-	-	-
RedMat	-	-	-	- 10	- 35	- 63	- 100	- 135
ExtLifeTime	-	-	-	-	- 0	- 5	- 30	- 62
RedMat_ExtLifeTime	-	-	-	- 10	- 35	- 67	- 120	- 176
RedMat_ExtLifeTime_GHG_Info	-	-	-	- 10	- 35	- 67	- 120	- 176
RedMat_ExtLifeTime_GHG_Low	-	-	-	- 10	- 35	- 67	- 120	- 176
RedMat_ExtLifeTime_Recycling	-	-	-	- 10	- 35	- 67	- 120	- 176
BAT	-	-	-	- 10	- 35	- 67	- 120	- 176
Relative difference to BAU								
BAU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat	0.0%	0.0%	0.0%	-30.9%	-31.3%	-31.0%	-30.2%	-29.9%
ExtLifeTime	0.0%	0.0%	0.0%	0.0%	-0.2%	-2.6%	-9.0%	-13.7%
RedMat_ExtLifeTime	0.0%	0.0%	0.0%	-30.9%	-31.4%	-32.7%	-36.3%	-39.1%
RedMat_ExtLifeTime_GHG_Info	0.0%	0.0%	0.0%	-30.9%	-31.4%	-32.7%	-36.3%	-39.1%
RedMat_ExtLifeTime_GHG_Low	0.0%	0.0%	0.0%	-30.9%	-31.4%	-32.7%	-36.3%	-39.1%
RedMat_ExtLifeTime_Recycling	0.0%	0.0%	0.0%	-30.9%	-31.4%	-32.7%	-36.3%	-39.1%
BAT	0.0%	0.0%	0.0%	-30.9%	-31.4%	-32.7%	-36.3%	-39.1%

Table 7-46: EOL costs in € bln. /year (EU-28 battery system stock)

of that,EoL costs, in € bln./year	2010	2015	2020	2025	2030	2035	2040	2045
BAU	0	0	0	0	1	3	12	24
RedMat	0	0	0	0	1	3	12	24
ExtLifeTime	0	0	0	0	1	2	8	18
RedMat_ExtLifeTime	0	0	0	0	1	2	8	18
RedMat_ExtLifeTime_GHG_Info	0	0	0	0	1	2	8	18
RedMat_ExtLifeTime_GHG_Low	0	0	0	0	1	2	8	18
RedMat_ExtLifeTime_Recycling	0	0	0	0	1	2	8	18
BAT	0	0	0	0	1	2	8	18
Absolute difference to BAU								
BAU	-	-	-	-	-	-	-	-
RedMat	-	-	-	-	-	-	-	-
ExtLifeTime	-	-	-	- 0	- 0	- 1	- 4	- 6
RedMat_ExtLifeTime	-	-	-	- 0	- 0	- 1	- 4	- 6
RedMat_ExtLifeTime_GHG_Info	-	-	-	- 0	- 0	- 1	- 4	- 6
RedMat_ExtLifeTime_GHG_Low	-	-	-	- 0	- 0	- 1	- 4	- 6
RedMat_ExtLifeTime_Recycling	-	-	-	- 0	- 0	- 1	- 4	- 6
BAT	-	-	-	- 0	- 0	- 1	- 4	- 6
Relative difference to BAU								
BAU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
RedMat	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
ExtLifeTime	0.0%	0.0%	0.0%	-22.7%	-25.6%	-27.5%	-35.7%	-26.1%
RedMat_ExtLifeTime	0.0%	0.0%	0.0%	-22.7%	-25.6%	-27.5%	-35.7%	-26.1%
RedMat_ExtLifeTime_GHG_Info	0.0%	0.0%	0.0%	-22.7%	-25.6%	-27.5%	-35.7%	-26.1%
RedMat_ExtLifeTime_GHG_Low	0.0%	0.0%	0.0%	-22.7%	-25.6%	-27.5%	-35.7%	-26.1%
RedMat_ExtLifeTime_Recycling	0.0%	0.0%	0.0%	-22.7%	-25.6%	-27.5%	-35.7%	-26.1%
BAT	0.0%	0.0%	0.0%	-22.7%	-25.6%	-27.5%	-35.7%	-26.1%

Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage under FWC ENER/C3/2015-619-Lot 1

TASK 7 Report

Policy Scenario Analysis

Annex C Stakeholder position papers

VITO, Fraunhofer, Viegand Maagøe

August 2019

Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs

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Quality Review:	Jan Viegand – Viegand Maagøe A/S
Project website:	https://ecodesignbatteries.eu/

Version history:

Version 1: Draft for discussion in the stakeholder meeting of 2/5/2019

Version 2: Updated version taking into account the written feedback from the stakeholders and those of the stakeholder meeting.

Main changes in the policy analysis are:

Minimum criteria for auxiliary BMS power are shifted to information requirements

- In the carbon footprint requirements some recommendations are added to review/simplify the PEFCR to be used.
- Separate information requirements are added for battery cells to be used in the intended application.
- In the other minimum battery pack design and construction requirements a requirement has been added to provide a vehicle-to-grid(V2G) and complementary vehicle-to-test(V2test) interface.

EUROPEAN COMMISSION

Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs

Directorate Directorate C – Industrial Transformation and Advanced Value Chains

Unit Directorate C1

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Contents

Annex C Stakeholders position papers & comments

Annex C1. Stakeholder ED Battery Comments - DEA

DG ENER Lot 37: Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage

Please note that the comments will be published and used for the work of this preparatory study. If you have useful data that can be disclosed in an aggregated form that requires an NDA please contact the study team.

Organization:	**Name:**	**Date:**
Danish Energy Agency	**Jesper Ditlefsen**	

Task#	Section#	Page#	Topic	Comment	Proposed change	Study team reply
7	7.1.2.1	18-19	Proof-reading comments	Table 7-2 If max. capacity fade (relative to declared value) is 90%, it would seem that minimum remaining capacity is only 10% ? Table 7-3 Capacity must be stated as “usable energy capacity in kWh x number of cycles”. (Capacity is not measured in kW). No space before %-sign, only before regular SI-units like kW, kWh, V, or A.	For automotive applications, leave out requirements on auxiliary power, cooling and heating needs.	

Task#	**Section#**	**Page#**	**Topic**	**Comment**	**Proposed change**	**Study team reply**
7	7.1.2.1	19	*Table 7-3* Total Functional Unit Warranty	A warranty limit related to lifetime information registered in the battery management system would be an invitation to have the system manipulate this information, so as to avoid warranty claims. Also, if the battery management system breaks down, the battery owner will no longer have the data necessary for a warranty claim. Last but not least, consumers may not easily understand the concepts of "Total Functional Unit" and energy throughput or how these translate, depending on a consumer's use profile, into a warranty cover expressed in more familiar terms like number of years or distance driven. Instead, the warranty limit should be expressed in parameters which are familiar, already registered for other purposes and not easily manipulated. For automotive applications, the most meaningful would be a warranty on a minimum number of km/miles and years in use (in the vehicle for which the battery was produced), whatever comes first, as is already the case for existing warranties on motor vehicles. A warranty of this kind, rather than on energy throughput, would in itself be an incentive to design EVs for battery use that maximizes	1) Change proposed minimum warranty on "Total Functional Unit" into a warranty on years in use and, for automotive applications, distance driven. 2) Include labelling-type requirement so as to foster competition on warranty extent. 3) Consider warranty extent to 80 % or 70 % capacity rather than 90 %.	Added to the position papers and discussed in the specific section

				battery lifetime. This would of course benefit consumers as well as the environment. In many cases, the lifetime warranty offered for an EV battery is already better (7-8 years) than most warranties for internal combustion engine vehicles. This can be an important argument in favour of an EV. Therefore, in so far as EVs are considered less environmentally harmful than ICE-vehicles, it would seem important to maintain that warranty extent for the two technologies can be compared directly, rather than introducing a new warranty format for EV batteries, which would hinder or complicate direct comparison. Also, knowing whether the warranty is still valid would be straightforward, because the distance driven and number of years in use are already registered for other purposes (e.g. tax, insurance and maintenance). Since authorities are not meant to test whether a battery performs as per the lifetime guarantee (as we understand it, this will be tested only by the market, because lab test cost and duration would be prohibitive), the warranty requirement could be extended to 80 % or 70 % of original capacity rather than to 90 %, as set out in Table 7-2. This would seem more in line with the 7-10 years warranties already offered for EVs.		

				For ESS, the warranty could simply cover a minimum number of years in use, but the extent might be linked to the type of application, cf. comments above to section 7.1.2.1 regarding test standard for such applications. For both types of application, a minimum warranty could be supplemented by a labelling-type requirement so as to foster competition on warranty extent between manufacturers.		

Task#	**Section#**	**Page#**	**Topic**	**Comment**	**Proposed change**	**Study team reply**
7	7.1.2.2	20	Requirements on auxiliary power, cooling and heating needs for automotive applications	For automotive applications, the energy efficiency effect of auxiliary power, cooling and heating needs is already included in the overall efficiency under test conditions as found in the WLTP test. It seems questionable whether specific requirements on these parameters would improve overall efficiency or reduce overall environmental impact. In particular, it would seem that manufacturers of EVs already have a powerful incentive to design vehicles and batteries in such a way that overall efficiency and, hence, vehicle range, is maximized. And this is also an incentive to minimize needs for auxiliary power etc. Also, it is not inconceivable that e.g. a new	For automotive applications, leave out requirements on auxiliary power, cooling and heating needs.	

				battery management system could consume more than existing solutions but nevertheless reduce overall energy consumption. Therefore, there is a risk that a requirement specifically on auxiliary power etc. could be counterproductive with regard to overall efficiency. Last but not least, no test method or standards exist for the evaluation of these parameters, so there is significant risk that it would delay adoption and effect of the regulation if they were to be included.		

Annex C2. Stakeholder ED Battery Comments – ACEA

DG ENER Lot 37: Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage

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Organization: **ACEA**	**Name:** **Jens Warsen**	**Date:** **24/05/2019**

Task #	**Section #**	**line #**	**Topic**	**Comment**	**Proposed change**	**Reply study team**
7	7.1.3		Page 21, Objective	General comment: a multitude of aspects that are mentioned in this section are already covered under the scope of other legislation (e.g. Battery Directive, ELV Directive). Industry implemented several processes and measures to fulfil requirements stemming from these regulations. It is therefore imperative to make sure that there are no overlaps or even contradictions created under this initiative.	.	Agreed, Text added in the scope to highlight this issue.
7	7.1.3.2		Rationale	General comment: How will all this information be used by dismantlers/recyclers, i.e. how will it practically facilitate their processes?		Added to the challenges
7	7.1.3.2	8-10	Page 26, Responsible sourcing	How can such information promote sustainable sourcing? Sustainable sourcing is already part of OEMs sourcing strategies (see www.drivesustainability.org)	Delete the paragraph	Link https://drivesustainability.org/raw-materials/ added in a footnote but we do not want to conclude already in the study on how and where such information should be provided

Task #	Section #	line #	Topic	Comment	Proposed change	Reply study team
	7.1.3.2	9-11	Page 28, dismantling info	Information on disassembly/dismantling is already available and provided via IDIS. No additional datasource needed.		Thanks. Added to the text.
7	7.1.3.3	11-25	Page 31, requirement on Carbon footprint	Despite the Commission's activities to establish European battery production capabilities, it is economically vital to keep battery value chains global. A responsible regulation must therefore address sustainability requirements that apply to raw materials, components and batteries manufactured and recycled beyond the European boundaries. ACEA is concerned that ill-defined measures, like the prescriptive PEF methodology, could become a major trade barrier for the sourcing of automotive batteries. The automotive industry acknowledges the merits of LCA as a voluntary method to assess the environmental profile of a vehicle across its entire life cycle and to support target-oriented product development. However, LCA studies shall be based on ISO 14040/44 standard in order to guarantee a global level playing field	Refrain from prescribing usage of the PEF methodology	Noted. The proposal is for information requirement only. Added in challenges 'The PEF methodology reduces the flexibility of ISO 14040/44 standard and does therefore not provide as such a global level of playing field'.

Task #	**Section #**	**line #**	**Topic**	**Comment**	**Proposed change**	**Reply study team**
7	7.1.3.4	1-14	Page 34	The requirements shall be the same level as conventional ICE vehicle and/ or feasible.		Noted. Also reference was made to IDIS. Up to the EC to decide on how to maintain this.

Annex C3. Stakeholder ED Battery Comments - ANEC BEUC

Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage

Please note that the comments will be published and used for the work of this preparatory study. If you have useful data that can be disclosed in an aggregated form that requires an NDA please contact the study team.

Organization: **ANEC / BEUC – European Consumer Organsiations**	**Name:** **Maigret Aline, Ecodesign project coordinator**	**Date:** **May 2019**

Task #	Section #	line #	Topic	Comment	Proposed change	Reply study team
7	General		Proposed policy measures Requirements for battery management and requirements for battery information	Under Task 7, the study team puts forward the following policy options: Requirements for battery management and requirements for battery information Minimum battery pack/system lifetime requirements Maximum auxiliary power consumption of the battery system Requirements for carbon footprint information Minimum battery pack design and construction requirements to support reusability/recyclability/recoverability **Overall, we welcome the options proposed, and comment on them individually below.** **We strongly support the proposal to have requirements on battery management and battery information.** This is in line with the circular economy goals, and for consumers, such information can furthermore increase resale values of used vehicles and provide better and independent access to repair professionals. **We also support information on enabling fast and proper disassembly and recycling** (including detailed information on contained materials and for facilitating direct recycling instead of melting), SoH information, information for independent service professionals for diagnosis, maintenance, battery / cell replacement and repurposing of batteries.		Noted. Added to the position papers/

Task #	**Section #**	**line #**	**Topic**	**Comment**	**Proposed change**	**Reply study team**
7	7.1.2.1		Minimum battery pack/system life time requirements	**We support the definition of clear minimum performance requirements that must be achieved for a minimum lifetime**. While defining appropriate test standards will be of paramount importance, alternative instruments should also be considered, e.g. manufacturer information on expected lifetime and performance.		
7	7.1.3.4		Other minimum battery pack design and construction requirements to support reusability/recyclability/recoverability	We support the proposal to have **requirement on minimum battery pack design and construction to support reusability/recyclability/recoverability**		Noted FYI: this is not supported by any manufacturer.
7	Table 7-5		Table 7-5: Concept format on scoping enquiry (to be decided later)	We encourage the study team to **consider a scope extension** and necessary modifications in policy measures as indicated in Table 7-5.		Noted FYI: this is not supported by the Recharge battery manufacturers neither Applia as a federation of Appliance manufacturers.

Annex C4. Stakeholder ED Battery Comments – APPLiA

DG ENER Lot 37: Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage

Please note that the comments will be published and used for the work of this preparatory study. If you have useful data that can be disclosed in an aggregated form that requires an NDA please contact the study team.

<table>
<tr><td colspan="4">Organization: APPLiA</td><td>Name: Giulia Zilla</td><td colspan="2">Date: 23 May 2019</td></tr>
<tr><td colspan="4"></td><td></td><td colspan="2"></td></tr>
<tr><td>Task #</td><td>Section #</td><td>line #</td><td>Topic</td><td>Comment</td><td>Proposed change</td><td>Reply study team</td></tr>
</table>

	7.1.4.	35	**Recommendations on opportunities to extend the scope of policy measures**	APPLiA strongly supports the recommendation given by the Consultants at page 35. Among the valid reasons provided already by the consultants, we would like to stress the need to exclude from the scope batteries < 2kWh and in particular batteries contained in cordless home appliances for the following reasons: **1.** Broadening the scope of the preparatory study would require a new preparatory study, including an examination of all existing low-capacity battery applications and life-cycle analyses in collaboration with relevant stakeholders. **2.** The draft tasks clearly show how the highest environmental and energy benefits rely on batteries above 2kWh and in particular to e-vehicles application. As it was displayed during the 2nd Stk meeting (here) in the Task 2, indeed, the largest energy savings and environmental benefits come from the production phase. Knowing that batteries produced in Europe are mainly the one meant for e-transport (above 2kWh), there would be no real benefit in regulating low capacity batteries which are mainly produced outside Europe. **3.** We do support the MEErP methodology and we invite the Consultants and/or the Commission to use a similar method in developing the future regulatory framework for this study.	***We do not recommend extending or review the scope relative to the proposal in Task 1.***	Noted; we will add this to the position papers

	7.1.4.	35	**Recommendations on opportunities to extend the scope of policy measures**	Other rational and technical reasons are the following: Small battery packs (< 2kWh) in cordless home appliances are already subject to regulation under the WEEE Directive (e.g. collection) Home appliances are subject to product-specific ecodesign regulations and should be regulated coherently; 'double regulation' must be avoided There are no standards to underpin policy proposal for low capacity batteries	***We do not recommend extending or review the scope relative to the proposal in Task 1.***	Noted we will add this to the position papers

Annex C5. Stakeholder ED Battery Comments - Nissan

From: TAKEHANA, TOMOKO <takehanatomoko@mail.nissan.co.jp>

Sent: Monday, 27 May 2019 05:22

To: ZZ Email ED Batteries

Cc: HASEGAWA, TETSUO; IKEDA, MAKOTO; YOSHIDA, MAKOTO; TSUZUKI, MIKIO; SUZUKI, YUKAKO; IWASAKI, MASAHIKO; UMETSU, MASAAKI

Subject: Nissan comments for Task7

Dear Sirs or Madams,

My name is Tomoko Takehana and I am responsible for EV technical affairs at Nissan Motor Co.Ltd. We have no specific comments, however, we are herewith sending you the Nissan's general comments below;

Nissan supports the activity to study on battery sustainability.

In the era of widespread use of electric vehicles, battery reuse is the necessary efforts in order to prevent global warming on the carbon footprint and resource circulation. Nissan has been continuously working on battery 4R(Reuse, Resell, Refabricate and Recycle).

At the next stage of this activity, Nissan would like to focus on the following discussion for the implementation such as the FU (functional unit) from the viewpoint of the environmental impact and life cycle energy storage capacity, and requirements relating to the battery life time and BMS information, etc. And we would like to discuss with you if needed and contribute to EU market sustainability.

Best regards, Tomoko Takehana Senior Manager

Global Technical Affairs Department

Tetsuo Hasegawa General manager

Global Technical Affairs Department Nissan Motor Co. Ltd.

Annex C6. Stakeholder Position Paper – ECOS, EEB, Coolproducts, IFixit, RREUSE

Brussels, 17 May 2019

Europe needs an ambitious regulatory framework to guarantee sustainability of batteries

Adopting sustainability requirements for batteries is crucial, as the electrification and decarbonisation of various sectors, such as mobility and energy storage, depends on the rechargeable battery technology. Lithium-ion batteries represent a rapidly growing global market which warrants an EU level response to avoid lock in to linear sub-standard industrial patterns and give a competitive advantage to EU industry to compete on quality. To fully capture the benefits of decarbonising the economy through electrification we need to address the environmental impact of battery production in terms of CO_2 emissions, resource depletion and ethical sourcing.

Although batteries will be an essential product in the EU's pathway to decarbonization, their material composition and non-use phase impacts necessitates that they are viewed as highly valued and strategic products from the EU environmental policy point of view. In the context of sustainable production and consumption, this means accelerating the roll out of well-designed clean, circular and durable batteries, while avoiding stifling innovation or that unnecessary, wasteful and polluting products reach the market. If batteries are made easy to refurbish, re-use and maintain for as long as possible, there is also an occasion to create new local jobs in the EU.

Following the discussions at the stakeholder meeting on the preparatory study on Ecodesign and Energy Labelling which took place on 2nd May, we are concerned about the lack of a clear vision on what could be an ambitious, effective, and fit-for-purpose European regulatory framework for batteries.

A robust stand-alone European Regulation for sustainable batteries.

In that respect, we call for an ambitious set of rules regarding the sourcing of raw materials, the design and manufacturing stages of batteries, as well as the necessary information to be conveyed to end users and the supply chain actors to be set **in (a) European Regulation(s)**. Batteries put on the single market must have robust sustainability requirements ensuring, *inter alia*:

- A **reduced carbon footprint** over the whole product value chain and the full production cycle.
- An **ethical and responsible sourcing** of raw materials.

- A **circular design**, incorporating recycled material and facilitating the reuse, repurposing, remanufacturing and ultimately recycling.
- **Transparent communication and tracking of performance** across these criteria and on material/chemical contents to end users and supply chain actors.

Although it became increasingly clear that these rules will not be set under the framework of the Ecodesign Directive, we urge the Commission to keep a high level of ambition in terms of legal instruments and requirements to place batteries on the EU market. A Regulation has the potential to set harmonized rules across the single market, reduces the risks of fragmented national implementation, and will apply to all batteries placed on the EU market. Similarly high ambition should apply to the **revision of the Batteries Directive**, which we expect to set high collection and recycling targets for critical battery materials, clearly define the responsibilities of each actor in the value chain and drive the circularity of batteries. This would reinforce and complement the requirements to be set for the design stage and the placement on the market outlined in this letter.

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Annex C7. Stakeholder Position Paper – RECHARGE

Advanced Rechargeable and Lithium Batteries association

January 2019

Ecodesign Directive for Batteries

RECHARGE View on Criteria for Sustainable Batteries

Introduction

Over the next 15 years, a **significant and constant growth is expected in battery volumes** placed on the market, driven *inter alia* by the introduction of Battery Electric Vehicles (BEVs) which are expected to take a sizeable share of the Personal Car (PC) and Light Commercial Vehicle (LCV) markets.

Issues such as **sustainability** and **minimal environmental impact** of battery and its industry have been raised as **key aspects to be addressed**. In this context, the Ecodesign directive for batteries has been considered as a potential legislative tool to address most of these issues.

RECHARGE acknowledges this effort towards a sustainable industrial policy for batteries, however would like to stress that **the quality of the work should not be undermined in favor of a quicker legislative process**. Particularly, **the scope of the ECODESIGN for batteries should be enlarged to include the impacts from cradle to grave**, throughout all phases of a battery life from manufacturing (including the supply chain), use and to the end of life.

RECHARGE suggests some proposals, based on the key takeaways from RECHARGE's internal working groups, and the project for batteries within the Commission pilot "Product Environmental Footprint".

Key priorities for sustainability requirements for batteries

- **A result-oriented Ecodesign directive for batteries, focused on recognized and measurable impacts.**

As an overall recommendation, RECHARGE stresses that the Ecodesign directive **should not impose requirements on the very technical choices related to design and the process,** due to the infancy stage of batteries designs and industry processes for e-mobility, as many competing solutions are foreseen to increase the battery performance, and many more will be identified.

- **Raw materials:** Ensure the setup of take back and recycling systems.

Market projections for 2030 point to volumes up to 400 GWh or more[1]of batteries placed on the market per year, which equates to approx. 1.6 million tons a year. High performance Li-ion batteries require the use of some rare metals with a limited supply. It is therefore **necessary to establish take back and recycling systems, so that this source of secondary raw materials becomes available in Europe.**

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[1] CEPS report No 2018/05, July 2018, Eleanor Drabik and Vasileios Rizos

It is however important to note that within the EU, an **Extended Producer Responsibility regime is already in place thanks to the battery directive**, whereby all used batteries must be taken back by Producers and recycled. This directive is currently undergoing a revision process, which could be used to further improve this instrument, should the need arise. For example, we recommend to recycle metals such as cobalt and nickel in Li-ion batteries *"to the highest degree that is technically feasible while avoiding excessive costs"*).

- **Climate change:** $CO_{2\ eq}$ content of finished e-mobility batteries as a criterion to discriminate across products placed on the EU market

Electrification of road vehicle transportation aims at improving air quality within urban areas and reducing CO2 emissions. The manufacturing of a battery, which weighs up to 40% of the vehicle for a BEV, is a new source of CO2 emissions, and should be a component of the assessment the European Commission lays out (see annex).

The DG Environment PEF, despite still in need of much improvement and simplification, highlighted that **batteries impact can differ significantly across models on this criterion**, and demonstrated that a large fraction of impacts arises from metals extraction and refining as well as in the manufacturing of other components, whereas actual manufacturing operations (under the roof of the battery maker) and use in the vehicle have relatively limited impacts (see annex).

$CO_{2\ eq}$ content of finished e-mobility batteries, normalized by total kWh output throughout the life of the battery, **should be a critical criterion to discriminate across products placed on the EU market**. Furthermore, low performing products should not be placed on the market, and identification should be implemented **to differentiate and incentivize higher performance products**.

- **CSR principles:** Encourage the industry to source from supply chains located in countries implementing the 8 ILO conventions and truly apply them within their facilities.

Much has been published on the way some supply chains either violate workers' rights or show disregard for the behavior of upstream operators. International bodies have created a legal framework to ensure a minimum set of standards be introduced in all national legislation, namely the 8 fundamental International Labor Organizations (ILO) Conventions.

To **avoid a possible trade-off between better environmental performance and degraded treatment of workers**, the legislative environment should encourage industry to source from supply chains located in countries, which fully implement these 8 ILO conventions and truly implement them within their facilities.

- **Implementation principles** in line with Understandable, Standardized, Accurate, Discriminating and Auditable Standards

These criteria should be implemented along with U.S.A.D.A. standards, which means they ought to be **Understandable**, **Standardized**, **Accurate**, **Discriminating** and **Auditable**. The complete PEF methodology is not fulfilling these criteria.

Comments of the proposed policy options of the inception impact assessment are presented in annex.

About

RECHARGE aisbl is the Advanced Rechargeable and Lithium Battery Association representing the specific interests of the Rechargeable Battery Industry in Europe. RECHARGE's mission is to promote the value of advanced rechargeable batteries through their life cycle. RECHARGE's Members include Rechargeable Battery Manufacturers, Original Equipment Manufacturers, Rechargeable Batteries Recyclers and Raw materials suppliers to the Battery Industry.

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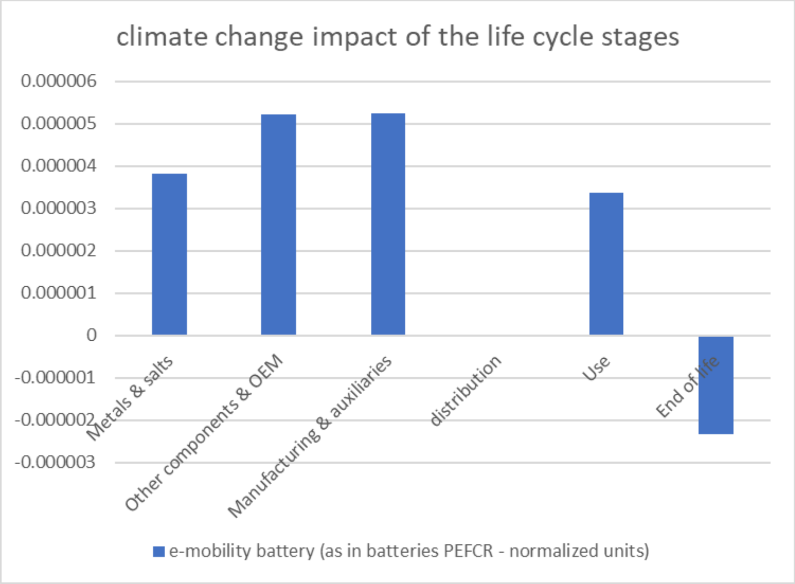
ANNEX: Batteries climate change impact (based on Batteries PEFCR)



Explanation of graph

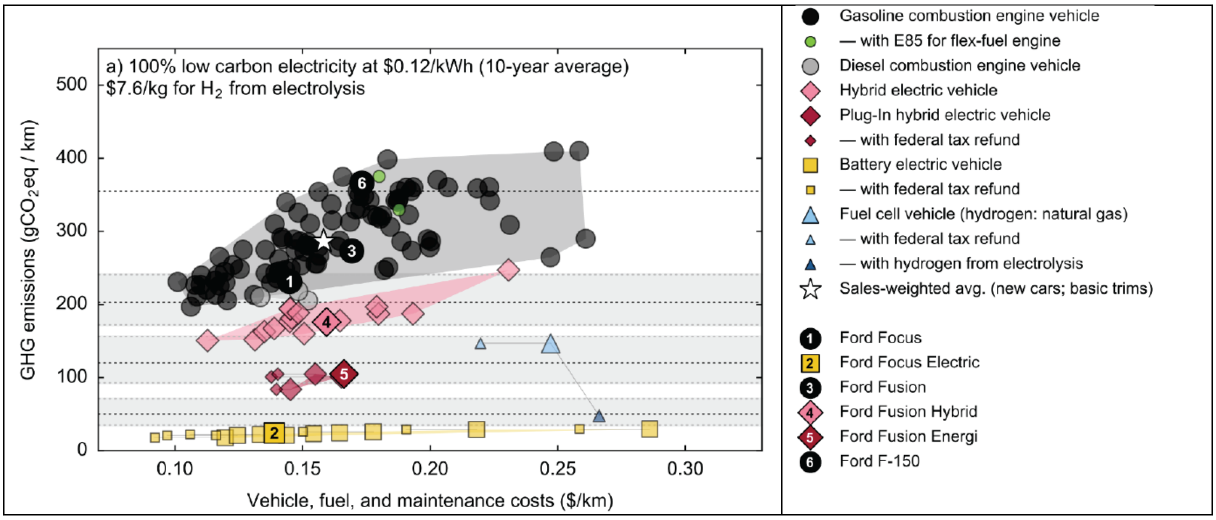
- The climate change impact is measured in “kg CO_2-equivalent”, before normalization (according the batteries PEFCR).
- ***Metals and salts:*** impact of the acquisition of the raw materials and transformation as batteries active materials (batteries cells material).
- ***Other components and OEM***: impact of the batteries components such has electronics for safety protection and management, cooling systems as designed by the OEM (Original equipment manufacturer).
- ***Manufacturing and auxiliaries***: impact of the cells and batteries manufacturing and assembly
- ***Distribution:*** impact of the transport and distribution, including intercontinental transport for the active materials.
- ***Use:*** impact of the electrical energy used in the battery during the use phase. Only the electrical energy losses of the battery are taken into account: the electrical energy transmitted to the vehicle is used by the vehicle, not by the battery.
- ***End of life:*** net impact credit of the recycling operation, calculated according the circular economy formula of the PEFCR, after deduction of the impact due to the process of recycling itself.

Comments on Batteries climate change impact

- The impact of the use phase represents only around 20% of the total impact throughout the product life cycle.
- The main sources of impact are the materials and components acquisition, as well as the manufacturing phase.

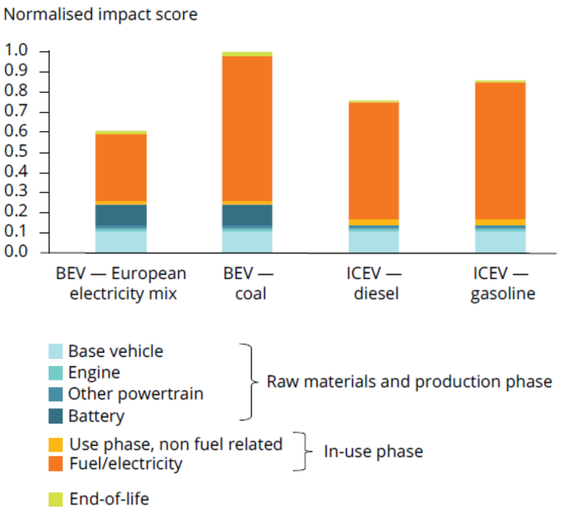
Vehicles climate change impact

On a full lifecycle basis and decarbonized grids (24 gCO2e/kWh), electrification is the THE ONLY known technology to meet the 2050 climate target of 80% reduction vs. 1990.[2] [3]



TODAY, on a full lifecycle basis, EV lifecycle emissions are better than all other options, at EU average mix (276 gCO2e/kWh).

Figure 6.1 **Climate change impacts: example comparison of BEVs with ICEVs**



Note: See footnote 8 for a description of the study system.

Source: Hawkins et al., 2013.

○ [4]

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[2] Trancik, J.E. et.al, Personal Vehicles Evaluated against Climate Change Mitigation Targets, Environ. Sci. Technol. 2016, 50, 10795−10804

[3] European Environment Agency (EEA) 2018: https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-2/assessment

[4] https://www.eea.europa.eu/publications/electric-vehicles-from-life-cycle

Analysis and proposals for the policy options

As a general comment on sustainability requirements, RECHARGE stresses that the Ecodesign Directive should **avoid any overlaps with the Battery Directive** and any **specification of a technical solution**, but should rather focus on the criteria rewarding environmental and social performance of the product. Moreover, the selected **criteria should be evenly applicable to all batterie**s in the scope which are used in Europe, **including the imported products**.

Consequently, RECHARGE supports the implementation of a combination of targeted parts of the policy option outlined in the European Commission's Inception Impact Assessment:

Option 1 *No EU Action*

- RECHARGE does not consider option 1 is an efficient way to reach the objective, due to the high competition in battery manufacturing which does not leave room for a fair development of best social and environmental practices if not rewarded.

Option 2 *Self-regulation by industry on the performance and sustainability of batteries*

- RECHARGE considers crucial to only propose regulation whereby economical competition does not drive the product design and manufacturing in a 'sustainable direction'.

Option 3 *Minimum energy performance requirements*

- RECHARGE stresses the importance of a differentiated approach for the battery performances requirements: some of the suggested life duration measures are not applicable due to the different nature and combination of the performance criteria depending on the application.
- Requirements for energy efficiency performance can be considered, as long as they provide potential benefit for a recognized environmental impact: the climate change. In this case, RECHARGE recommends creating a criteria for climate change impact of the complete life cycle, based on CO2 eq content of finished e-mobility batteries, normalized by total kWh provided.

Option 4 *Minimum sustainability requirements*

- As in option 3, RECHARGE stresses the importance of a differentiated approach. In case of recyclability, there are already existing criteria in the Batteries Directive. To avoid any overlaps, RECHARGE suggests redefining the **criteria for recycling only in the Batteries Directive,** if changes are needed.

Option 5 *Criteria on ethical sourcing of raw materials for the production of batteries*

- RECHARGE supports the set-up of a criteria for Corporate Social Responsibility, such as the ILO standards, in particular for raw material sourcing but not limited to it.

Annex C8. Stakeholder Position Paper – HIU, ITAS

Comments on:

DG ENER Lot 37: Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage

- Position paper –

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An eco-design and circular economy directive should consider all aspects of environmental sustainability. Thus, we consider the current scope of the study as problematic, with its very exclusive and, in our opinion, very one-sided focus on the carbon footprint (CF). While being the CF highly relevant, there are other potential environmental impacts that might me as least as relevant or critical [1,2]. Apart from the resource demand itself, we know of high environmental impacts from resource mining, especially cobalt, but also nickel and copper required for current lithium-ion batteries (LIB). These include toxic impacts for workers, but also acidic emissions from ore roasting (acidification) and leaching of toxic and acidic substances from mine tailings. The current knowledge base in this regard is admittedly weak, but a comprehensive Ecodesign should not disregard potential impacts simply because of missing information or higher uncertainties. Existing LCA studies indicate that the toxic impacts from battery manufacturing are very high and would lead to highly unfavourable lifetime results for EV in comparison to internal combustion engine vehicles (ICV) [1].
This might be a consequence of the comparably superficial literature review done in Task 5, which does not consider major studies and disregards relevant impact categories (as also addressed in the review comments). Here, a more comprehensive review would be helpful for providing a sound basis for the following tasks. This is surely a work intensive task and would probably affect the timing of the project, but we consider a thorough knowledge of the current state of the art as a key for providing further recommendations.

A second aspect little considered in the current draft of the study but essential under a circular economy paradigm is assuring the right fate for waste batteries. While talking a lot about second life options, a look into the current ICV market shows that, given a sufficiently high stock of vehicles within the economy, a second hand market might evolve where parts (and possibly also batteries) are traded as second hand products for automotive use until their very end of life. This also includes international trade and the export of used batteries and electric vehicles (EV) into non-EU countries (in 2016, approx. 6 Mio EoL vehicles were recycled in Europe, while 17 Mio were newly registered [3]). In these countries, a proper recycling cannot be assured, and we know the fatal recycling practices in the informal sector from waste electric and electronic equipment (WEEE) and waste lead-acid batteries, leading to severe environmental and toxic impacts, affecting especially the poorest and less informed [4,5]. Thus, again following precautionary principles, it should be assured as far as possible that recycling takes place only in premises following high environmental standards. As long as recycling of LIB under these standards is associated with a cost, there will be little incentive for e.g., scrapyard operators to bring the battery to the recycler, and he/she will rather sell it for export. Although not a technical issue, we consider this aspect as highly relevant under sustainability aspects and ask for a mandatory deposit sufficiently high as to incentivise the return of used batteries to the OEM (the deposit return must be higher than the value an informal recycler could obtain from the raw materials). This would be a real step forward under circular economy aspects well worth considering in an eco-design directive.

Finally, we would like to comment on the questions raised regarding the scope of the study. As now, the scope is not properly defined from our point of view. The study neither covers a certain battery technology (lithium-ion), since it excludes relevant applications like mobile and handheld, toys, drones, robots and other (semi-) autonomous mobile applications. On the other hand, it neither covers all battery types potentially suitable for the considered applications (automotive and stationary). While for automotive applications LIB prevail (though solid state might become relevant in near term future), for stationary installations there is a competition between very different battery technologies (e.g., redox-flow, LIB, lead-acid, etc.). Applying eco-design requirements to just one of these battery technologies while disregarding the others or applying different eco-design requirements to different batteries seems odd under policy aspects and might even lead to market imbalance. As now, the study is limited to the eco-design of rechargeable lithium-ion batteries for automotive and stationary applications. We would urge extending the scope and applying an eco-design directive for lithium-ion batteries including all possible applications. Alternatively, the directive could be organised according to the application, resulting in a directive on automotive applications, one on stationary and one on mobile. This would allow considering better the specific requirements of the application, but requires finding a common base for defining requirements valid generically for all battery types.

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Annex C9. Stakeholder Position Paper EPBA

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EUROPEAN PORTABLE BATTERY ASSOCIATION

Brussels, 24 May 2019

EPBA's statement on

The preparatory study on eco-design and energy labelling of rechargeable electrochemical batteries with internal storage

The European Portable Battery Association (EPBA) is the leading voice of the portable power industry. The association supports the common interests of its members regarding portable primary and rechargeable batteries and battery chargers with European institutions and other leading international bodies to provide consumers with complete power solutions which are sustainable throughout their life-cycles.

EPBA has been following with great interest the discussions on eco-design and energy labelling of rechargeable batteries. Although the scope of this study – *high energy rechargeable batteries of high specific energy with lithium chemistries for e-mobility and stationary energy storage (if any)* - falls outside the remit of EPBA, we recognise that certain principles which are being discussed can also be of relevance towards the portable battery segment.

As a starting point, it is important to understand that various battery types have different technical specificities. This basically means that what can be applied to an industrial battery can very likely not be applied in the same manner as for portable batteries. For this reason, statements which have been made at the stakeholder workshop to include in its scope also portable batteries should be approached very carefully. So far, the eco-design discussions only looked into batteries for electric vehicles/stationary power. Any inclusion of portable primary and/or rechargeable batteries should therefore require a separate discussion.

This distinction is also reflected in the discussions concerning reusability, reparability and recyclability. The application of these *circular economy* principles can differ subject to the battery type. Again, what can work for a large industrial rechargeable battery does not necessarily work for a small consumer battery. The EPBA has developed a document which explains how the fundamental aspects of the circular economy apply to the portable battery sector. In the case of primary and rechargeable batteries, the reparability and reusability concepts are not applicable for the reasons outlined in the document however, resource efficiency, recyclability and resource management are well integrated in the practice of the battery industry (link to document).

Finally, this study is being developed in parallel to the revision of the Batteries Directive 2006/66/EC. In addition, guidelines will be developed on setting modular fees in the context of EPR which will be largely based on circular economy principles. It will therefore be important that all these discussions will lead up to a coherent policy framework. In order to have workable and efficient legislation, definitions should be aligned and coherent and inconsistent overlaps should be avoided.

We remain available for further discussion and can be reached via:

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