CLIMATE CHANGE

40/2019

GHG-neutral EU2050: scenario of a European Union with net-zero greenhouse gas emissions

Technical Annex

German Environment Agency

Umwelt Bundesamt

CLIMATE CHANGE 40/2019

Ressortforschungsplan of the Federal Ministry of
Environment, Nature Conservation and Nuclear Safety of
the Federal Ministry for the Enviroment, Nature
Conservation and Nuclear Safety

Project No. (FKZ) 3716 41 109 0

Report No. FB000147/ZW,ANH,2,ENG

GHG-neutral EU2050: scenario of a European Union with net-zero greenhouse gas emissions

Technical Annex

by

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On behalf of the German Environment Agency

Imprint

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Report performed by:
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Report completed in:
April 2019

Edited by:
Section V 1.2 Strategies and Scenarios for Climate and Energy
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Publication as pdf:
http://www.umweltbundesamt.de/publikationen

ISSN 1862-4804

Dessau-Roßlau, November 2019

Abstract:

GHG-neutral EU2050: scenario of a European Union with net-zero greenhouse gas emissions

Given that the Paris Agreement has strengthened the long-term temperature goal and that it calls for a balance of greenhouse gas (GHG) emissions and sinks within the 21st century, there is the urgent need to re-assess the long-term targets of the EU and to show how the target of GHG neutrality can be reached in the EU. The aim of this study was to design a scenario called "GHG-neutral EU2050" as one way to realize a European Union with net-zero greenhouse gas emissions under further sustainability criteria. The scenario shows that a GHG-neutral EU is feasible even without the use of carbon capture and storage and with limited amounts of bio-energy. Key components of the scenario in all energy-consuming sectors are a strong increase in energy efficiency as well as far-reaching electrification. These measures can reduce the final energy demand (incl. international transport) by about 37% and the share of electricity can be increased to almost 50%. In addition, a broad portfolio of other renewable energy options has to be exploited and substantial quantities of renewable fuels are required, which are produced from renewable electricity via electrolysis or based on biomass. Due to unavoidable GHG emissions from agriculture, industrial processes and waste treatment, achieving GHG neutrality also requires lower activity of the agricultural sector and an increased GHG sink from forestry. Besides the detailed quantitative description of a sectoral setup for all GHG-emitting sectors, the study contains a qualitative discussion of the sectoral options to reach GHG-neutrality, cross-sectoral interactions as well as the challenges associated with realizing such a scenario. This Technical Annex complements the full project report respective project (FKZ 3716 41 1090) by Duscha et al (2019) UBA Climate Change 40/2019).

Kurzbeschreibung:

THG-neutrale EU2050: Szenario einer Europäischen Union mit Netto-Null Treibhausgasemissionen

Mit dem Übereinkommen von Paris hat die Weltgemeinschaft das globale, langfristige Temperaturziel verschärft. Alle Staaten streben damit gemeinsam ein Gleichgewicht zwischen Treibhausgasemissionen (THG-Emissionen) und -senken innerhalb des 21. Jahrhunderts an. Somit ist es auch für die EU dringend erforderlich, ihre langfristigen Ziele neu zu bewerten und aufzuzeigen, wie THG-Neutralität in der EU erreicht werden kann. Ziel dieser Studie war es, ein Szenario mit dem Titel „GHG-neutral EU2050“ als eine Option zur Realisierung einer Europäischen Union mit Netto-Null THG-Emissionen unter weiteren Nachhaltigkeitskriterien zu entwickeln. Das entworfene Szenario zeigt, dass eine thg-neutrale EU auch ohne den Einsatz der unterirdischen Speicherung von Kohlendioxid und mit begrenzten Mengen an Bioenergie machbar ist. Wesentliche Bestandteile des Szenarios in allen energieverbrauchenden Sektoren sind eine starke Steigerung der Energieeffizienz sowie eine weitreichende Elektrifizierung. Durch diese Maßnahmen kann der Endenergiebedarf (einschließlich des internationalen Verkehrs) um etwa 37% gesenkt und der Anteil des Stroms auf fast 50% erhöht werden. Dennoch muss das breite Portfolio anderer Optionen für erneuerbare Energien genutzt werden, und erneuerbare Brennstoffe, die aus erneuerbarer Elektrizität durch Elektrolyse oder auf Biomassebasis hergestellt werden, werden in erheblichem Umfang benötigt. Aufgrund der unvermeidlichen THG-Emissionen aus Landwirtschaft, Industrieprozessen und Abfallbehandlung sind jedoch eine geringere Aktivität des Landwirtschaftssektors und eine erhöhte THG-Senke aus der Forstwirtschaft erforderlich. Neben der detaillierten quantitativen Beschreibung der sektoralen Ausgestaltung aller thg-emittierenden Sektoren enthält die Studie eine qualitative Diskussion von sektoralen Spielräume zur Erreichung von Treibhaus-neutralität, von sektorübergreifenden Interaktionen sowie von Herausforderungen bei der Realisierung eines solchen Szenarios. Dieser Technischer Anhang ergänzt den Hauptbericht zum Projekt (FKZ 3716 41 1090; vgl. Duscha et al. 2019: UBA Climate Change 40/2019).

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CCS	Carbon capture and storage
CH_4	Methane
CO_2	Carbon dioxide
CO_2-eq.	Carbon dioxice equivalents
COP	Conference of the Parties
CRF	Common Reporting Format
DAC	Direct air capture of carbon dioxide
EC	European Commission
EU	European Union (with 28 MS as of 2018)
EU-ETS	EU Emissions Trading Scheme
F-gases	Fluorinated greenhouse gases
FTIP	Federal Transport Infrastructure Plan
GHG	Greenhouse gases
HGV	Heavy goods vehicle
HWP	Harvested wood products
ICAO	International Civil Aviation Organization
IMO	International Maritime Organization
KP	Kyoto Protocol
KSBV	UBA study Klimaschutzbeitrag des Verkehrs bis 2050 [UBA, 2016a]
LU	Livestock Unit
LULUCF	Land Use, Land Use Change and Forestry
MS	Member States of the European Union
NDC	Nationally Determined Contributions (in Paris-Agreement)
NEDC	New European Driving Cycle
Novel fuel	Renewable fuel based either on biomass or renewable electricity
N_2O	Nitrous oxide (laughing gas)
PJ	Petajoule (energy measuring unit)
PtG	Power-to-Gas (any power-based gaseous fuels)
PtH	Power-to-Heat (any power-based heat including heat pumps)
PtL	Power-to-Liquid (any power-based liquid fuels)
PtX	The total of PtG, PtH and PtL
PV	Photovoltaics
RDE	Real Driving Emissions
TWh	Terawatt hours (measuring units for energy)
UNFCCC	United Nations Framework Convention on Climate Change
WHO	World Health Organization

CCS	Carbon capture and storage
WLTP	Worldwide Harmonized Light-Duty Vehicles Test Procedure

A Energy supply

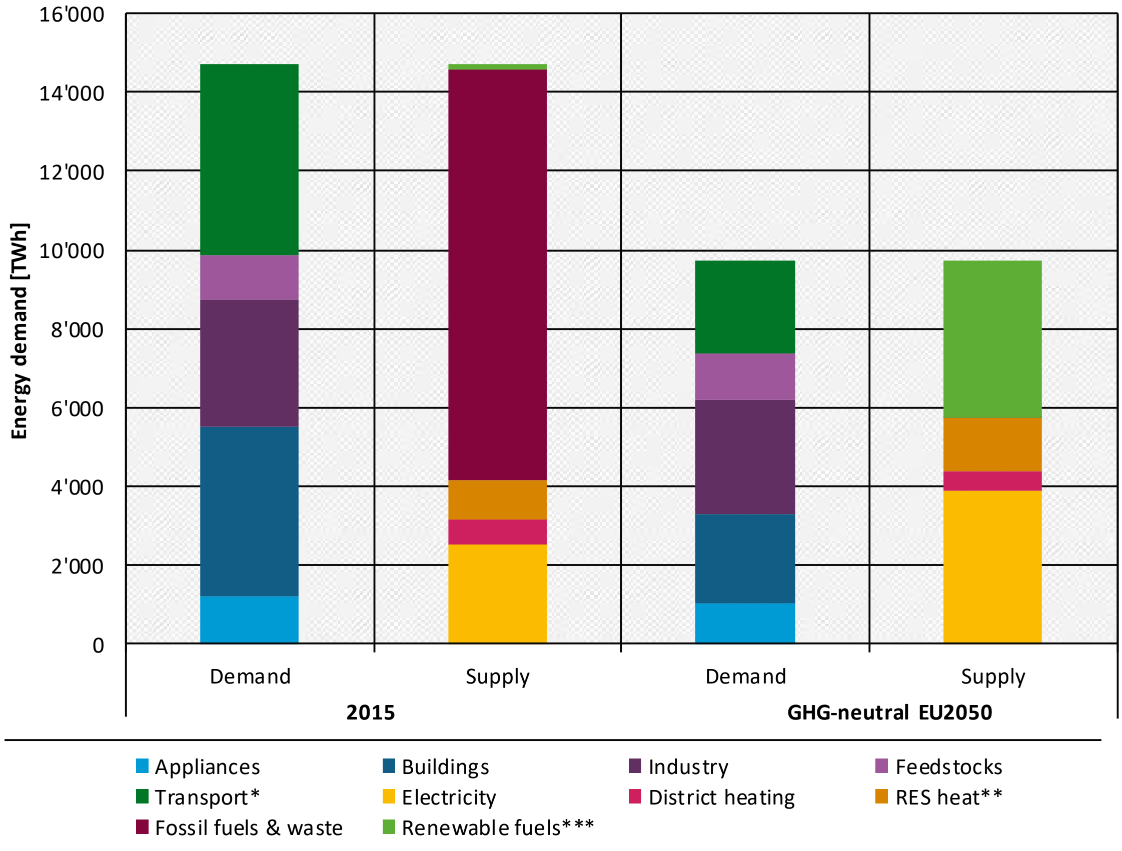
A.1 Introduction

The final energy demand including the demand for industrial feedstocks in the scenario GHG-neutral EU2050 is fully determined by the considerations of sectors in the Sections B – F. This section, hence, builds on the findings for those sectors and describes how this demand can be met in a GHG-neutral way, including all conversion losses. To this end, we aggregate the sectoral energy demands in the next subsection and turn to the supply side in the following one.

A.2 Final energy demand in the scenario GHG-neutral EU2050

The change of the final energy demand in each energy-consuming sector in the scenario GHG-neutral EU2050 is described in Sections B – F. The largest demand reductions take place in the transport and in the buildings sectors with 52% and 47% respectively, resulting from much more energy-efficient vehicles and buildings as well as a strong electrification in both sectors, see Figure A 1. Incremental efficiency gains lead a reduction of the energy demand of industry and appliances by 12% and 14% respectively, while the non-energy demand for industrial feedstocks even increases by 6% due to a slight increase in production, in particular in the chemical industry.

Figure A 1: EU final energy demand in 2015 and in the scenario GHG-neutral EU2050



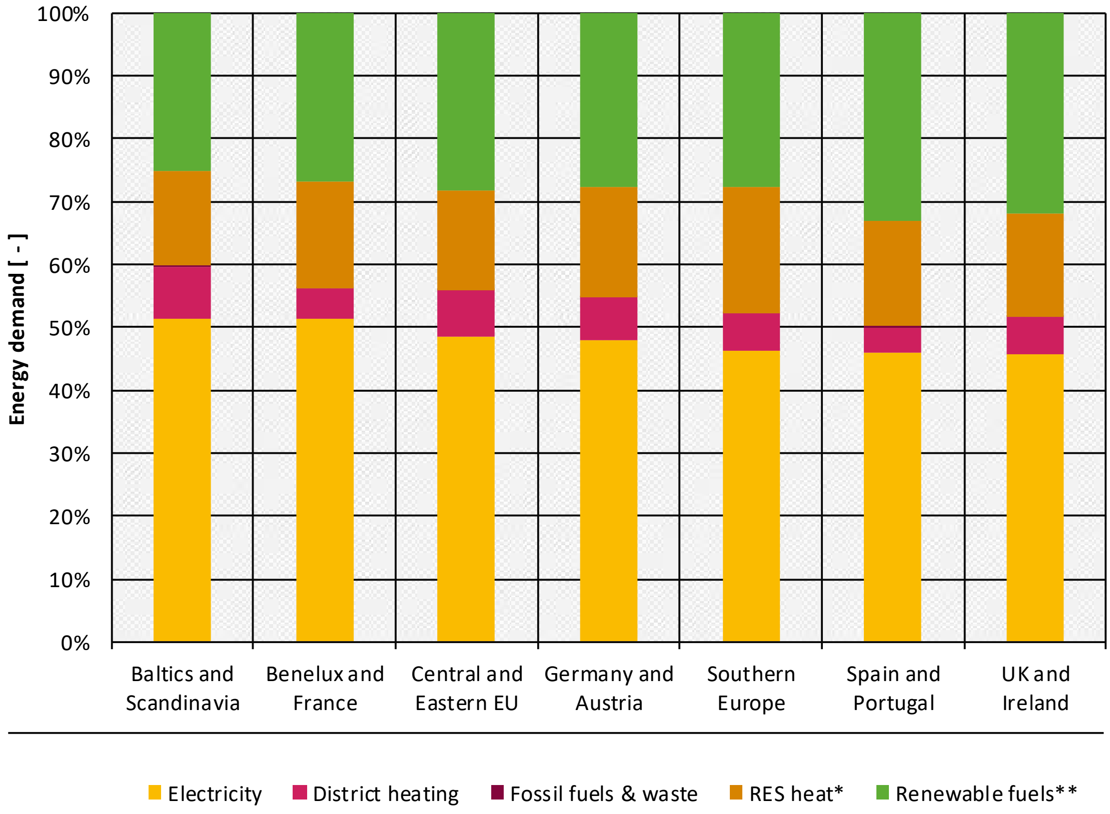
* including international aviation and navigation; ** including biomass use in industry in 2015; *** biofuels in 2015

Source: own calculation based on EUROSTAT (2017)

Aggregating those demand changes implies that the total final energy demand is reduced by roughly one third, from about 14.700 TWh in 2015[1] to about 9.700 TWh in 2050 (including industrial feedstocks as well as international aviation and navigation). The reduction of energy-related GHG emissions by 99% is further achieved by substituting fossil fuels, whose share in the energy mix was larger than 79% in 2015, completely with electricity, district heat, RES heat (ambient heat, solar thermal and bioenergy) and *novel fuels* (hydrogen, synthetic hydrocarbons and biofuels) so that emissions only remain from the incineration of unavoidable non-renewable waste. The strong electrification across all energy-consuming sectors results in an increase of final electricity demand by 53% compared to 2015, thereby increasing its share in the energy mix from 17% to 40% (almost 50% excluding feedstocks). The use of district heat only slighty increase from 4% to 5%, while the share of RES heat doubles from 7% to 14%. The remaining demand for fuels, which mainly stems from international transport, industry and industrial feedstocks, is covered by *novel fuels*, reaching a share of 41% in 2050 (32% without feedstocks) compared to 1% covered by biofuels in 2015.

The scenario GHG-neutral EU2050 takes regional differences in the energy demand structure into account (see Figure A 2). The electricity share is always in the order of 50% of the total final energy demand (excluding feedstocks and international transport), with the highest share in Scandinavia due to the large and cheap hydropower potentials.

Figure A 2: Regional final energy mixes in the scenario GHG-neutral EU2050



Source: own calculation based on EUROSTAT (2017)

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[1] Even without international navigation, the final energy demand in 2015 according to EUROSTAT (2017) has been about 3% lower. This mainly reflects that the official statistics contains no climate adjustment.

The district heating share ranges from 4% and 8%, with the highest share also in Scandinavia. Fossil fuels and non-renewable waste play a marginal role across all regions. The RES heat share varies between 15% and 20%, with the highest share in Southern Europe due to the higher solar energy potentials. The novel fuel share ranges from 25% and 33%, with the highest share on the Iberian Peninsula. In summary, the resulting regional energy mixes in the year 2050 do not differ strongly anymore because on the one hand, there is a high level of electrification across all sectors and regions and on the other hand, because *novel fuels* are needed to a certain extent in all regions for high-temperature heat and to compensate for seasonal fluctuations. Accordingly, the following more description of the supply side will not focus on the regional differences but provide an overview for the EU as a whole.

A.3 Methodology, assumptions and the underlying data set for the energy supply in the scenario GHG-neutral EU2050

All energy used in the scenario GHG-neutral EU2050 is either local renewable energy, such as solar thermal energy or biomass, or is supplied by the energy sector through district heating, electricity or novel fuels. The compositions of these three will be summarized in the following in ascending order of their share of final energy consumption. Before, we will take a closer look at the potential to use biomass for energy and feedstock purposes in a sustainable way. We end by discussing the resulting changes of the GHG emissions of the energy industries.

A.3.1 Biomass supply

The scenario GHG-neutral EU2050 applies rather strict sustainability criteria for the use of bioenergy. In general, the scenario assumes that arable land is used for food production and that harvested wood is increasingly used for non-energy purposes, e.g. in the construction sector. The biomass used for energy purposes predominantly comes from agriculture and forestry residues. The import of biomass from outside the EU is prohibited.

The sector results, in particular for LULUCF, agriculture and waste, mainly determine the available total biomass. However, the sector analyses could not cover a detailed quantification of the different bioenergy sources, in particular for residues. For this reason, the sector analyses are complemented by the detailed assessment of bioenergy potentials in Ruiz et al. (2015). That study considers three scenarios (high, medium and low availability of biomass) and provides quantitative results for each of the different types of biomass. This enables us to choose for each type of biomass the individual scenario that fits best with our sector assumptions. We summarize the main assumptions here.

For the development of bioenergy potentials, we assume that:

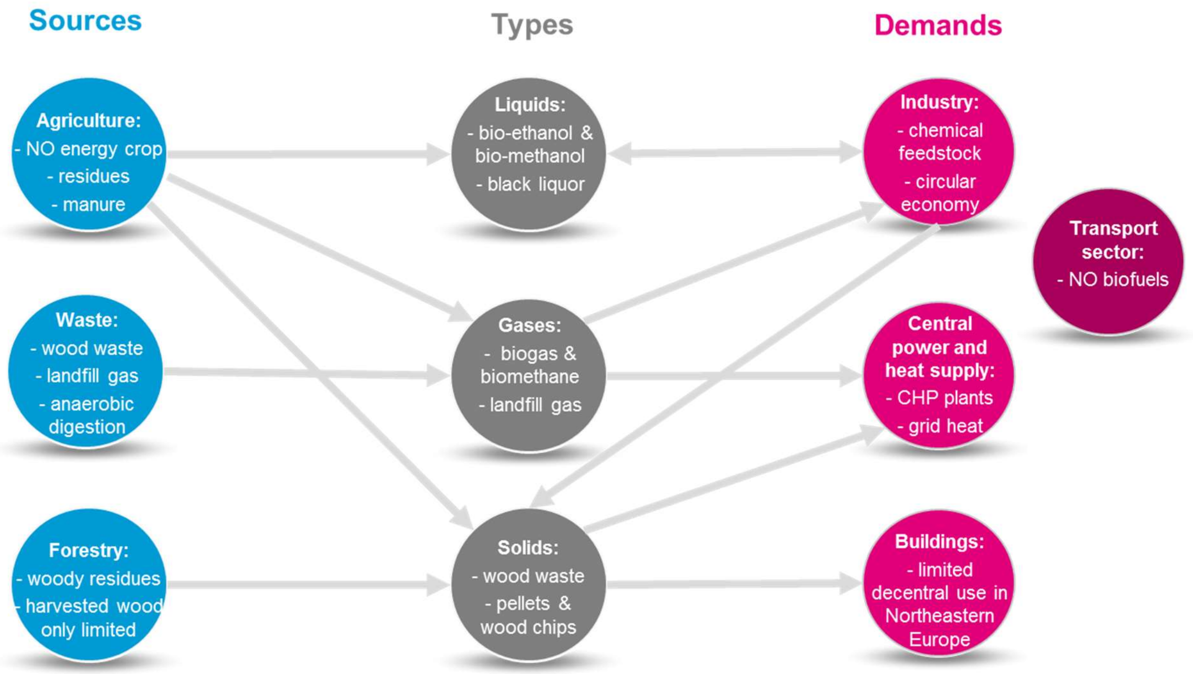
- Arable land is not used to grow energy crops anymore, i.e. there is no bioenergy from energy crops. Agricultural residues (e.g. straw) are collected and used for energy purposes according to the medium availability scenario from JRC 2015. For straw, however, the rate of collection is reduced to 20% based on sustainability considerations.
- Manure is used for producing biomethane according to the medium availability scenario from Ruiz et al. 2015 (50% of manure used for energy purposes), however, with animal numbers reduced to the assumptions for the agriculture sector.

- Waste of biogenic origin is used to produce biomethane via anaerobic digestion and recovery of landfill gas according to our assumptions in the waste sector.
- In accordance with our assumptions for LULUCF, total harvested wood is assumed to be stable. The share of harvested wood used for energy purposes is assumed to reduce from 45% of today to 25% in 2050.
- Forestry residues (sawdust, woodchips …) except for logging residues are collected and used for heating purposes according to the low availability scenario from Ruiz et al. 2015, which is consistent with our assumptions that harvested wood is stable.
- Total wood waste for energy purposes is assumed to remain stable at the level of 23.3 Mt. As non-energy use of wood increases, total wood waste should also increase so that the assumption implies also higher recycling rate for wood waste.
- Residues from the pulp and paper industry such as black liquor are used for energy purposes, as is the case today.

For the end use of bioenergy, we assume that biomass is not used to produce biofuels for the transport sector at all. Biomethane is predominantly converted to biomethanol to be used as a feedstock in the chemical industry, in particular for the production of propylene and BTX, as described in the annex on the chemical industry. Recycled plastics (which is then also of biogenic origin) is re-fed into the chemical industry as a feedstock as well.

The qualitative scheme applied to the use of biomass for energy purposes in GHG-neutral EU2050 is sketched in Figure A 3.

Figure A 3: Biomass scheme applied in GHG-neutral EU2050



Source: own representation (Fraunhofer ISI)

The resulting figures are presented in Table A 1. In total, the gross consumption of bioenergy amounts to 1062 TWh, which corresponds to roughly two thirds of the gross consumption in

2015 of 1584 TWh. Biogas, which can be converted into biomethane, is mainly provided by manure digestion. Liquid biofuels mainly originate from processing agricultural residues. Sources for solid bioenergy are more diverse with main contributions from wood waste, residues of the paper industry and the share of harvested wood available for energy purposes.

Table A 1: Gross bioenergy production assumed in GHG-neutral EU2050

Bioenergy [TWh]	Total
Gaseous bioenergy	**208**
- Manure digestion	173
- Anaerobic waste digestion	26
- Landfill gas recovery	9
Liquid bioenergy	**212**
- Agricultural residues	212
Solid bioenergy	**540**
- Forestry residues	30
- Wood waste	100
- Paper residues	67
- Harvested wood	343

Source: own calculation (Fraunhofer ISI) based on Ruiz et al. (2015)

A.3.2 District heating

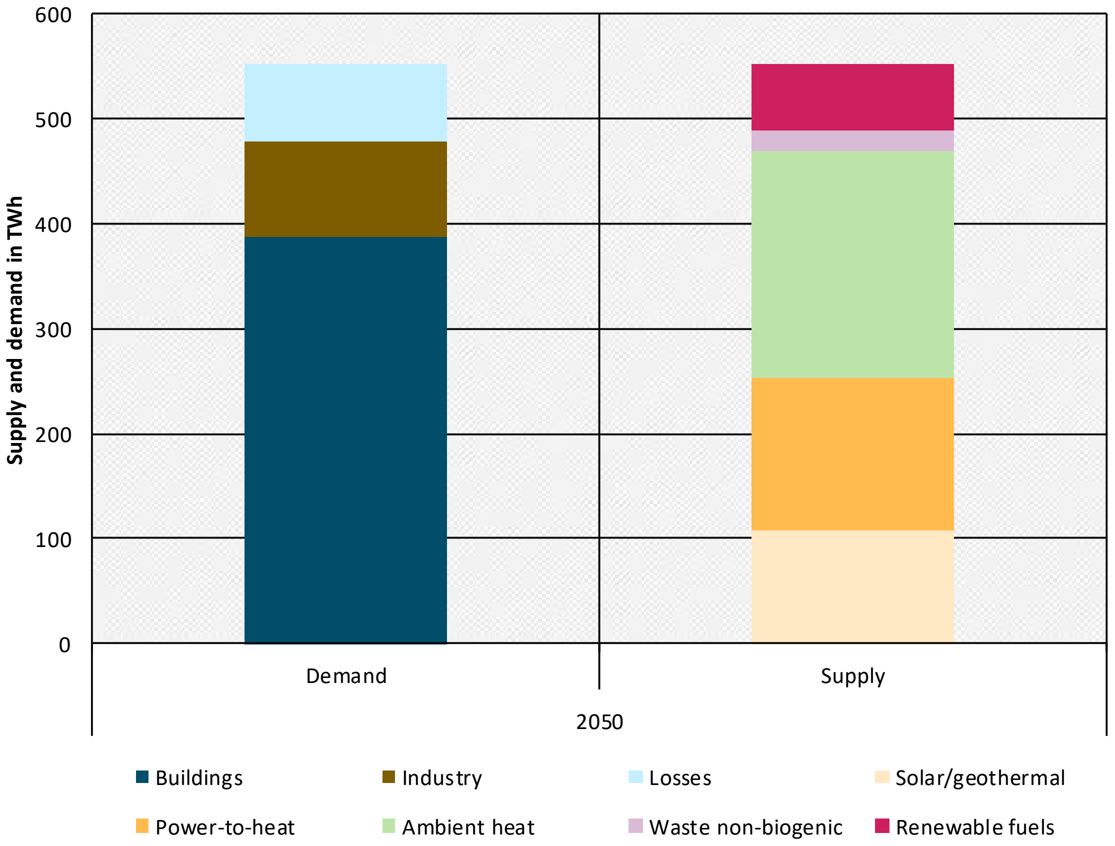
District heating plays a central role in the decarbonisation of the heat supply. The benefit of district heating is twofold: Firstly, it allows for an easier and cheaper integration of certain technological options. Heat storages, especially seasonal storages, are less costly at large scales, and they are critical for realising large share of solar energy on the supply side. The supply side can also profit from the economies of scale and from being situated close to, but not directly within densely populated areas. Secondly, heat grids allow for a smoother change during the transformation process. Heat grids initially supplied by gas can be switched to higher shares of renewable sources gradually. Steering the transformation by policy measures for a number of heat grids is less complicated then addressing a similar change in numerous individual heating systems.

The district heating demand, shown in Figure A 4 encompasses two demands: *Buildings*, consisting of heat demand for both households and the tertiary sector, as well as *Industry* demand, which includes demand for the industry buildings as well as certain process heats at low temperature levels. The total final energy demand amounts to 480 TWh. Losses are assumed to be at 15%, making up another 60 TWh. The – compared to today levels of around 12% -- relatively high losses account for the use especially in seasonal storages.

The district heat supply shows drastic changes from today's systems dominated by fossil fuels and waste firing. Fossil fuels are not burned at all anymore and non-renewable waste covers only 4% of the demand in the scenario GHG-neutral EU2050. 20% of generation is assumed to come from local renewable sources, i.e. solar and geothermal energy. This value has to be estimated, as there are currently no detailed studies in the required level of detail analysing the potential of these sources in a very deep decarbonisation scenario. While the value can probably be surpassed in several heat grids of small towns, reaching such a value will be challenging for large cities without geothermal resources. It will also only be possible by utilizing seasonal storage to counter the poor match between solar supply and heat demand.

The remaining part of supply has to come from electricity, either directly through Power-to-heat (PtH), i.e. heat pumps and electrode boilers, or indirectly through *renewable fuels*. While PtH has the advantage of a higher system efficiency, it is subject to the timely availability of RES or limited by the capacity of the heat storage systems. *Novel fuels* in turn show a substantially smaller system efficiency due to the losses in the conversion from electricity to the fuel, but can be stored almost without losses for long times. Therefore, the optimal ratio between PtH and *novels fuels* is essentially a question about the best way to store electricity from RES for a later conversion into heat. Exploratory model runs show that the better conversion efficiency leads to majority of the heat supply coming from PtH, namely 65% of total demand. The heat to power ratio is assumed to be 2.5; this is a cautious assumption, accounting for the fact that it is uncertain how many of the heat pumps will have to be air source heat pumps, which achieve lower efficiency than ground-source heat pumps. Furthermore, the share of generation electrode boilers is also uncertain, as it depends on a variety of factors not modelled in detailed here. The remaining 15% come from *renewable fuels*, which can be either hydrogen, or synthetic hydrocarbons (see following section) or come from biogenic sources; however, the potential of the latter is largely used in industry processes.

Figure A 4: District heating by demand and energy source in the scenario GHG-neutral EU2050



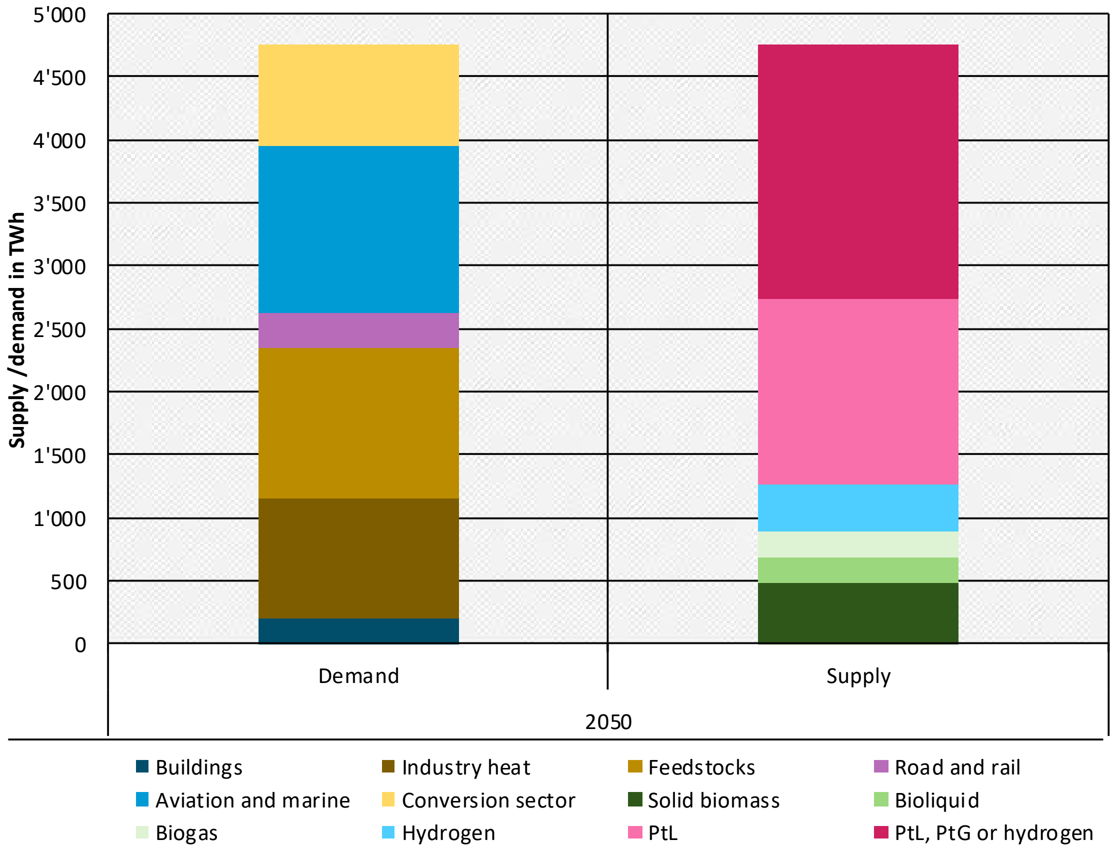
Source: own calculations (Fraunhofer ISI)

A.3.3 Renewable fuels

Renewable fuels are an important part of the energy balance of the GHG-neutral EU2050 scenario. It encompasses not only material energy carriers generated from electricity, such as hydrogen or synthetic hydrocarbons, but also biogenic energy sources and their derivatives not directly used locally. This categorisation is based on the observation that for many applications a material energy carrier is needed, but for the application itself it makes little or no difference whether the fuel comes from biogenic sources or from the conversion of electricity. In some areas either hydrogen or hydrocarbon could be used. However, for a range of other applications, a carbon-based fuel is necessary. The use of bioenergy follows a clear hierarchy in the scenario: the use as a raw material, in particular for the construction sector and the chemical industry are to be preferred.

Figure A 5 shows the composition of energy demand and supply for *renewable fuels*. Demand from heat in buildings shrinks substantially compared to today making up for only 5% of the *renewable fuel* demand in the scenario GHG-neutral EU2050. The demand from the industry is much higher, reaching almost 1,000 TWh for industry process heat and almost another 1,200 TWh for feedstocks. Overall, the industry sector is responsible for 45% of *renewable fuel* demand. The demand from the transport sector is largely driven by aviation and marine. Road and rail transport in turn amount to only about 6% of *renewable fuel* demand. The conversion sector uses another 800 TWh for peak gas turbines and district heating.

Figure A 5: *Renewable fuels* by demand and source in the scenario GHG-neutral EU2050



PtL = Power-to-Liquid, PtG = Power-to-Gas

Source: own calculations (Fraunhofer ISI) and Eurostat (2017)

It should be noted that we distinguish between different categories of *renewable fuels, namely* from

- biogenic sources (biomass, biogas, bioliquid)
- hydrogen,
- PtL and
- PtL, PtG or hydrogen.

The last category accommodates for the ambivalences and uncertainties of the *novel fuel* balance. While for example *hydrogen* refers to the use of hydrogen specifically – as opposed to hydrocarbons–, *"*PtL, PtG or hydrogen*"* means that basically any GHG-neutral fuel could be used.[2]

In the scenario GHG-neutral EU2050, a specific use of hydrogen is foreseen in two industry processes, steel production and as feedstock in ammonia production (in total 361 TWh). For many other energy demands, hydrogen is an option but not a necessity. For steel, hydrocarbons are also an option, but the applied models chose direct reduction with hydrogen as the decarbonisation route (see Section C).

The potential for hydrocarbons from biogenic sources amounts to 921 TWh in total: 501 TWh come from solid biomass that is not used locally for heating, 208 TWh come from biogas and 212 TWh in liquid form from agricultural residues (see Section A.3.1). When applying the hierarchy described in the beginning of this section, most biogenic sources are used for feedstock: Of the 1,198 TWh *renewable fuels* demanded therein virtually every process requires carbon, except for ammonia production (114 TWh, see above) and some minor other processes. This means that the novel fuel demand for feedstocks virtually consumes the full biogenic potential, which implies that biogenic sources can be factored out to simplify the calculations. While a different allocation of biogenic sources would be possible, it would not change the overall demand for novel fuels or change their compositions substantially.

In aviation and navigation, power-to-liquid is required totaling about 1,300 TWh. Overall, the demand for biogenic or electricity-based hydrocarbons totals about 2,400 TWh. The remaining demand for renewable fuels ("PtL, PtG or hydrogen") of 2,000 TWh could be supplied by hydrogen or liquid or gaseous hydrocarbons. Which energy carrier is preferable depends on a variety of factors, some of which are discussed in the following section.

A.3.4 Electricity

Virtually all energy carriers used in the scenario GHG-neutral EU2050 stem from renewable sources: they are either the direct or indirect use of electricity generated from renewable sources, local renewable heat such as solar thermal, or of biogenic origin. As biogenic sources contribute only a small part to energy supply due to their limited potential, electricity and energy carriers derived from electricity make up for the vast majority of total energy supply in the scenario GHG-neutral EU 2050.

Figure A 6 shows the composition of demand and supply for electricity. The first obvious difference to today in the increase of demand and supply in the order of 260%. The demand side is in 2050 divided in two components of similar size. The bottom parts are the direct use of

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[2] Of course, that does not mean that a fuel switch would be possible after the application has been installed, but that technological options exist to supply the demand from a range of fuels.

electricity: Buildings, referring to heat pumps and other PtH applications in buildings, and appliances and lighting create an electricity demand of 1,567 TWh, with an additional demand of 117 TWh for PtH in district heating. Industry consumes additional 1,535 TWh for process heat and mechanical energy. Road and rail contribute a demand of 761 TWh. Losses are assumed to increase to 7% of the previously mentioned types of consumption. Consequentially, electricity consumption of all demands besides novel fuel production amount to 4,338 TWh.

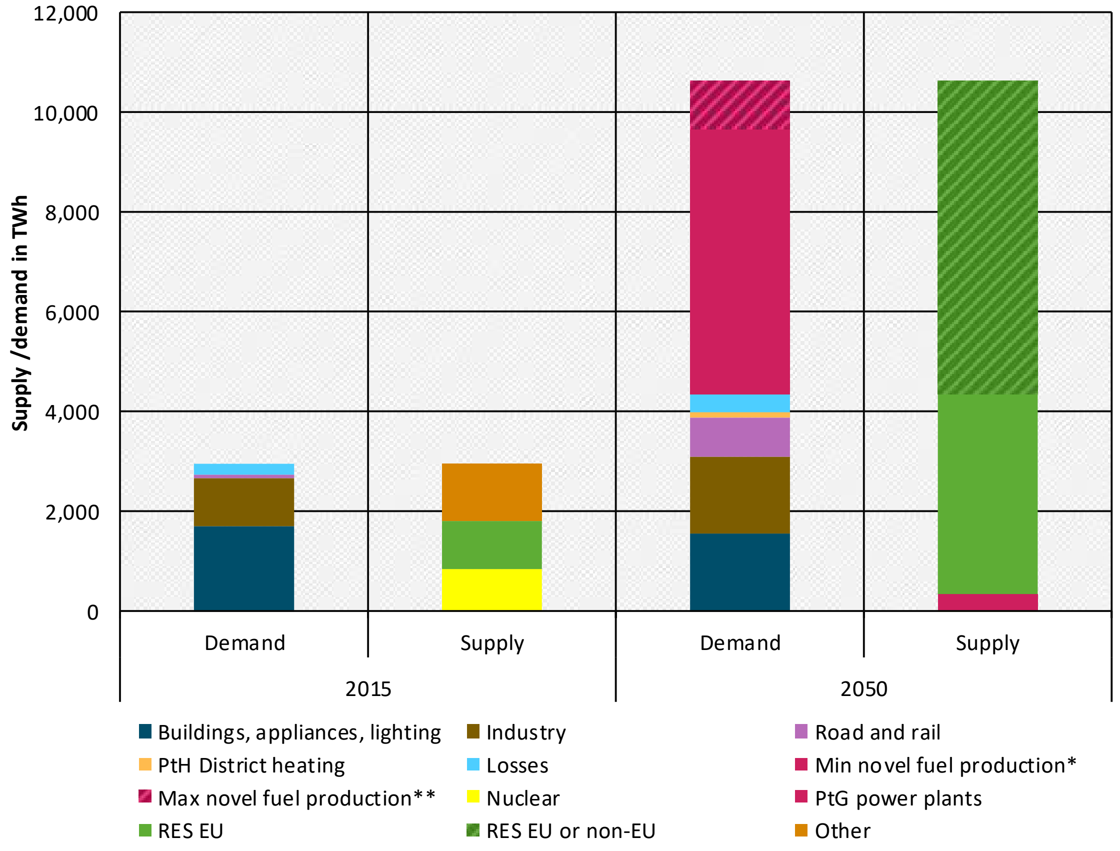
The concrete electricity demand for the production of *novel fuels* depends on the composition of the generated energy carriers: If all unspecified novel fuels (PtL, PtG or hydrogen) from the previous section would be implemented in the form of hydrogen, the minimum electricity demand for the generation of novel fuels would be 5.315 TWh. This would mean that all cars that are not BEVs would be fueled by hydrogen, and that both industry heat and building would rely on hydrogen. Whether such a development is feasible or economically desirable depends largely on the feasibility and costs of a future hydrogen infrastructure.

If all unspecified novel fuels would be hydrocarbons, this would lead to another 980 TWh of electricity demand, due to the losses in the additional conversion processes and the energy demand for generating CO_2-neutral carbon. In this calculation, we assumed the following conversion efficiencies:

- Hydrogen electrolysis: 85%
- PtG production: 62% (including electrolysis and CO_2 supply from direct air capture)
- PtL production: 58% (including electrolysis and CO_2 supply from direct air capture)
- PtL/PtG production: 60% (i.e., if the unspecified *novel fuels* are implemented as hydrocarbons, a 50/50 mix of PtG and PtL is assumed)

Hence, depending on the composition of the novel fuels, the electricity demand for their production varies between 5.315 and 6.296 TWh in the scenario GHG-neutral EU 2050.

Figure A 6: Electricity by demand and source in the scenario GHG-neutral EU2050



PtH = Power-to-Heat, PtG = Power-to-Gas

* Minimum novel fuel demand, if hydrogen is used wherever possible

** Maximum novel fuel demand, if synthetic hydrocarbons are used wherever possible

Source: own calculations (Fraunhofer ISI) and Eurostat (2017)

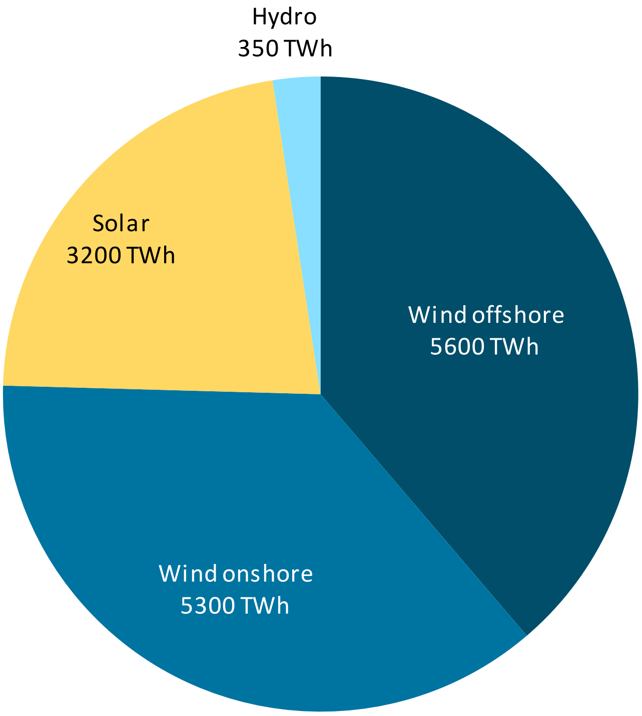
The supply side is dominated by generation renewable energy sources. The three nuclear reactors currently under construction contribute only 33 TWh, even when running almost continuously; all currently running reactors are assumed to be decommissioned before 2050. All electricity demand besides novels fuels is covered by electricity generation from RES in Europe. Furthermore, all hydrogen production also takes plays in Europe, preferably at the sites of consumption, as hydrogen transport is relatively costly in terms of efficiency. In consequence, the scenario requires a minimum RES production in Europe of 4.006 TWh. The remaining up to 6.296 for the production of *novel fuels* could be generated in the EU or in other countries.

What combination of production sites inside or outside the EU should be used for novel fuel production depends on a variety of factors not considered here in detail. However, the EU's RES potential alone would be sufficient to cover even the upper value of RES demand; this is true even when only wind, solar and hydropower are taken into account (see Figure A 7). Whether there is public acceptance for such an extensive utilization of RES in Europe is beyond the scope of this scenario.

In certain other regions, such as Norther Africa or the Middle East (MENA), potential restrictions and public acceptance may be less of a challenge. The solar potential of the MENA region dwarfs even the high power demand concluded for necessary for supplying all of EUs demand for synthetic hydrocarbon. However, water supply, climate neutral CO_2 sources and transport still have to be taken into account.

The question of how much *novel fuel* is needed to balance a system based largely in renewable energy is also not modelled in detail in this study. It is certain that reaching such high RES shares will require some form of electricity storage or backup power plants. In the scenario *GHG-neutral EU2050*, 300 TWh of power generation come from peak gas turbines using *renewable fuels*. This corresponds to approximately 7% of the electricity production needed for covering all power demand besides novel fuel production.[3] This value is estimated to be sufficient to cover demand in times of low RES supply, under the condition that grids are expanded adequately and other flexibilities options, such as demand side management, further contribute to the flexibility of the electricity system.

Figure A 7: Potential for RES electricity generation from wind, solar and hydropower in the EU[4]



Source: own calculations (Fraunhofer ISI) using the Enertile model

A.3.5 GHG emissions

In the scenario GHG-neutral EU2050, the central production of electricity and heat is free of GHG emissions, except for 8 Mt CO_2-eq. from the incineration of non-biogenic waste. Further-more, the production of *novel fuels* is assumed to be completely based on renewable electricity and thus also without any GHG emissions, given that the CO_2 used in its production is GHG-neutral. Since fossil fuels are not used anymore, current emissions from petroleum refining and other energy industries such as the manufacture of solid fuels are fully mitigated, too. Table A 2gives

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[3] As novel fuel production would take place only in times of high RES availability – which is the case very often in a scenario with such a high RES share – it would not increase demand for backup plants.

[4] The potential analysis is performed by the Enertile model based on a large number of parameters not discussed here. They include considerations of suitable sites, restricted areas, distance regulations, assumptions on maximum shares of land usage for RES power plants for the different land types as well as a detailed generation potential analysis derived from weather data. All of the potential shown here has electricity generation costs below 100 EUR/MWh.

an overview of historic and present day emissions, of which in total 99.5% are mitigated in the scenario GHG-neutral EU2050.

Table A 2: GHG emissions of EU energy industries in 1990, 2015 & in GHG-neutral EU2050

	UNFCCC 1990 [Mt CO_2-eq.]	UNFCCC 2015 [Mt CO_2-eq.]	GHG-neutral EU2050 [Mt CO_2-eq.]
Electricity & heat supply	1439	1075	8
Petroleum refining	123	116	0
Other energy industries	116	54	0
TOTAL	**1678**	**1245**	**8**
change vs. 1990		-26%	-99.5%

Source: UNFCCC (2017) and own calculation (Fraunhofer ISI)

A.4 Challenges

All pathways leading to a full decarbonisation face substantial challenges. It is necessary to distinct the “general” challenges that come with such ambitious transformation from the ones that come with the specific strategy of GHG-neutral EU2050. Broadly speaking, a possible classification of the challenges on the supply side is as follows:

1. Challenges related to cost
2. Challenges related to transformation speed
3. Challenges related to acceptance
4. Challenges related to coordination

These challenges in turn apply to almost all areas of the energy system, in which the transformation requires a substantial change from the status quo: The most obvious aspects is the required increase in the speed of the RES expansion and the expansion of facilities to produce (and transport) novel fuels.

For **district heating**, the challenges are comparatively low. That does not mean that the heat grid expansion required in the in the scenario GHG-neutral EU2050 will happen without policy measures. Still, in the four types of challenges listed above, the transformation speed is the most relevant; the other dimensions can be overcome by stringent policies. Furthermore, it will require a swift change towards heat pumps, renewable energy like geothermal and solar and *renewable fuels*. This will like require lowering the temperature of the heat grids, as well as the installation of thermal storages.

For the **renewable electricity**, the last three challenges discussed above are most important: transformation speed, acceptance and coordination. The current growth rates of RES in Europe are not in line with the necessities of GHG-neutral EU2050. Although the exact mix or location of the RES plants is not determined in this study, the order of magnitude can be estimated: Let us assume that of the almost 4,000 TWh RES electricity necessary in the EU – meaning that most novel fuels production takes place outside Europe – 2,000 TWh will be from wind and 1,000 TWh from solar. Let us further assume that wind will have an average of 3,500 full-load hours, and solar 1,200 full-load hours. That would require an installed capacity of 571 GW wind energy and 833 GW photovoltaics. For reaching and maintain these capacities, gross installations need to reach 22.9 GW/a for wind energy and 33 GW/a for photovoltaics[5]. If the novel fuel production would be completely in Europe, these values would increase to 40 and 49 GW/a, correspondingly. Even without the additional electricity demand for novel fuel production, securing public acceptance remains for such an expansion will be challenging. Furthermore, the almost 100% RES share will require very substantial grid expansions, which will also face acceptance challenges. This applies both to the national grids (on both transmission and distribution levels) and also the interconnectors between the Member States (MS). The latter is particularly important to enable a cost-efficient expansion of the supply with renewable energies.

The costs of the expansion however are less of challenge, at least compared to the previous aspects. By 2050, the costs of wind and solar technologies will have decreased to levels, in which electricity generations will be in the order of magnitude as they are today.

The next area of challenges lies in the production of ***novel fuels***. In spite of a high level of electrification in the scenario GHG-neutral EU2050, there remains a demand for gaseous and/or liquid energy carriers in all energy-consuming sectors, with extent and type depending on the sector, as well as for feedstocks. To mitigate all energy-related GHG emissions, this demand has to be covered by *renewable fuels*, which are either biogenic or generated from renewable electricity, like RES-methane, hydrocarbons from PtL or PtX synthesis or hydrogen. Currently, biomass is the most important RES in industry, transport and buildings. However, sustainable biomass potentials are limited, in particular when the demand for biomass of other sectors are taken into account. Therefore, RES-electricity based *novel fuels* play an important role in all sectors. A carbon-neutral electricity generation is therefore a central prerequisite.

A particularly high share of *novel fuels* is necessary in the transport sector, supplying roughly two thirds of the energy. Due to ambitious efficiency measures, the energy demand for navigation decreases, despite rising activity. In aviation, the efficiency increase cannot outweigh the rise in activity. Since a direct use of electricity seems impossible from today's perspective, both subsectors depend entirely on *novel fuels* to meet their energy demand in the scenario GHG-neutral EU 2050. For road transport, the scenario GHG-neutral EU2050 assumes an increase in the market penetration of electric vehicles and electric trucks from just a few percent today to 75% in stock in 2050. Nevertheless, in this scenario there remains a significant need for *renewable fuels* for road transport, too.

In the industry sector, the scenario GHG-neutral EU 2050 also assumes an increased direct use of electricity. But depending on the subsector, *renewable fuels* will play an important role to meet the energy demand. The iron and steel industry stand out, using hydrogen to meet roughly 50% of the energy demand. A certain amount of *renewable fuels* is used in every sector, led by the production of non-metallic mineral products (cement and lime among others) and the chemistry industry. In the latter, it is also important to replace fossil carbon feedstocks by renewable sources. Here, hydrogen and CO_2 may serve as feedstock to produce platform chemicals.

For the building sector the scenario GHG-neutral EU2050 is more cautious assumptions about the use of *renewable fuels*. Other RES options like solar thermal or ambient heat are available to decarbonize this sector. Still, *renewable fuels* play an important role and supply about 10% of the energy for space heating hot water in this scenario GHG-neutral EU2050. Finally, *renewable fuels* are also necessary to some extent for fuelling power plants that compensate for the fluctuations of fluctuating RES electricity generation from wind and PV plants.

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[5] Assumption: Lifetimeof wind solar power plants: 25 years.

The energy needed to produce all kinds of *novel fuels* will be a key driver for electricity demand. The use of hydrogen is generally more efficient because losses during the synthesis of hydrocarbons and for supplying CO_2 are avoided and moreover because the use of hydrogen in fuel cells is also more effective than burning hydrocarbons in combustion engines. However, transporting hydrogen has higher infrastructure requirements. Nevertheless, given the large amounts of *novel fuels* present in the scenario GHG-neutral EU2050, the utilization of the infrastructure can be expected to be high, which limits the additional infrastructure costs. In total, these arguments, hence, suggest that maximizing the share of hydrogen in the *novel fuels* is favourable.

In spite of that, there remains a need for hydrocarbons in certain sectors, in particular in maritime and air transport as well as in chemical industry. To achieve GHG neutrality, all carbon used in energy carriers and feedstocks needs to be renewable except in the cement sector and in the small remaining share of non-renewable waste. Renewable carbon sources are both biomass and direct air capture (DAC); for the amounts needed in this scenario, the overwhelming majority will have to come from DAC. There is no use in separating these two sources once the carbon has been feed into the energy and/or material cycle.

While it is hardly possible to re-capture the carbon in decentral applications like in the transport sector, it is beneficial to re-capture the emitted CO_2 in the centralized industrial processes, as this requires usually less effort than DAC and is therefore cheaper. Capture rates of up to 90% are feasible already today (see Hermann et al. 2014). The captured CO_2 can be used to produce renewable hydrocarbons based on renewable hydrogen. To organize the production of the hydrocarbons in an effective way, it can be useful to pool the captured CO_2. To this end, an infrastructure for transporting CO_2 that connects regional industrial production clusters is necessary. One option for this is to convert gas pipelines not used anymore due to the lower demand for gas (see Trinomics 2018). If the production of novel fuels should take place outside of Europe, the CO_2 would have to be transported to these sites. Nevertheless, carbon losses require an additional input of carbon here, too. This can again come from DAC or biomass. Moreover, since the CO_2 from biogenic sources is limited as explained above and capture is only meaningful in centralized processes, there remains a large demand for hydrocarbons based on DAC of CO_2. In particular, this applies to all *novel fuels* used in aviation and navigation, due to the use of biomass for these applications has been excluded for sustainability reasons in the GHG-neutral EU2050 scenario. As DAC is currently in the pilot phase, further research is necessary, as well as a swift roll-out.

It should be pointed out here that there is a sufficient technical potential to provide renewable electricity for the production of all the *novel fuels* in the EU, with levelized costs of electricity (LCOE) generation in the not unreasonable order of 100 EUR/MWh. Nevertheless, the land use requirements are extensive and are likely to increase the acceptance challenges of a RES expansion in the necessary magnitude. Therefore, the import of *novel fuels* is an important option to take into account. For hydrogen, however, the transport is rather expensive so that a production within the EU could be favourable. For hydrocarbons, transport is cheap and the high additional electricity demand for DAC of the required CO_2 can be met much easier in regions with lower LCOEs of RES power generation, such as Northern Africa (cf. UBA 2016).

Nonetheless, the costs of *novel fuels* will be another obstacle. Even under optimistic technologic advancements, the fuels will cost a multiple of their fossil counterparts. At least in next decades, even a very high carbon price will not be sufficient to incentivise demand for *novel fuels*. Furthermore, in order to prevent carbon leakage, any attempt for large scale diffusion of *novel fuels* in the industry sector has the subject to international coordination; otherwise, companies using *novel fuels* will be disadvantaged to their international competitors using fossil fuels. This is, however, true for aspects of decarbonisation as well.

Furthermore, the gas infrastructure plays an important role in the realization of a scenario like GHG-neutral EU 2050. The scenario GHG-neutral EU2050 envisages a use of hydrogen mainly in regional industry clusters. This requires building local hydrogen pipelines for interconnection. However, hydrogen could also be used as a complimenting fuel in the transport sector and/or fed into the gas grids to a certain extent. This would require an EU-wide harmonization of the gas infrastructure. While the consumption of natural gas has to be phased out to the largest possible extent, the supply with renewable gases becomes key to ensure the supply with residual fuels. To this end, the European gas infrastructure needs to be adapted, as the production and import of electricity-based fuels can be expected to lead to new import routes. In addition, there is a trade-off between introducing ambitious demand-side mitigation options and using more synthetic renewable fuels. This suggests a vast range of the remaining demand for renewable fuels, which entails challenges to keep the gas infrastructure economically viable. Hence, early policy action is necessary to avoid possible lock-ins with regard to the gas infrastructure (cf. UBA 2019).

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B Transport

B.1 Introduction

The transport sector is responsible for about one quarter of GHG emissions in Europe (EEA 2017). Decarbonisation of the transport sector is particularly challenging since activity growth has over compensated efficiency improvements for many years and transport activity is expected to grow further in many areas over the next decades. For the past, the activity growth made the transport sector the only sector with GHG emission growing since 1990 levels in the EU28 (EEA 2017).

The transport sector is divided by the general means of transport into Aviation, Navigation, Road and rail transport. Aviation covers national, intra-EU and international flights. For this study, *navigation* covers domestic shipping, as well as intra-EU water borne transport and international maritime transport. Road transport in terms of GHG emissions covers passenger cars, lorries of all sizes, busses and motorized two-wheelers. Lastly, rail transport covers all forms of railway bound transport. Transport is further divided by the main type of object transported: passenger transport measured in passenger kilometres (pkm) and freight or goods transport measured in tonne kilometres (tkm).

Today, transport is dominated by the use of fossil oil-based hydrocarbons such as gasoline, diesel, and kerosene. More recently, electricity has begun to play a role in road transport and gaseous fuels such as natural gas are presently being discussed as alternative fuels in transport.

In the following, we will discuss trends, modelling assumptions and scenario results for passenger and freight transport in the four sub-sectors aviation, navigation, road and rail.

B.2 Status quo

Today's freight transport performance in Europe amounts to 3,516 billion tkm (EEA 2017). Almost half of this takes place on roads (49%). The second most important transport mode is Intra-EU maritime transport with a share of 31.6%, followed by 12% on railways and about 4.2% on inland water (EEA 2017).

The total passenger transport performance by any motorized means of transport amounts to 6,602 billion pkm mainly driven by passenger cars (71.5%). The other modes of transport have lower shares with 9.8% for intra-EU air transport, 8.2% with buses & coaches, 6.7% on railways, 1.9% for powered two-wheelers, and 1.6% for tram and metro. On average, European citizens travels around 12,962 km per year (EEA 2017).

The GHG emissions from transport (cf. Figure B 1) are mainly from road transport (73%), aviation (13%) and navigation (13%) – all are dominated by the use of fossil fuels. This is in contrast to rail transport, which has a lower share in GHG emissions than in transport performance.[6]

The GHG emissions have developed quite differently between the transport modes from 1990 to 2015. Emissions decreased compared to 1990 only on rail (-50% compared to 1990) and most markedly increased in aviation (+90%) due to a strong increase in transport performance. GHG

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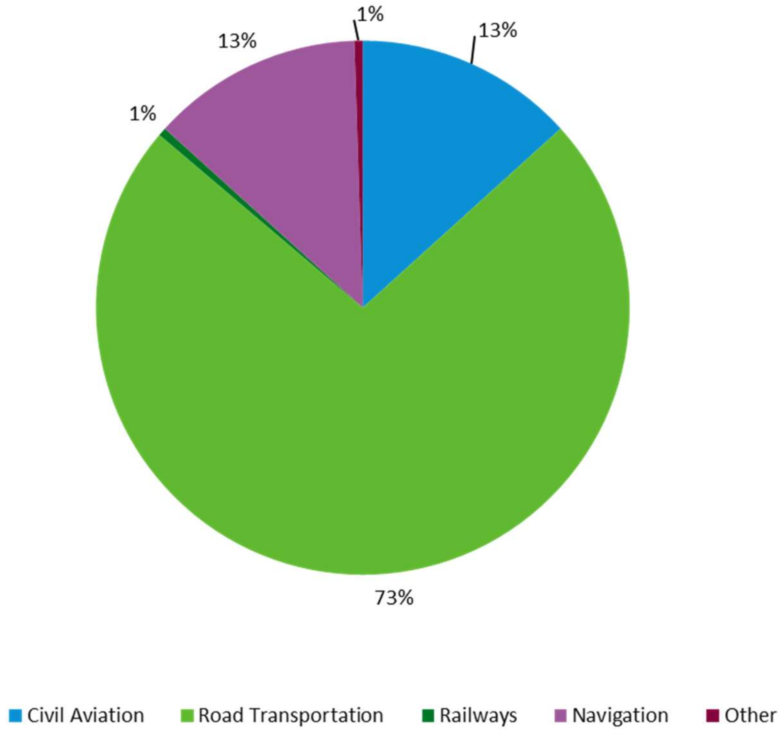
[6] Note that emissions from electricity generation are not covered, but that a large share of rail traffic is already electric and that the GHG emissions including electricity generation are comparably good in Europe.

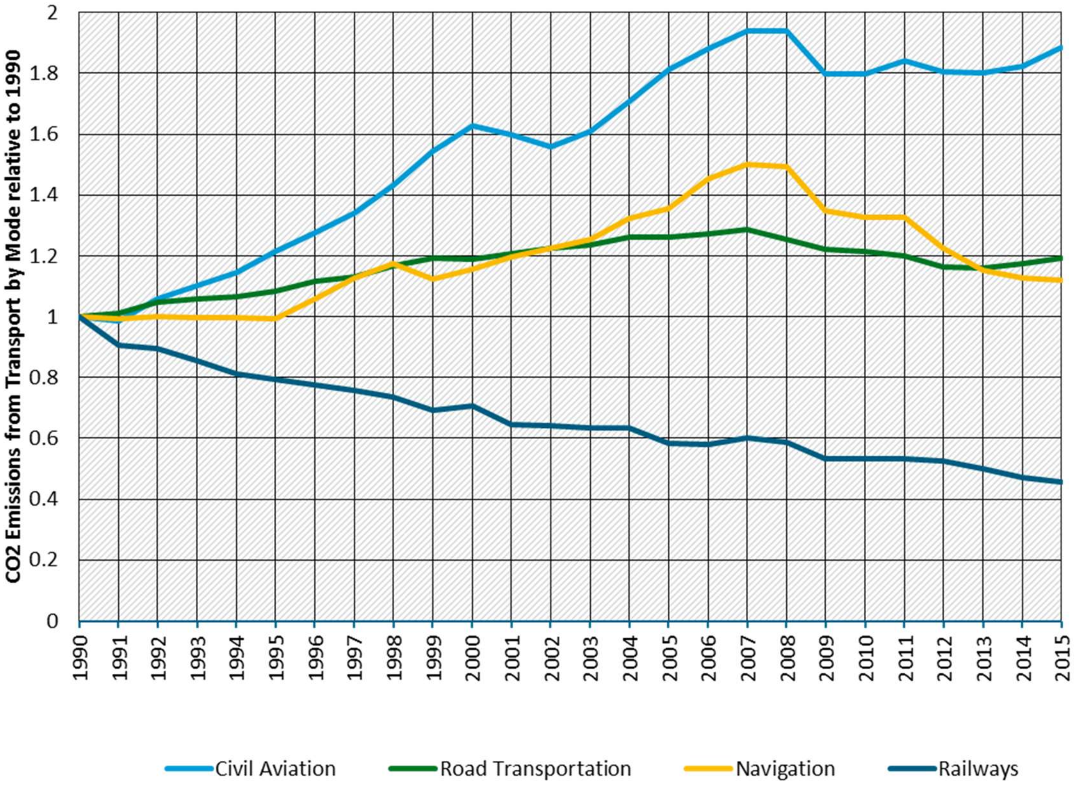
emissions from road transport and navigation increased by about 20% in the EU28 since 1990, see Figure B 2.

Figure B 1: CO₂ Emissions from Transport by Mode in EU28 in 2015



Including international bunkers, and excluding indirect emissions from electricity consumption.
Source: European Environment Agency (EEA 2017).

Figure B 2: **CO_2 Emissions from Transport by Mode relative to 1990**



Including international bunkers, and excluding indirect emissions from electricity consumption.
Source: European Environment Agency (EEA, 2017).

In summary, GHG emissions in the transport sector are dominated by road transport. Electrification of road and rail transport accompanied by increased shares of renewable energy sources in electricity generation appear as technical options to decrease GHG emissions in transport. Aviation will grow strongly and poses a particular challenge since high-density energy carriers are required here and electrification is not an option.

B.3 Methodology, assumptions and underlying data set for 2050 scenario

B.3.1 Transport activity

Transport activity is one of the main drivers for energy consumption in transport. For a consistent set of assumptions, we follow the PRIMES reference model for activity data for both 2015 and 2050 here. It is important to bear in mind that no significant changes in the modal split have been recorded in the reference development and have accordingly not been assumed here.

The Primes data on road and rail differ less than 10% from the EU statistics. A comparison with navigation and aviation is not straightforward due to the inclusion of the different levels of transport there. The development of transport activity for international navigation is not available in the PRIMES reference scenario. Therefore, it is estimated based on a regression analysis, using the same data as in the reference scenario.

High growth rates in all modes of transportation are expected while the highest are expected in international transportation. Road passenger transportation increases by nearly 30% up to 2050 while the freight transport on roads rises even by nearly 50%. Similarly, rail transport activity is expected to increase noteworthy by almost 60% for passengers and almost 70% for freight until 2050. Both in international and domestic flights (intra EU-flights) the number of passenger kilometres is expected to double from around 2.000 billion pkm in 2015 to ca. 4.000 billion pkm in 2050. The activity of international navigation increases almost threefold from 2015 to 2050, whereas domestic navigation increases slightly by about 25%. The activity assumptions are summarised in the following table.

Table B 1: Transport activity data in EU28

Billion pkm	**2015**	**2050**	**Billion tkm**	**2015**	**2050**
Aviation			**Aviation**		
Intra-EU	640	1,270	Intra-EU	2.6	4.4
Leaving EU	1,400	2,750	Leaving EU	*no data*	*no data*
Navigation			**Navigation**		
Intra-EU	40	50	Intra-EU	360	492
Leaving EU	*no data*	*no data*	Leaving EU	23,700	61,500
Road	4,900	6,840	**Road**	1,700	2,500
Rail	560	880	**Rail**	400	700
Total	**7,500**	**11,800**	**Total**	**27,300**	**67,000**

Notes: Road passenger transport contains cars, two-wheelers and busses, rail contains railway and Tram and Metro. Navigation contains inland waterways and intra-EU28 transport. Values for 2015 from PRIMES and growth rates until 2050 from PRIMES reference scenario. Intra-EU includes national transport and transport between MS.

B.3.2 Aviation

The development of energy demand for domestic and international aviation is based on PRIMES data. Based on the assumption of high increases in efficiency (ca. 40%), these data are considered suitable for the purpose of this study. PRIMES data are only available for the transport activity of domestic flights; the transport activity of international flights is calculated based on the assumption that its share on total aviation transport activity is 70% (EU COM 2016).

Decarbonisation of this sector is achieved by a combination of an ambitious efficiency increase and the deployment of novel fuels. Novel fuels are primarily fuels that are produced from renewable electricity. In aviation, these will be the so-called power-to-kerosene. Alternatively, conceivable are also biofuels. Since it is assumed that sustainably produced biofuels will only be available for aviation to a limited extent, it can be assumed that a large proportion of the novel fuels will be produced based on electricity using Fischer-Tropsch synthesis.

This study does not take into account the fact that, in addition to CO_2, other emissions such as nitrogen oxides, water vapour, sulphur oxides, soot, condensation trails and cirrus in high air layers also contribute to the climate impact of air traffic and must be taken into account accordingly. These can be described with the Emission Weighting Factor (EWF), which compares the CO_2 and non-CO_2 effects resulting from the combustion of fuels at high altitudes with the CO_2 effect on the ground. This means that the actual climate impact of aviation is significantly higher than if only the climate impact of CO_2 emissions were considered. Thus, novel fuels reduce direct CO_2 emissions, but the indirect climate impact remains.

B.3.3 Navigation

The development of energy demand of *inland navigation* for 2050 is based on PRIMES (EU COM 2016). According to the state of knowledge at that time no alternative to the internal combustion engine is assumed. Thus, the main option for decarbonisation in domestic navigation in 2050 is the use of novel fuels combined with a slight increase of efficiency.

The national GHG inventory shows the emissions from fuel sales in the different countries in Europe to ships in international traffic. Due to the long range of ships, however, there is only a weak link between fuel sales and ship traffic in one country. As a rule, ships bunker where the fuel is cheapest. The connection between GDP and fuel consumption is stronger. Energy consumption in navigation is therefore correlated with GDP.

Energy demand of *international navigation* in the reference scenario is projected using two different methods:

- Regression analysis of the development of energy demand and GDP based on GDP forecasts (EU28: Reference Scenario 2016)
- Regression analysis of the development of transport activity based on forecasted global development of transport activity (IMO 2014; RCP2,6, SSP4) and the development of EU28 and global GDP. The projected development of energy demand is based on an assumed average increase in efficiency of 37% (IMO 2014, own calculations).

Both methods yield similar results: the first method results in an energy demand in 2050 of 842 GWh, the second method yields 947 GWh.

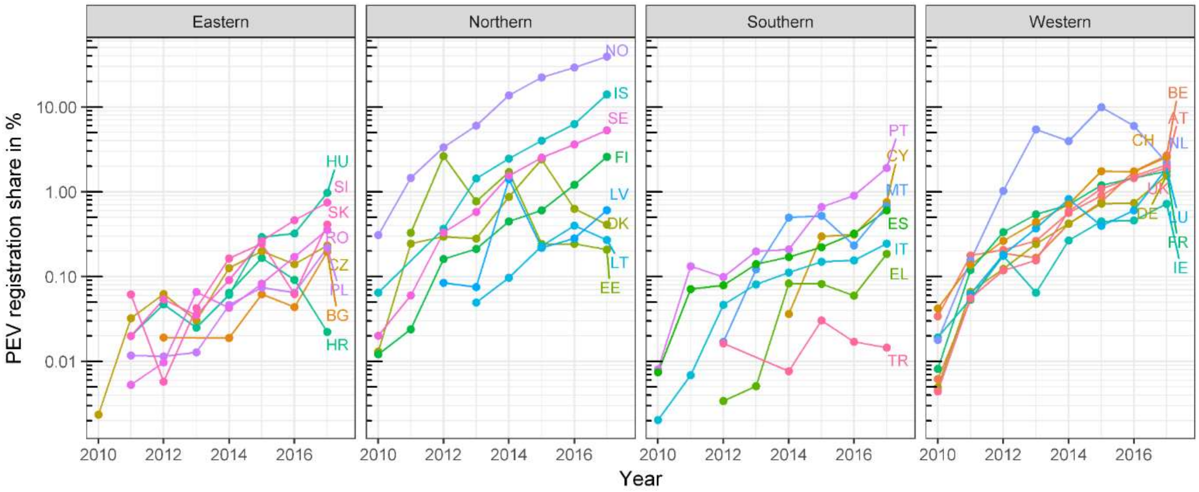
The development of energy demand is estimated based on the assumption of a high increase in efficiency of 69% compared to 2010 (IMO 2014, own calculations). Energy demand is provided by novel fuels as alternatives to the internal combustion engines in international navigation are not predictable as well. The share of PtG and PtL on total energy demand is 25% and 75% respectively.

B.3.4 Road transport

The development of activity data (pkm and tkm) for on road transport is based on the PRIMES reference scenario (EU COM 2016). Passenger cars and duty vehicles are treated separately. For passenger cars and light duty vehicles (below 3.5 tonnes gross vehicle weight), a scenario with strong electrification is developed based on the ALADIN model (cf. https://www.aladin-model.eu/) and adapted to the specific vehicle turnover rates and energy prices in the different European countries. Despite high electric vehicle penetration rates in sales, stock turnover requires many years and the scenario contains a stock weighted average of 75% EVs in stock in 2050 in Europe with an average energy consumption of 13 kWh/km and average occupancy of 1.2 passengers per car (as average occupancy has been falling for many decades, it is assumed to decline further). The remainder of cars is assumed to use a synthetic renewable fuel.

Figure B 3: Market shares of plug-in electric vehicles (PEV) in Europe 2010 – 2017

Market share on logarithmic scale in Eastern, Northern, Southern and Western Europe



PEV are both battery electric (BEV) and plug-in hybrid electric vehicles (PHEV).
Source: Münzel et al. (2018)

For medium and heavy-duty vehicles, we also assume strong electrification by the broad market introduction of catenary trucks using overhead lines. The creation of a European overhead line grid on about one third of the European highway network is assumed. The market penetration follows the ALADIN model estimate for Germany in all European countries. It results in 85% of all medium and heavy-duty truck sales being catenary trucks and 77% of stock by 2050. With the future development of battery technologies, these are assumed to drive fully electrically, that is using energy stored in a battery when driving off an electrified highway. The remainder of trucks is assumed to use a synthetic renewable fuel and pure battery electric trucks are assumed unsuitable for heavy-duty trucks.

B.3.5 Rail

The future development of activity data (pkm and tkm) for rail transport is based on the PRIMES reference scenario. Electrification and use of renewable fuels are the easiest GHG reduction path for rail transport and it is assumed that more transport is transferred to already electrified networks, such that, e.g., networks with 30% of track-km electrified achieve 75% electrification of transport performance instead of today’s 50%. This is accompanied by 20% fuel efficiency increase in rail transport. The remaining rail transport is assumed to use a synthetic renewable fuel.

B.4 Scenario GHG-neutral EU2050

Our transport scenario for GHG-neutral EU2050 is dominated by a strong increase in transport activity as well as strong electrification wherever possible.

Although demand in passenger transport is rising by around 50% and in freight transport by as much as nearly 150%, total energy demand in the transport sector is halving due to the high level of electrification and a massive increase in the efficiency of conventional engines.

Road passenger transportation increases by nearly 30% up to 2050 while the road freight transport rises even by nearly 50%. In 2050, about 75% of the mileage on road will be driven electrically leading to a significant decrease in energy demand by 70% with the direct use of electricity amounting to 697 TWh. The remaining need of 263 TWh liquid fuels will be provided by novel fuels.

Both in terms of international and domestic flights (intra EU-flights) the number of passenger kilometres doubles, while energy demand rises just by nearly 15% over the same time period due to assumptions of high increases in efficiency (ca. 40%). Kerosene will be totally replaced by novel fuels in 2050.

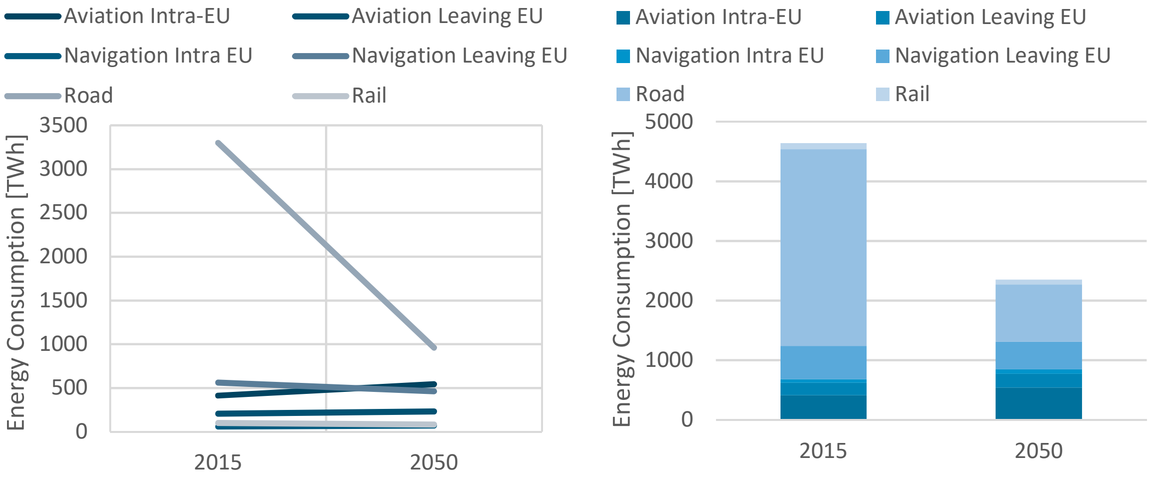
The activity of the international navigation increases almost threefold from 2015 to 2050, whereas domestic navigation increases slightly about 25%. The decrease in energy demand will be only around 15% due to the increasing energy efficiency assumed for navigation (+69%). While diesel serves as main fuel in 2015, it will be replaced by novel fuels in 2050.

Table B 2: Energy consumption in EU28 by transport mode

Energy Consumption [TWh]	2015	2050
Aviation	689	774
Navigation	619	534
Road	3,299	960
Rail	100	83
Total	**4,708**	**2,351**

Source: Own Compilation.

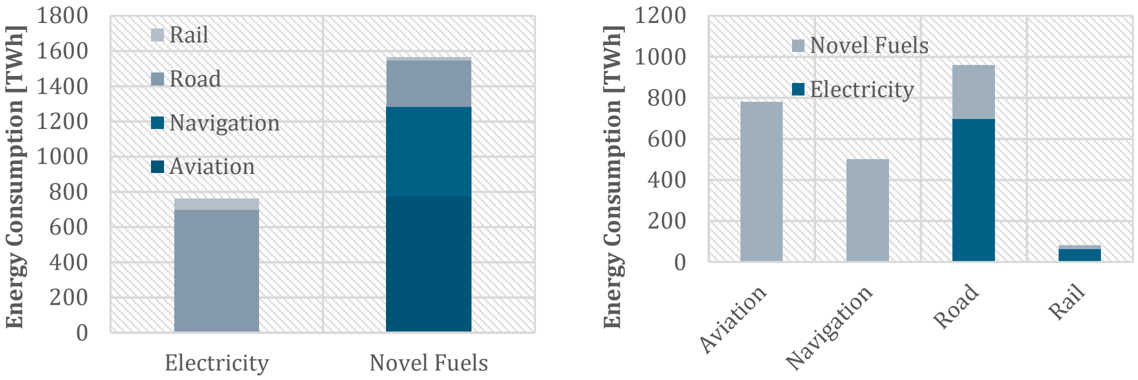
Figure B 4: Energy Consumption in EU 28 by Mode in 2015 and 2050



Source: Own Compilation.

The overall most dramatic change by 2050 is the reduction in energy consumption in road transport 2050 due to ambitious assumptions for electrification. Furthermore, aviation is the only mode with growing energy consumption and thus noteworthy increases its share in transport energy demand until 2050.

Figure B 5: Energy Consumption in EU 28 by Mode and Fuel type in 2050



Source: Own Compilation.

Novel fuels with high energy density are used whenever electricity is not applicable. For sustainability reasons, the use of biogenic fuels has been excluded in the transport sector. The strong growth in aviation and remaining use of liquid fuels on roads lead to a demand of about 1,600 TWh novel fuels in 2050. Thus, in the Scenario GHG-neutral EU2050, liquid fuels still account for about two third of transports energy demand despite strong ambitions in electrification of transport. Yet, the higher efficiency of electric propulsion implies that more than one third of transport activity is based on direct use of electricity.

B.5 Challenges

Even with very ambitious assumptions about the market penetration of electric vehicles and electric trucks (from just a few percent today to 75% in stock in 2050), there remains a significant need for novel fuels for road transport. And for the high proportion of electrified road vehicles, it must also be kept in mind that this requires EU-wide harmonised infrastructure development, both for cars and in the form of overhead lines for heavy-duty transport.

The high growth rates in aviation and navigation, where direct use of electricity seems impossible from today's perspective, result in a high demand for novel fuels. Thus, not only technical options for CO_2 reduction are required in transport, but also non-technical options for a reduction of motorised traffic and a shift to energy-efficient modes of transport have to be addressed. A reduction in final energy demand through a change in passenger transport demand can be achieved through shorter distances (city and region of short distances) and a shift to non-motorised transport or public transport by a promotion of these environmentally friendly transport modes. However, corresponding reductions in passenger car mobility will only be achieved in scenarios in which an improvement in the supply of services is accompanied by a significant increase in the user costs of motorised private transport.

It is expected that the volume of freight traffic will continue to grow until 2050. The transportation of goods can be reduced by strengthening regional economic cycles. For this, however, in addition to "non-financial" support (certification of the environmental impacts of transport or product-specific logistics processes), a significant increase in freight transport costs or financial incentives for regional production and supply processes are necessary. Additionally, a significant shift of freight transport from road to rail helps to reduce final energy demand in freight transport.

In summary, not only strong monetary signals are required to reduce energy consumption in transport but also a behavioural change towards more environmentally friendly modes of transport, possibly supported by monetary incentives.

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C Industry

C.1 Introduction

Industry is currently responsible for about 25% of EU final energy demand and uses gas, electricity, coal, and oil as the dominant energy carriers making industry critical for the achievement of European climate goals. Within industry, three types of greenhouse gas (GHG) emissions sources can be distinguished:

- **Energy-related direct emissions** from on-site fossil fuel combustion.
- **Process-related direct emissions** from chemical reactions within the production process (process emissions).
- **Indirect emissions** from the consumption of electricity and/or district heat.

Reducing process emissions appears to be a particular challenge for the industrial sector, as these types of emissions can at least partially be reduced only by the use of carbon capture and storage (not considered in this study; see section C.3.2) or by radical changes in the production process or product mix.

This contribution presents a transition scenario for the EU28 that achieves an ambitious reduction in GHG emissions of 87% by 2050 compared to 2015 for the industrial sector. The shown transition scenario contains different mitigation options: incremental and best-available-technology (BAT) energy efficiency improvements, advanced energy- and resource efficient processes as well as fuel and feedstock switching (e.g. towards renewable electricity or hydrogen).

C.2 Status quo

In 2015, the industry sector[7] was responsible for about 25% of EU final energy demand and uses mainly gas, electricity, coal, and oil (see Figure C 1). This high share in final energy demand is primarily caused by energy-intensive industries such as iron and steel and the chemical sector. Within these industries, specific energy-intensive products/processes (e.g. steel, ammonia) are particularly relevant for the future achievement of European climate targets. Some sectors such as the paper industry already use a high share of electricity and biomass. In general, however, industry still needs to make substantial further efforts to reduce the use of fossil fuels in the next decades to achieve ambitious GHG-mitigation targets.

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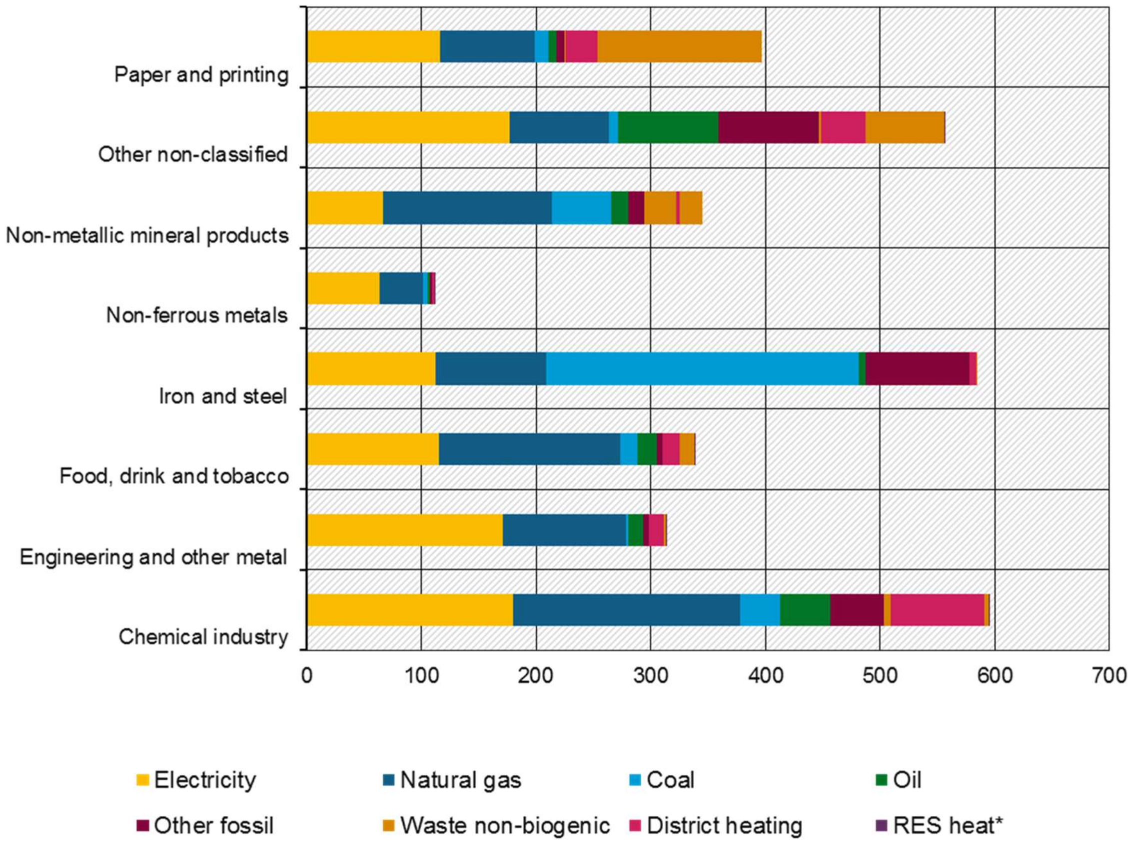
[7] The definition of industry in this study follows final energy definitions and excludes the refinery sector as well as electricity onsite generation.

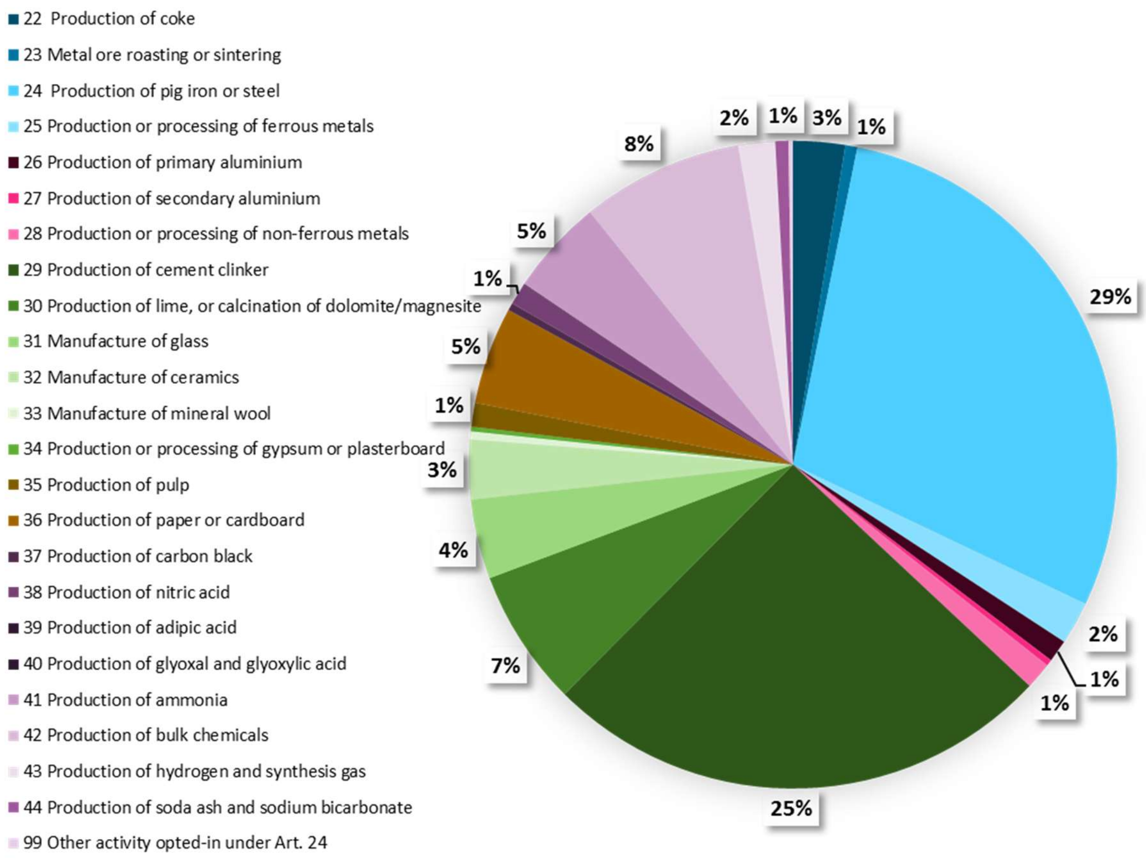
Figure C 1: EU 28 industrial final energy demand in TWh by subsector (2015)



* Here, RES heat includes ambient heat, solar thermal heat and other RES.
Source: Herbst et al. 2018 based on Eurostat

The **non-metallic minerals** sector is the biggest contributor of **verified industrial CO_2 emissions**. It is dominated by the production of cement clinker, which emits about 0.5 tonnes of process CO_2 emissions per tonne of clinker produced. Other CO_2-intensive products of the non-metallic minerals sector include lime, the calcination of dolomite/magnesite, glass, bricks and ceramics. The production of pig iron or steel in the **iron and steel** industry is also responsible for around one third of verified industrial CO_2 emissions in 2015. The main emissions are from the (technically required) use of coal and coke in blast furnaces. In addition, **chemical processes** such as ammonia, ethylene or methanol production contribute to industrial emissions, making the chemical industry the third biggest emitter of CO_2 emissions.

Figure C 2: EU28 verified industrial CO_2 emissions by ETS activity (2015)



Source: EAA 2018

In terms of end-uses, most industrial GHG emissions are from high-temperature process heat, either in the form of steam or hot water, or from the direct firing of various types of furnaces. These two end-uses have shares of 23% and 45% of total direct industrial GHG emissions, respectively. The high temperatures and the specific requirements of furnaces limit the use of renewable energies here to biomass or secondary energy carriers. Process-related emissions account for about 21% of all direct emissions. It is technically difficult or even impossible to mitigate them in the processes used at present.

In addition to energy- and process related CO_2 emissions, the emissions of fluorinated GHG gases ("F-gases") during industrial production processes and mainly through the later use of the products have a relevant share of the GHG emissions of the industry sector. The emission of F-gases in the EU has increased from 72 Mt CO_2-eq. in 1990 to 121 Mt CO_2-eq. in 2015. This is mainly due to the use of substitutes for ozone depleting substances, with a share of over 90% in 2015.

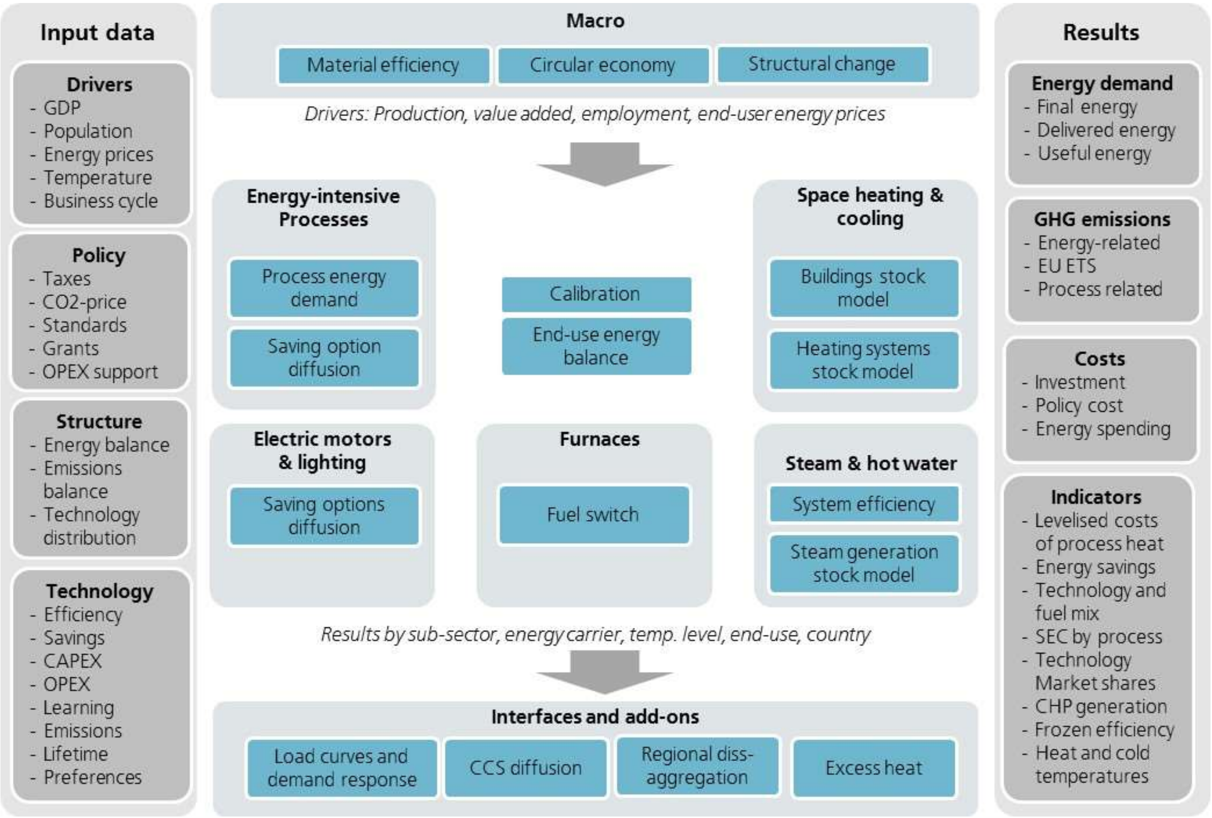
C.3 Methodology, assumptions and underlying data set for 2050 scenario

The scenario calculation has been conducted using the FORECAST modelling platform (www.forecast-model.eu) which aims to develop long-term scenarios for future energy demand of individual countries and world regions until 2050.

C.3.1 Bottom-up simulations of the industry sector

FORECAST is based on a **bottom-up** modelling approach considering the dynamics of technologies and socio-economic drivers. The model allows addressing various research questions related to energy demand including scenarios for the future demand of individual energy carriers like electricity or natural gas, calculating energy saving potentials and the impact on greenhouse gas (GHG) emissions as well as abatement cost curves and ex-ante policy impact assessments. Energy-intensive processes are explicitly considered, while other technologies and energy-using equipment are modelled as cross-cutting technologies. FORECAST is a **simulation model** used to support investment decisions, taking into consideration barriers to the adoption of energy efficient technologies as well as various policy instruments.

Figure C 3: Bottom-up simulation model FORECAST-industry structure



Source: FORECAST

Different approaches are used to simulate technology diffusion, including diffusion curves, vintage stock models and discrete choice simulation. Main macro-economic drivers are industrial production for over **70 individually modelled basic materials products**, gross value added, and employment for less energy-intensive sub-sectors. **Five sub-modules cover: basic materials processes, space heating, electric motor systems, furnaces and steam systems.** Saving options (incremental changes, radically new production processes) unfold their impact on energy consumption and GHG emissions by diffusing through the modelled technology stock and, thus, reducing the specific energy consumption or specific process related emissions of individual production processes. (Herbst et al. 2018, Fleiter et al. 2018)

C.3.2 Scenario GHG-neutral EU2050

For the Scenario GHG-neutral EU2050 analysis with FORECAST the underlying macroeconomic framework data as well as the wholesale fossil fuel prices (gross domestic product, population, prices for coal, gas, and oil) have been taken from the European Reference Scenario 2016. In this scenario, industry value added is expected to continue growing moderately until 2050. However, energy-intensive industries like the iron and steel industry and the non-ferrous metals industry grow below industrial average in the scenario. Stronger growth is to be expected in non-energy-intensive sectors like engineering (including vehicle construction) and the food industry, which reflects structural change in industry towards less-energy-intensive branches (for details see European Commission 2016).

In terms of physical production, blast furnace steel, electric arc steel, paper and cement are among the most important industrial products. In the scenario GHG-neutral EU2050 only the cement production shows a clearly increasing trend due to needed investment in infrastructure, refurbishment and renewable energy sources (e.g. wind) for the achievement of an ambitious mitigation target. Production in the European steel industry is stagnating assuming a constant development in established steel producing countries (e.g. Austria, Germany) as well as a decoupling of value added and physical production based on historic trends while for selected new MS, still slight increase in steel production is assumed.

Recycling and secondary production routes are considered for steel, aluminium, copper, paper and glass. For cement production, a reduction of the clinker ratio (share of clinker input compared to cement output) is considered. For all products, the technical restrictions vary and the starting point of the individual countries is very different. Production data for cement, steel, paper and other selected industrial products are provided in Table C 1.

Table C 1: Production data of selected industrial processes for the EU28 [Mt]

Subsector/Product	2015	2050
Chemical industry		
Adipic acid	0.6	0.6
Nitric acid	17	17
Soda ash	8	8
Calcium carbide	0.3	0.3
Carbon black	1.5	1.5
Chlorine	11.4	11.4
Ammonia fossil-based	17.7	0.0
Ammonia novel-fuel-based	0.0	19.1
Ethylene Naphta-based	15.6	0.0
Ethylene novel-fuel based	0.0	18.4
Methanol fossil-based	1.3	0.0
Methanol novel-fuel-based	0.0	1.3
Iron and steel		
Coke	40.6	0.0
Sinter	109.8	0.0

Subsector/Product	2015	2050
Crude steel	166.1	169.4
- thereof BOF steel	100.6	0.0
- thereof EAF steel	65.5	74.4
- thereof DR RES H2 + EAF steel	0.0	47.5
- thereof Plasma steel (H2)	0.0	47.5
Rolled steel	150.6	153.6
Non-ferrous metals		
Aluminum, primary	2	1.8
Aluminum, secondary	3	3.4
Non-metallic mineral products		
Clinker	130.6	74.7
Cement	167.2	205.6
- thereof conventional cement	167.2	127.1
- thereof Less-carbon cement -30%	0.0	9.8
- thereof Low-carbon cement -50%	0.0	39.3
- thereof Low-carbon cement -70% (recarbonating)	0.0	19.6
- thereof Low-carbon cement -95% (recycled concrete)	0.0	9.8
Lime	37.2	15.1
Gypsum	111.9	115
Container glass	22.9	4.3
Flat glass	13.1	3.
Container glass electric furnace	0.0	17.2
Flat glass electric furnace	0.0	12.1
Paper and printing		
Chemical pulp	26.4	28.5
Mechanical pulp	8.3	8.5
Recovered fibres	48.7	57.3
Paper	93.2	102.4

Source: FORECAST and sector statistics

The Scenario GHG-neutral EU2050 is defined as an industrial decarbonisation scenario excluding the use of CCS (for sustainability reasons), but including a variety of different mitigation options in industry:

- incremental process improvements (BAT + innovation >= TRL5[8]),

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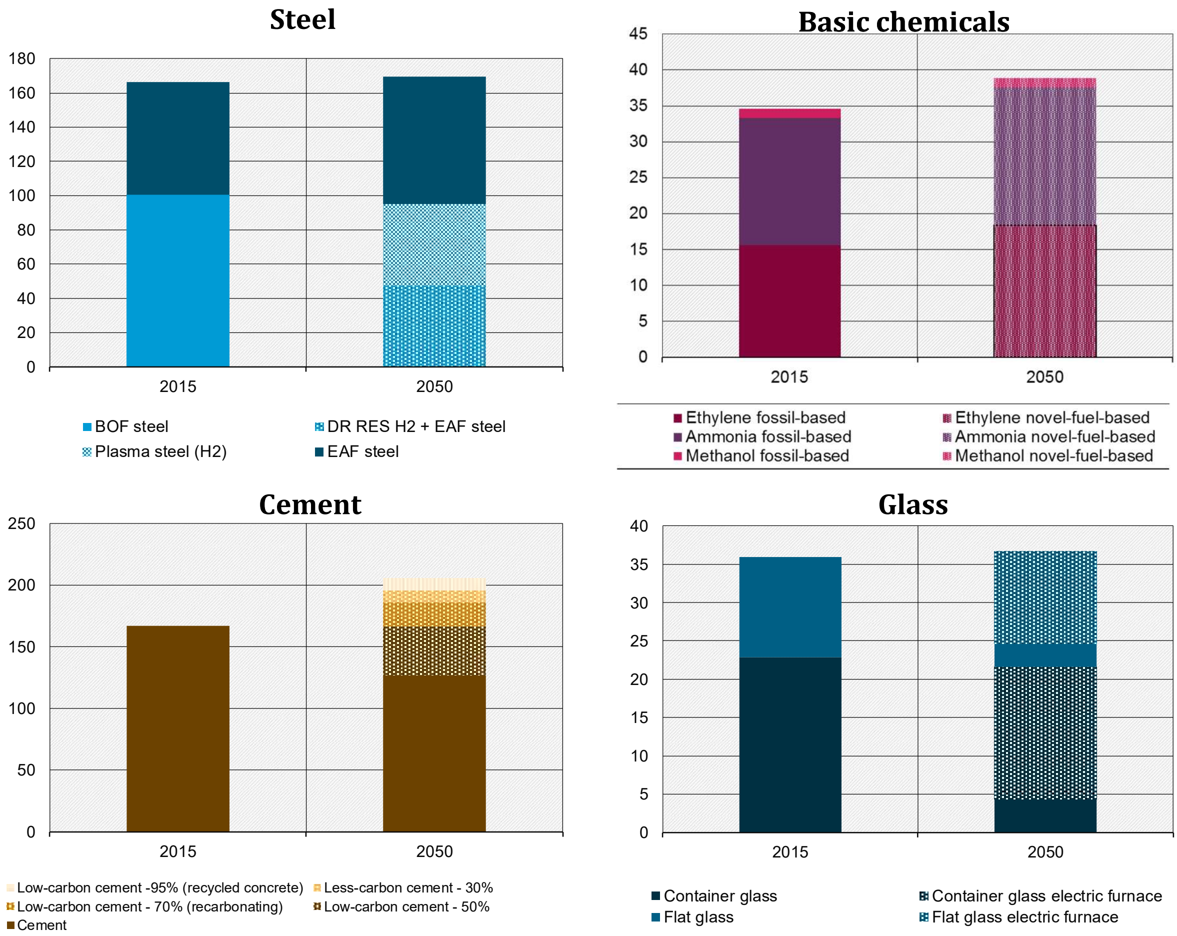
[8] TRL stands for technology readiness level. A TRL >= 5 means that the technology is currently on pilot stage (=TRL 5) or has advanced to demonstration scale or higher.

- radical process improvements (>= TRL5; e.g. low carbon cement sort),
- fuel switch to RES electricity and synthetic energy carriers (e.g. hydrogen) as well as
- stronger switch to secondary production.

The following figure shows the assumed changes in production processes for selected important energy-intensive goods (crude steel, cement, glass and basic chemicals like ammonia, methanol and ethylene) from 2015 to 2050.

Figure C 4: Physical production in Mt by process/product (2015-2050: crude steel, basic chemicals, cement, and glass)



Source: FORECAST

In the iron and steel industry an increase in the share of secondary steel production (EAF steel) from 39% in 2015 to 44% is seen in 2050 due to the assumed higher scrap availability (BCG 2013). The remaining primary steel production is completely substituted by hydrogen steel production technologies: RES H2 plasma steel (voestalpine) and DR RES H2 + EAF steel (SSAB 2017). In basic chemical industry, conventional ammonia and methanol production is completely substituted in 2050 by production technologies using RES hydrogen electrolysis for feedstock generation instead of e.g. methane steam reforming. Ethylene production is assumed to be replaced by 100% RES methanol-based production substituting conventional steam cracking of naphtha (Dechema 2017). In the cement industry, new binders are assumed to replace conventional Ordinary Portland cement (OPC) in the cement industry (70% of OPC in 2050). Less carbon cements -30%, low carbon cements -50% to -70% as well as recarbonating cement products enter the market and consequently lead to reduced clinker production. For details on the different technologies see Eichhammer et al. (2018). Limited amounts of concrete recycling that allow replacing limestone are assumed to take place in the Scenario GHG-neutral EU2050 (10% of OPC). In the glass industry, 80% of the conventional glass production will be substituted by electric melting processes in 2050.

As the emission of F-gases is not covered by FORECAST, F-gases are not treated with the same level of detail as CO_2 emissions in the scenario GHG-neutral EU2050. Instead, the results of the study "Germany in 2050: a Greenhouse-Gas-Neutral Country" (UBA 2015) for the various applications of F-gases are transferred to the EU level based on the EU's current F-gas inventories. This is justified by the homogeneity of F-gas sources among the EU MS.

C.4 Scenario GHG-neutral EU2050

The scenario GHG-neutral EU2050 uses mitigation options of various types including energy-efficient and low-carbon production innovations, renewable-based electricity and hydrogen as well as the use of *novel fuels* (e.g. RES methane). The scenario excludes the use of CCS and reduces the need of biomass to more or less the level of use as in 2015. The scenario includes ambitious changes in the entire industrial production system. The speed of change is rapid and targets a nearly 100% transition by 2050. In some cases, this requires early replacement of technologies before they reach their ordinary end-of-life, which increases overall investment needs and costs.

Results show a reduction of 86% of GHG emissions by 2050 compared to 2015, which equals 92% reduction when compared to 1990 levels. The industry sector achieves major emission cuts by fuel switching to electricity for process heating and indirect use of electricity using hydrogen in steel production and chemical feedstock as well as low-carbon production innovations in other sub-sectors. In particular, all energy-related GHG emissions are mitigated, except for 5 Mt CO_2 from the incineration of non-renewable waste. The remaining emissions stem from chemical reactions within the industrial production processes (93 Mt in 2050). The biggest emitter in 2050 is the non-metallic minerals sector including smaller (distributed) sources e.g. lime and ceramics and remaining emissions from conventional cement production (not all cement uses are suitable for innovative cement products).

Table C 2: EU28 direct industrial bottom-up CO_2-emissions in Mt by subsector (2015-2050)

Subsector	2015	GHG-neutral EU2050	Change 2015-2050
Chemical industry	116	12	-90%
Food, drink and tobacco	38	<0.5	-100%
Iron and steel	171	1	-100%
Non-ferrous metals	15	5	-67%
Non-metallic mineral products	191	78	-59%
Other non-classified*	157	1	-100%
Paper and printing	24	1	-96%
Total Forecast sectors	**711**	**98**	

Subsector	2015	GHG-neutral EU2050	Change 2015-2050
Non-energy products from fuels and solvent use	10	0**	-100%
Other	<0.5	<0.5	
Total	**721**	**98**	**-86%**

* including the subsector “Engineering and other metal”, which is shown separately in the rest of this section

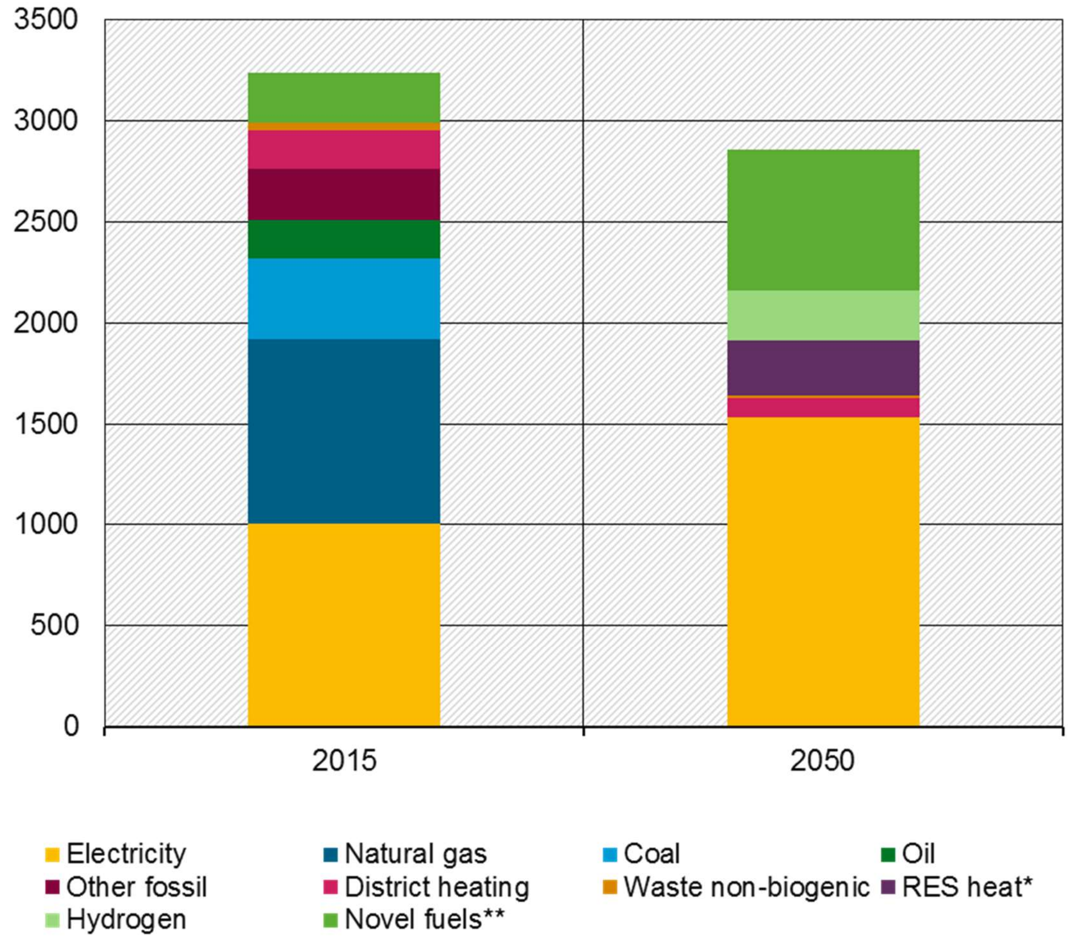
** based on the consideration on feedstocks in Section D

Source: FORECAST results calibrated to UNFCCC 2015 (bottom-up EU28 aggregates)

In the scenario GHG-neutral EU2050, final energy demand is decreasing driven by energy efficiency improvements by 12% compared to 2015 from 3240 TWh to 2860 TWh in 2050 (see Figure C 5). Electricity is the most important energy carrier in 2050 followed by the portfolio of flexible *novel fuels* (including biofuels, synthetic hydrocarbons but also hydrogen) and ambient heat. The demand for district heating falls substantially from 186.5 TWh in 2015 to 91.6 TWh in 2050. Where possible, the direct use of electricity is preferred over the indirect use; for example via electric furnaces in the glass industry. The resulting total electricity demand increases from 1004.5 TWh in 2015 to 1535.4 TWh in 2050.

In the iron and steel industry, 246 TWh of hydrogen are needed in 2050 for direct reduction - fully replacing oxygen steel production in addition to a more ambitious deployment of scrap-based (EAF) steel production. Overall, final energy demand in the steel industry decreases by 19% from 2015 to 2050 mainly substituting coal, natural gas and other fossils with hydrogen and electricity. In the chemical industry, major challenges are feedstocks, process emissions and the high share of natural gas in 2015 (197 TWh). Use of hydrogen as a feedstock is assumed to take place at a large scale in the chemical industry in 2050 (see the figure below). The additional demand for hydrogen used as feedstock is not shown in the industrial final energy demand results; for details on the volumes of H2 demand as feedstock in the chemical industry, see section D. Total final energy demand in the chemical industry excluding feedstock consumption decreases by 22% until 2050 in the scenario GHG-neutral EU2050 using electricity as dominant energy carrier (302.5 TWh in 2050).

Figure C 5: EU28 final energy demand by energy carrier (2015-2050)



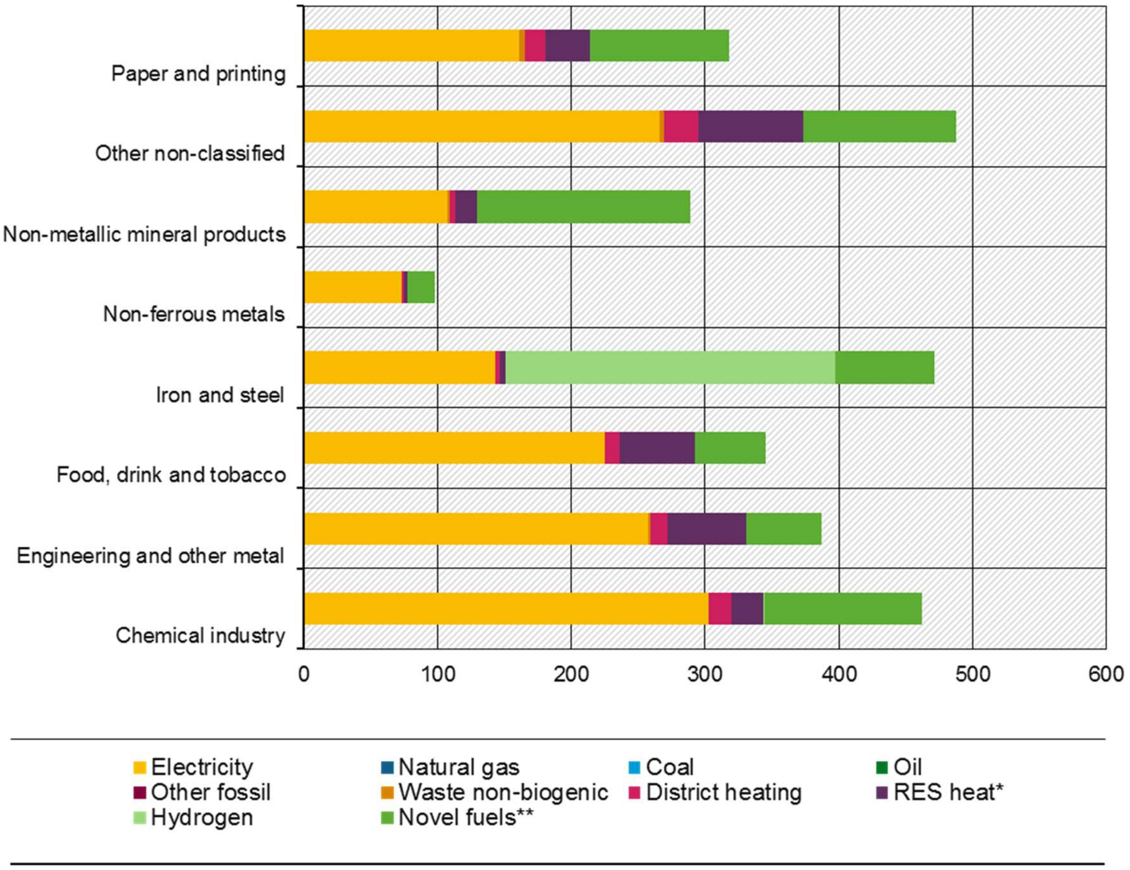
* Here, RES heat includes ambient heat, solar thermal heat and other RES.

** Here, novel fuels may include biofuels, synthetic hydrocarbons but also additional hydrogen.

Source: FORECAST

The non-metallic minerals sector uses electric furnaces for glass melting, ambitious diffusion of low-carbon cements and recycling improvements in the construction industry. Demand in this sub-sector switches from natural gas (147 TWh in 2015) to novel fuels (117 TWh in 2050) and electricity (107 TWh in 2050) as dominant energy carriers. In total, final demand in the non-metallic minerals sector decreases by 16% (from 345 TWh in 2015 to 289 TWh in 2050). Particularly the cement and lime production are major challenges in the decarbonisation of the industry sector. If CCS is not used, the effectiveness of decarbonisation depends to a large extent on the diffusion speed of low-carbon cements and fundamental improvements in the construction industry (e.g. concrete recycling). In the pulp and paper industry, a combination of supporting electric steam boilers (and heat pumps where possible), replacing natural gas (82 TWh in 2015) by novel fuels, in particular RES methane, and phasing out remaining coal-fired boilers and steam engines before end-of-life is assumed, leading a reduction in final energy demand of 20% from 397 TWh in 2015 to 318 TWh in 2050.

Figure C 6: EU 28 industrial final energy demand in TWh by subsector (2050)



Source: FORECAST

With regard to F-gases, the scenario GHG-neutral EU2050 assumes that the technical options to avoid the relevant substitutes for ozone depleting substances (ODS) are applied to the largest extent. Most other emissions of F-gases have already been decreased substantially, but will also be limited further. This leads to a reduction of F-gas emissions to 10 Mt CO_2-eq. (see Table C 3), which corresponds to a reduction by 87% compared to 1990 (92% compared to 2010).

Table C 3: F-gas emissions of the EU industry sector in 1990, 2015 & in GHG-neutral EU2050

Sub-sector	GHG emissions 1990 [Mt CO_2-eq.]	GHG emissions 2015 [Mt CO_2-eq.]	GHG emissions 2050 [Mt CO_2-eq.]
Chemical Industry	40.8	2.5	4.5
Metal Industry	22.4	0.6	1.5
Electronics Industry	0.8	0.8	0.9
Product Uses as Substitutes for ODS	0.0	110.0	2.0
Other Product Manufacture and Use	7.6	6.6	0.7
TOTAL F-gases	**71.6**	**120.6**	**9.6**
change vs. 1990		68%	-87%

Source: own calculation (Fraunhofer ISI) based on UNFCCC (2017) and UBA (2013)

C.5 Challenges

Industrial processes currently used to produce energy-intensive basic material products have been optimised over many decades. Consequently, the remaining energy efficiency potentials due to applying BAT are limited. In addition, fuel switching from fossil fuels like natural gas to renewable sources is limited due to the high temperature levels required in industrial furnaces and the competition for biomass with other sectors. Although incremental improvements of energy efficiency and fuel switching are important pillars of industrial decarbonisation pathways, these two options alone will not suffice to achieve a low-carbon industry sector by 2050.

Deep emission cuts require substantial changes in the iron and steel, cement and chemicals industries, but also support for RES and energy efficiency in other sectors and companies. Currently, biomass is the most important RES in industry. However, biomass resource potentials and their sustainability are limited. In the long-term, RES-based electricity (power-to-heat) and novel fuels like RES-methane and hydrogen can play a more important role, particularly if electricity generation becomes carbon-neutral. Currently, electricity is not yet competitive with biomass, meaning that replacing biomass by electricity would require additional policies.

The shown scenario envisages radical changes to industrial production systems like innovative processes and large-scale power-to-heat for steam generation mainly in the time horizon until 2050. However, in order to have new process technologies and innovations ready by 2030 in order to be able to unfold their effects until 2050, substantial research, development and innovation activities need to take place in the coming decade. Pilot and demonstration plants need to be built to prepare for market introduction. It might easily take 10 years for new processes in the materials industry to progress from lab-scale to market. Certification processes such as those needed for new cement types can prolong the time taken even more. Consequently, the current policy mix needs to be adjusted in order to effectively support R&D activities directed at the decarbonisation of industrial production. In general, it is necessary to set incentives towards a low-carbon industry as early as possible to accelerate the market entry of efficient and innovative processes as increases of CO_2 price probably take place after 2040 and consequently affect only a small share of investment decisions taken.

In addition, more ambitious mitigation efforts towards full CO2-neutrality need to address remaining smaller (distributed) sources of process emissions or focus on comprehensive circular economy and material efficiency improvements.

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D Feedstocks in the chemical industry

D.1 Introduction

In the chemical industry, the target is not to decarbonize the sector in the literal meaning of the word, i.e. remove carbon from the industrial cycle, but rather to combat the industry's use of fossil-based fuels and feedstocks. For feedstocks this means that all the carbon-based energy carriers used as materials should originate from renewable sources and that incinerating the products made from these raw materials at the end of their life cycle does not produce fossil-based CO_2 emissions.

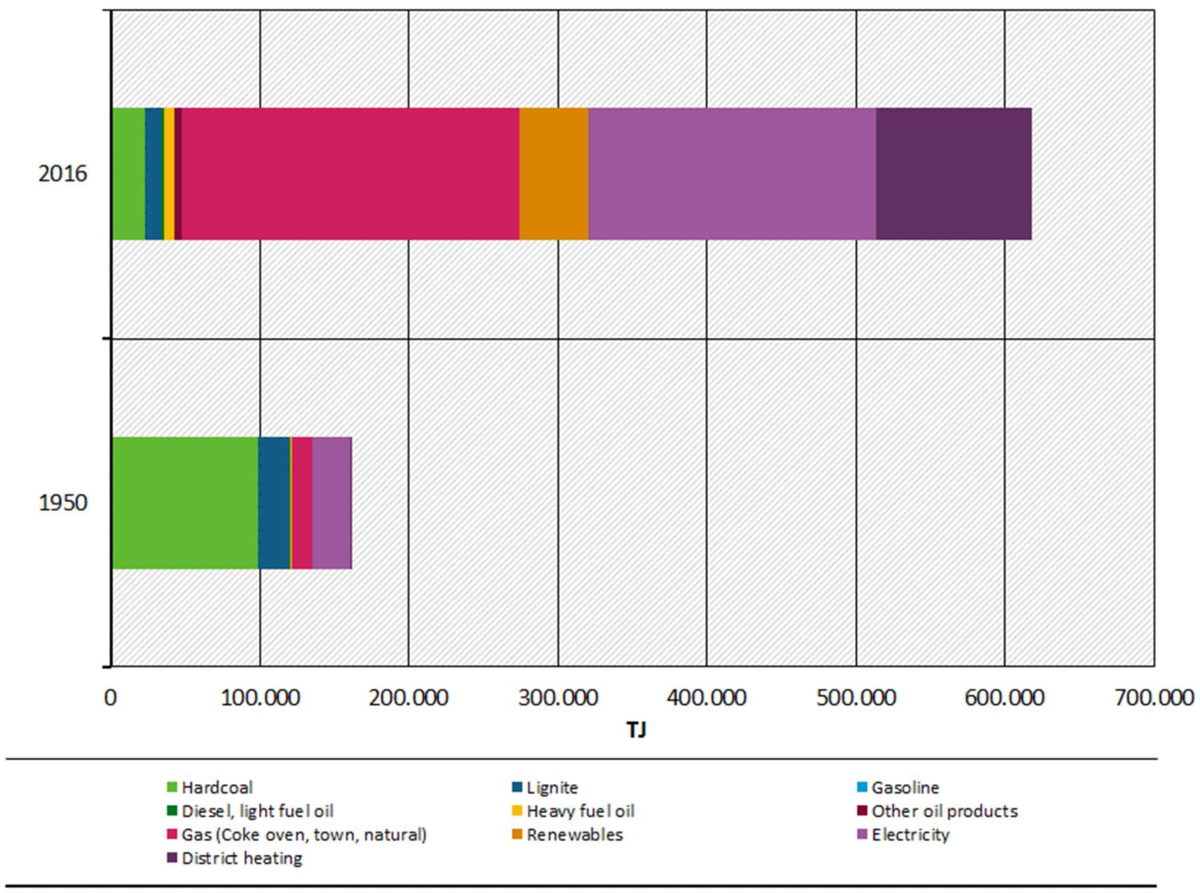
The following short analysis describes the resources used as (non-energy) materials in the chemical industry. In a second step, we present the platform chemicals manufactured from them (petrochemicals and basic chemicals). Subsequently, we discuss to what extent these platform chemicals can be manufactured directly or from alternative feedstocks without producing fossil CO_2.

D.1.1 Changes of energetic use of fossil energy carriers

Using Germany as an example, Figure D 1 clearly shows the massive changes in the past regarding the use of energy carriers associated with the transformation of production processes and the production spectrum in the chemical industry. Whereas coal was the dominant energy source for the German chemical industry in 1950 with more than 70%, this provided only approx. 5% of the energy needed in 2017. Overall, the picture for 2016 is more differentiated, but the energy carriers are dominated by natural gas (37%) and electricity (31%). CO_2-free renewable energy sources also play a role with about 7.5%.

This shows that the industry has experience in adapting to changing circumstances if given enough time. There have been already different suggestions in the past for how to radically transform the chemical and energy industry: In the 1990s, Nobel prize winner George Olah advocated a methanol economy. In 2006, he and co-authors published a summary of the state of fossil fuel and alternative energy sources, including their availability and limitations, before proposing a methanol economy (Olah et al., 2006). There are also transformative approaches for hydrogen (Ball et al., 2009) and various biorefinery concepts (Kamm et al., 2006; IEA, 2018). In the past, the reasons for transforming the raw material base were to reduce import dependency and use renewable resources; climate targets are the motivation today.

Figure D 1: **Change of energy use by energy carriers in the German chemical industry from 1950 to 2016 (AGEB, 1951 and 2018)**



D.1.2 Status quo of non-energy use of fossil energy carriers as feedstock in the EU28

Naphtha (petroleum) and other petroleum-based feedstocks like LPG or gasoil are currently the most important petrochemical feedstocks for the EU28 and therefore the most important source of carbon for industrial organic chemistry, see Figure D 2. Most of the 68 million tonnes of mineral oil-based feedstocks are used in steam cracker units to produce olefins. The amount of feedstock used in the petrochemical industry increased until 2007 (Figure D 3). The amount used fell below 80 million tonnes during the 2008/09 crisis and has been slowly recovering since then.

Natural gas is another important raw material for the chemical industry with 17%. In addition, coal is used as a raw material for chemicals like calcium carbide with a share of about 0.7 million t (1%), see Figure D 2.

Another 8% of the raw materials are renewables (CEFIC, 2018). These 7.8 million tonnes are mainly bioethanol (21%), starch and sugar (20%), vegetable oils (18%) and natural rubber (15%).

Figure D 2: Feedstocks for the EU chemical industry 2015 (CEFIC, 2017; EUROSTAT, 2018)

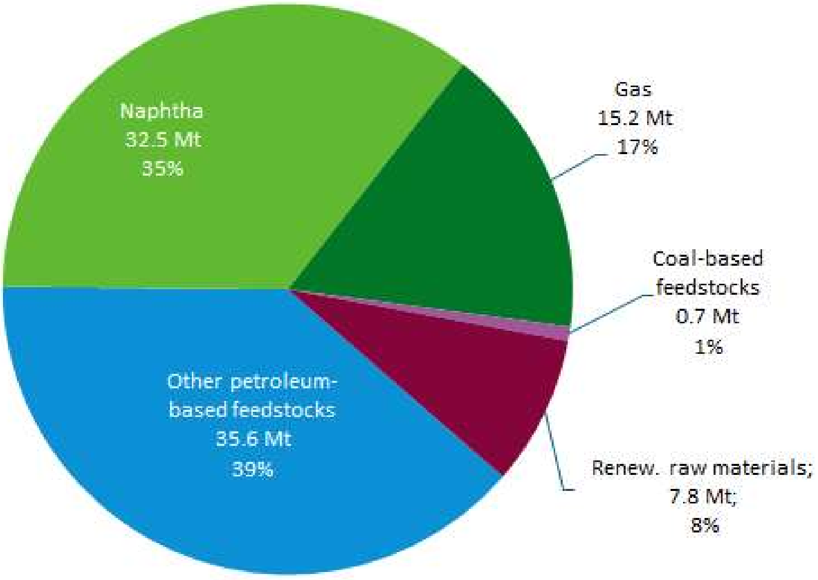
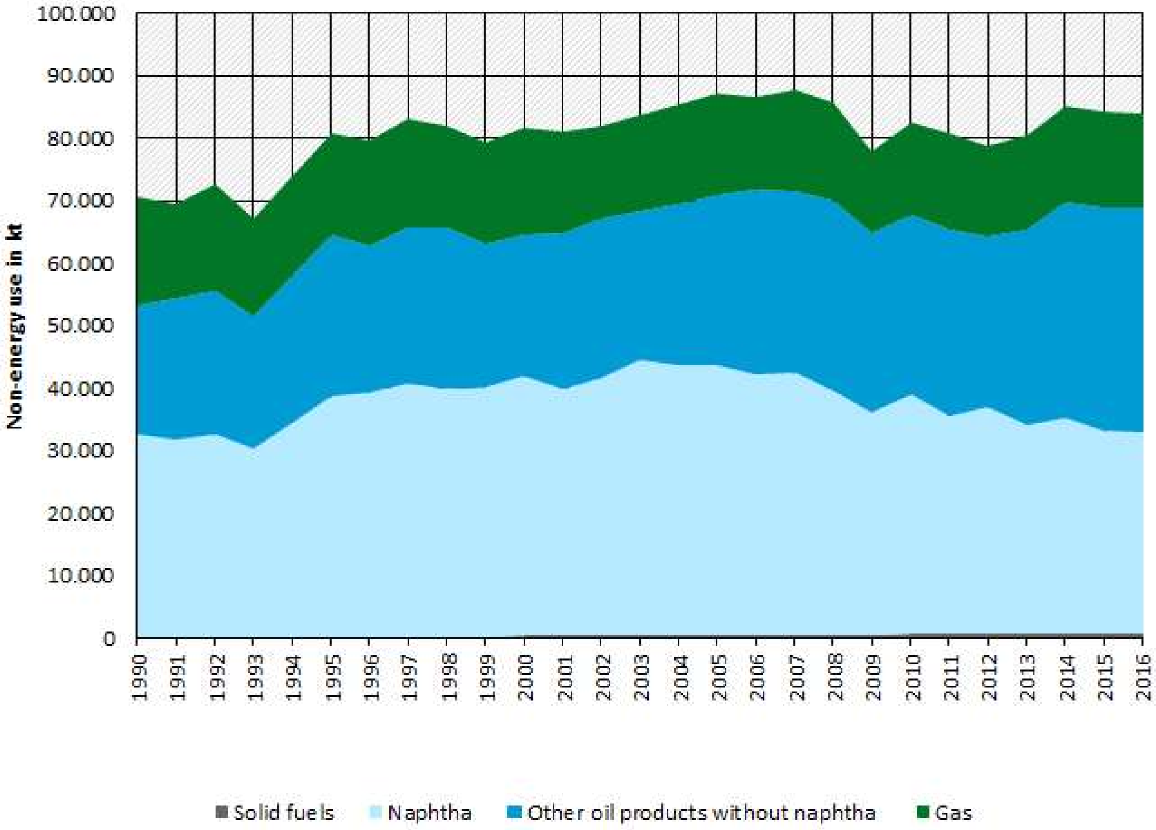


Figure D 3: Use of energy carriers as feedstocks in the EU28 chemical industry 1990 to 2016 (EUROSTAT, 2018)



D.1.3 Platform chemicals

Many different chemicals are synthesized from feedstocks like naphtha and natural gas. However, their precursors can be reduced to a few important platform chemicals (petrochemicals and basic chemicals), see Figure D 4 and Figure D 5.). These platform chemicals are propylene, ethylene, C4 stream, benzene, toluene and xylenes from naphtha and methanol and ammonia from natural gas (methane).

Figure D 4: Main platform chemicals made of naphtha as feedstock

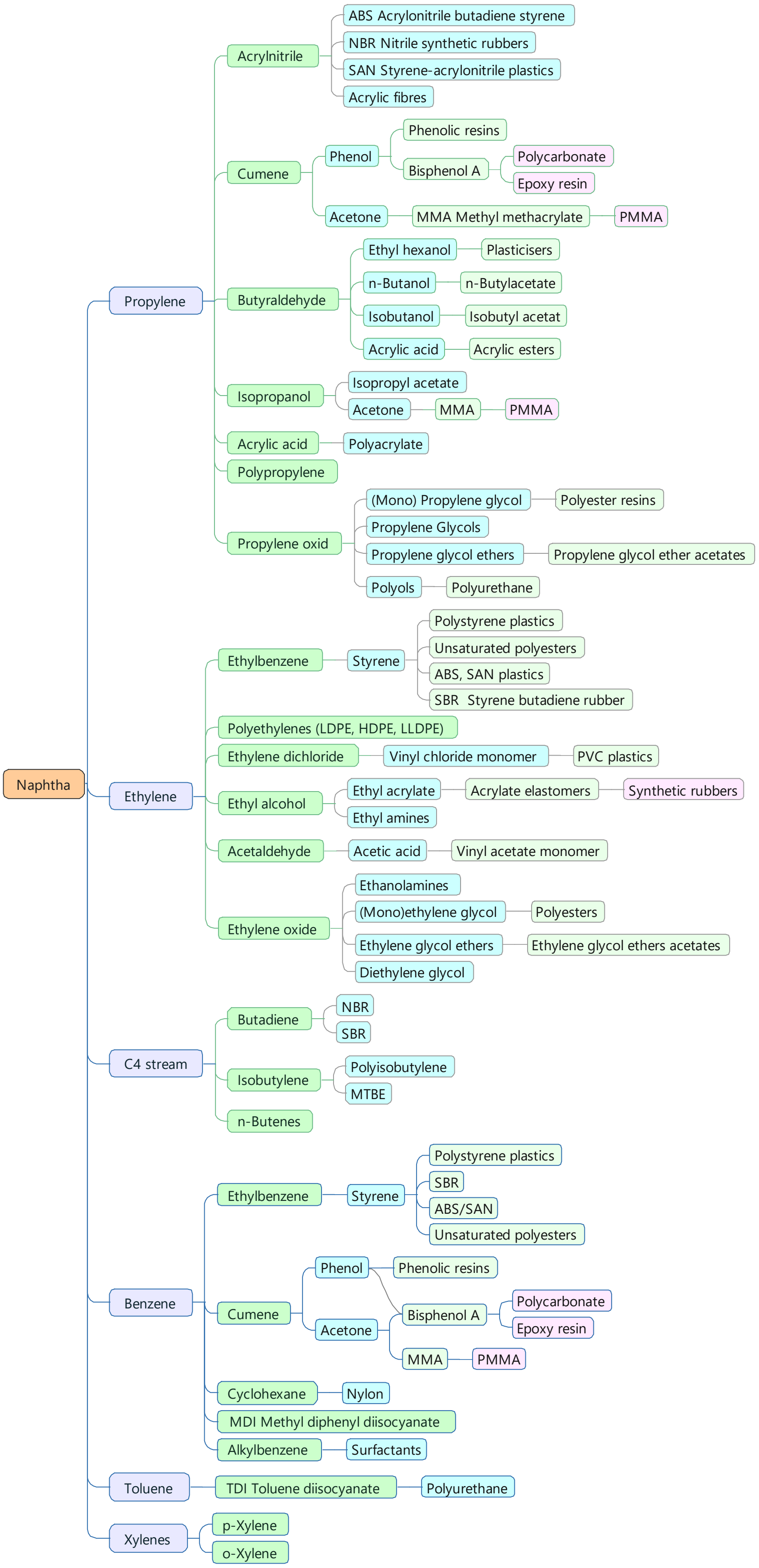
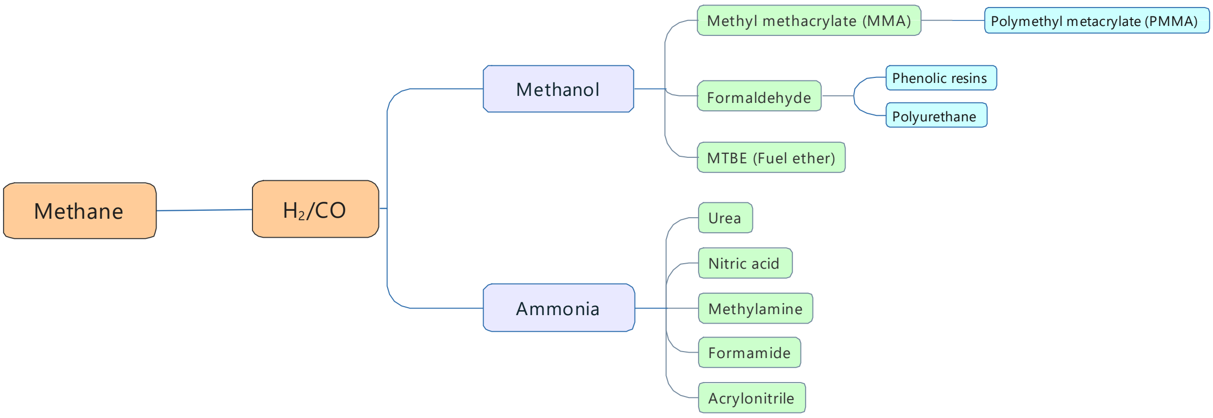


Figure D 5: Main platform chemicals made of natural gas as feedstock



If these chemicals could be produced directly from biomass and not from natural gas or naphtha, this would save the corresponding amounts of these feedstocks. This mainly concerns the chemicals listed in Table D 1. These basic chemicals form the foundation for the production of other fine and specialty chemicals and present therefore a “platform” for further syntheses. There are various approaches and individual descriptions of chemical synthesis with very low or zero CO_2 listed in the literature. The 12 principles of Green Chemistry already included calls for the use of renewable feedstocks and low-waste production (Anastas et al., 1998). Despite this, only a few syntheses based on biomass have become widely accepted so far due to economic reasons (Wagemann, 2014).

Table D 1: Production of platform chemicals in EU28 and in Germany for comparison in 2015

Chemical	Production in EU28 [t]	Production in Germany [t]	Examples for alternative production routes
Propylene*	12,872,033	3,960,516	dehydration of bioethanol, biomethanol via DME: MTP
Ethylene	15,632,357	5,133,818	bioethanol, biomethanol (via MTO)
C4 stream	4,894,846	2,146,118	
Benzene	6,549,820	1,968,893	Aromatics from lignin are not yet in commercial-scale production
Toluene	1,298,749	591,337	
o-,p-Xylenes	2,105,785	505,000	Hydroxymethylfurfural (HMF) formed by the dehydration from sugar, hydrogenation to 2,5-dimethylfuran and addition of ethylene, subsequent aromatization and dehydration
Methanol	1,290,737	976,192	Biomethane, H_2-electrolysis
Ammonia (N_{total})*	17,671,500	2,848,483	H_2-electrolysis, stripping exhaust air from livestock farming
Sum [t]	62,316,000		
Sum C [t]	37,750,000		

Sources: EU 28 data from PRODCOM database 2018; German data: Verband der Chemischen Industrie e.V. (VCI): Primärchemikalien-Erfassung 2017; *marked production figures taken from Statistisches Bundesamt (Destatis), 2018: Produzierendes Gewerbe. Produktion des Verarbeitenden Gewerbes sowie des Bergbaus und der Gewinnung von Steinen und Erden)

D.2 Methodology, assumptions and underlying data set for 2050 scenario

The assumptions and underlying data sets for the 2050 scenario correspond with the ones for the industry sector and are described there in detail. In this section, we focus on the assumptions regarding feedstock changes.

From the feedstock figures, we can calculate the amount of carbon required in 2015 as approx. 69 million tonnes, compare Figure D 2 and Table D 2. The platform chemicals listed in Table D 1 use roughly 63% of the carbon in the feedstock (36.5/57.7), if it is assumed, that the natural gas is used mainly for hydrogen, ammonia and methanol. So nor the gas neither the methanol is taken into the calculation.

Table D 2: Carbon demand for the chemical industry in 2015

Raw material	Million tonnes	Mean composition	Million tonnes carbon
Naphtha	32.1	$C_{10}H_{22}$	27.1
Other oil-based feedstocks	36.0	C_4H_{10}	29.8
Gas	15.0	CH_4	11.3
Solid feedstock	0.8	C	0.8
Sum	**83.9**		**69.0**

Source: Eurostat 2018; CEFIC, 2018; own calculations

When aiming at GHG neutrality, both the energy carriers used for energy and those used for raw materials have to be selected so that fossil CO_2 is not emitted to the atmosphere when manufacturing chemicals and when recycling them after use. Various possibilities for achieving this are discussed in the literature, such as the increased use of biomass (Carus, 2018) or the use of hydrogen from electrolysis plants operated using renewable electricity (Lechtenböhmer et al., 2016).

If there was a major shift in the transport sector towards electric mobility, significantly less crude oil would be refined into fuels in the medium term, so that correspondingly lower quantities of naphtha and oil-based feedstocks would be obtained as one of the fractions of the crude oil distillation.

There are different substances available as carbon sources. These can be renewable raw materials, forest and agricultural residues, biowaste from the food sector and from biogenic end-of-life products (e.g. waste bioplastics) as well as CO_2 from biogenic sources (compare the Section on biomass potentials).

- ► Use of biowaste

The EU potential of municipal waste biomass in 2050 is estimated to be between 400 and 850 PJ (Ruiz et al., 2015) and could be used as feedstock for basic chemicals. In some research projects also the production of end products is investigated, e. g. as part of the BMBF's strategic alliance ZeroCarbFP, enzymatic synthesis processes are developed for the production of high quality lubricant additives based on used edible fats and oils, residues from biodiesel production and lignocellulose (Brain, 2016).

- ► Use of bioethanol and biomethane

According to ePURE (the European Renewable Ethanol Association), 5.84 billion litres of bioethanol (approx. 4.6 million tonnes) were produced in the EU in 2017. In addition, 550 million litres were imported (ePure, 2018). Bioethanol was mainly used as a biofuel in 2017; only 19% were used industrially or in the food sector. In 2050, assuming the further decarbonization and electrification of transport, this quantity could be used completely in the chemical industry. There are additional further amounts of bioethanol that could be produced from lignocellulose, e.g. from waste straw. Following the roadmap of the European Biogas Association, there will be a production of 15 billion m^3/year in Europe 2030 (EBA, 2014). Feedstock will be energy plants and organic waste streams, including digestion of materials with high cellulose content like waste wood.

- ► Use of CO_2 in combination with hydrogen from renewable sources.

There are large quantities of CO_2 available in the EU28 for use in chemical reactions from industrial sources. Some of the large industrial CO_2 emitters will disappear over the course of the energy transition, but the remaining emitters such as, e.g. waste incineration plans, emit a total of approx. 55.5 million t CO_2 or 15 million t C today (2016); and the production of cement clinker and lime emits 145 million tonnes of CO_2 (42 Mt C) (E-PRTR, 2018). According to the model data, the direct process related emissions for non-metallic mineral products will be approximately 77 million tonnes in 2050.

Correspondingly, among other things, the current BMBF programs on using CO_2 as a feedstock attach particular importance to the formation of intersectoral alliances (Mennicken, 2016; CO2Net+, 2018).

- ► Use of waste plastics

In 2016, 60 million tonnes plastics were produced in EU28+NO/CH. In the same year 27.1 million tonnes of plastic waste were collected to be treated through official schemes in the (Plasticseurope, 2018). The main share of 42% (11.4 million t) was used for energy recovery, 31% (8.4 million tonnes) for recycling and 27% (7.3 million tonnes) for landfills. BASF, OMV and other companies run already pilot plants to produce synthetic crude oil via pyrolysis or catalytic cracking from non-recyclable mixed plastics (EUWID, 2018a; EUWID, 2018b). Because plastic products have partly lifetimes of decades, the plastic waste amount will be larger than 50 million tonnes in 2050, see the waste chapter. This quantity, properly recycled, could be enough to replace nearly the whole primary production of European polymers in 2050. In this chapter it is assumed that this substitution takes not place totally and it is also in 2050 necessary to produce virgin polymers for high technical applications.

At present, plastics are almost completely of fossil origin, but with increasing shares of bioplastics like PLA or bio-derived polyethylene, waste plastics will also increasingly become a source of renewable carbon, which can be used at various levels of recycling, like mechanical recycling or, at the end of the lifetime, in feedstock recycling.

D.3 Scenario GHG-neutral EU2050

In the scenario GHG-neutral EU2050, it will be necessary to exploit all the options to use domestic (European) raw materials for the chemical industry as much as possible. There are a lot of technical solutions, projects and concepts already prepared to make chemical synthesis and processes more energy and CO_2 efficient. On the other side, it is obvious, that a low carbon chemical industry is a tremendous goal and we have to start today with the first steps for the conversion of the chemical industry. This conversion includes the use of biogas, biowaste, bio-based resources and all other renewable carbon sources as well. This will require more circular economy approaches and thinking. From the viewpoint of CO_2 reduction, it will no longer be sufficient for industry to manufacture products, market them and then forget about them in the future. Products should be regarded as valuable renewable carbon carriers that should be recycled after use and then reused as raw materials (for example as biopolymers in packaging), as shown in Figure D 6.

Figure D 6: Possible circular loops for carbon (VCI, 2018)

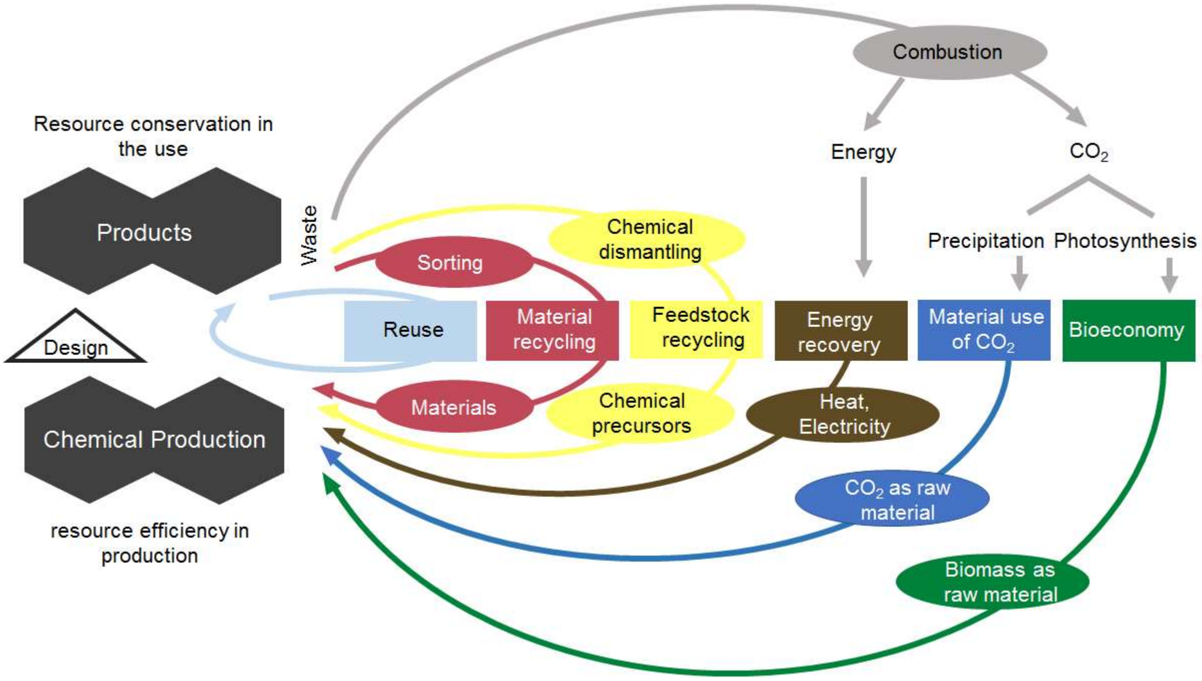


Table D 3 estimates the production quantities of some important platform chemicals by the European chemical industry for 2050, based on the production figures from the industry chapter. These chemicals are used as examples to show which feedstock could be used for their production in the future and how much of it would be needed.

Taking into account, that the analyzed platform chemicals in Table D 1 for the year 2015 only representing 63% of the feedstock demand, it can be assumed, that the overall feedstock demand will **be ca. 57 million tonnes carbon**. The total production quantity of methanol will be much higher than in Table D 1 because it is assumed that it is used to produce propylene and BTX through the MTP and MTA processes

As shown in Section D.2, it is possible to use carbon from biowaste, recycling of carbon products, bioethanol and biomethane to an amount as feedstock. The remaining demands can be met by producing PtX feedstocks in the EU or by importing sustainably produced raw materials, platform chemicals or PtX materials.

Table D 3: Production of platform chemicals in EU28 in 2050 and their feedstock

Chemical	Production 2050 in EU28 [Mt]	Carbon input 2050 in EU28 [Mt]	Potential alternative production routes
Ammonia	19.2	0.0	Production via H_2 (water electrolysis) --> Haber-Bosch. Haber-Bosch process is exotherm and thus has no energy demand. Demand of 0.178t H_2 per t of ammonia
Propylene	13.1	11.2	Production via biomethane -> methanol -> propylene. For the methanol-to-propylene (MTP) process, the stoichiometric amount is 2.3 t methanol/t propylene with a yield of ≈ 80%.
Ethylene	18.4	15.8	Dehydration of bioethanol. Yield 99%
BTX	10.0	8.5	Production via biomethane -> methanol -> methanol-to-aromatics (MTA). Methanol demand for MTA process 4.3 t/ t BTX. The process efficiency from biomass to methanol is given to be approximately up to 60%.
Other chemicals*	N/A	21.5	-
TOTAL	**N/A**	**57**	**-**

* The carbon input for the remaining chemicals was estimated based on today's relation to the listed platform chemicals.

Sources: Own calculation (Fraunhofer ISI) based on Bazzanella et al. (2018), Wagemann (2017)

The final non-energy consumption is derived from the production and units via the lower heating value of the inputs (methanol, ethanol, hydrogen). In total, the novel fuel demand for the 57 million tonnes C platform chemicals from Table D 3 in the scenario GHG-neutral EU2050 is estimated to be 114 TWh primary energy of hydrogen (for ammonia production) and 1084 TWh of hydrocarbons (see Table D 4). This is a small increase with regard to the total of 1077 TWh of fossil feedstocks in industry in 2015 (see EUROSTAT 2018), which reflects the assumed increase of production units but also a slight increase of conversion losses.

Table D 4: Novel fuel demand of platform chemicals in EU28 in 2050

Chemical	Hydrogen input 2050 in EU28 [TWh]	Hydrocarbon input 2050 in EU28 [TWh]	Remark
Ammonia	114		120 GJ/t H_2 energy content
Propylen		208	19.9 GJ/t CH_3OH energy content
Ethylen		230	26.7 GJ/t C_2H_5OH energy content
BTX		237	19.9 GJ/t CH_3OH energy content
Other chemicals		408	Estimate based on average input for propylen, ethylen and BTX
TOTAL	**114**	**1084**	

D.4 Challenges

A shift away from fossil raw materials is unavoidable. As is frequently the case, there is not one ideal solution. Instead, there will be a mix of technologies and production routes that are suitable for producing chemicals without fossil feedstocks and that will compete with each other. This already happened more than 50 years ago with the introduction of petrochemicals when acetylene chemistry no longer played a major role. The chemical industry adapted their processes to the new general conditions coming up with the cheap petro-based feedstock.

The chemical industry will adapt again. This works all the better, if the framework conditions are early determined and the transition pathway towards CO_2-free chemical production are well settled. Proposals for how to do this have already been made (Carus, 2018; Wesseling et al., 2016). During a transitional period, waste such as waste plastics and transition technologies can be used, e. g. such as methane pyrolysis, which produces hydrogen from methane. The resulting carbon can be sold as carbon black or stored underground (Bode, 2017). However, there are still many challenges along the way forward, including:

- **Biomass:** A challenge when using larger quantities of agriculturally produced biomass is not to transform the landscape by planting, e.g. energy maize, in a way that has negative impacts on the soil, ground- and surface water, biodiversity, landscape etc.
- **Need for electricity:** Large amounts of electricity are needed to produce hydrogen for synthesis gas. Electrolysis using renewable power is considered the key technology for this (Smolinka et al., 2018). Assessments are required that encompass not only the processes but the plants as well in order to ensure the renewable electricity is used in a way with the greatest benefit.
  Initial estimates of renewable power production (wind, PV) in the MENA region indicate that an area of land as large as Schleswig-Holstein would be required if only a quarter of German passenger cars makes use of PtX fuels. This makes it very clear that the establishment of these plants in the countries concerned will be accompanied by societal changes that have to be planned, prepared and accompanied.
- **Sustainability:** Since the chemical industry features complex processes, it is important to conduct comprehensive sustainability analyses of alternative processes. If the analyses consider only the carbon footprint and processes are optimized accordingly, there is a risk of increasing other emissions. This happened, for example, in the case of wood-based heating systems, where particulate emissions were only considered later (UBA, 2007).
- **Openness for radically different ways:** For instance, in 2004 already, the GDCh proposed greening desert areas rather than pursuing more expensive technical solutions for the sequestration of CO_2 like CCS (Hüttermann et al., 2004). They estimated lower costs per tonne of stored CO_2 and pointed to the fact that the biomass obtained could be used in a carbon-neutral way. This would also have many additional positive effects such as stabilizing the global water supply, creating jobs, increasing food supplies and others.
  Another possible way forward is to develop artificial photosynthesis or the development of an inverse methanol fuel cell, in which water and CO_2 is converted to methanol (Bullis, 2006).

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E Buildings

E.1 Introduction

About 40% of energy consumed in the EU-28 is in buildings highlighting the importance of this sector. CO_2 emissions of buildings in the EU-28 account for 26% of all CO_2 emissions (EU COM 2016b).

The buildings sector is addressed directly or indirectly by three main EU directives: the energy performance of buildings directive (EPBD, 2018/844), the energy efficiency directive (EED, 2012/27/EU) and (RES-D, 2009/28/EC). The latter two are currently being revised, but close to being finalised. Energy-related targets for the EU28 in the buildings sector are shown in Table E 1. The already decided upon targets in the directives currently under revision are also shown in Table E 1.

Table E 1: EU28 building-related targets

	2020	2030	2050
CO_2-eq reduction compared with 1990	-20%	-40%	-80 to -95%
Renewable energy share of the total gross final energy consumption	20%	32%	
Reduction in final energy consumption (“energy efficiency goal”)	-20%	-32.5%	

Source: own representation (Oeko-Institut and Fraunhofer ISI)

The modelling approach taken for the buildings sector is a two-step process: first, the energy demand needed is determined and second, the energy carrier distribution is adjusted. The first step aims at reducing the final energy demand in buildings as much as possible with very ambitious energetic standards for new and refurbished buildings. The second step tries to minimise the use of fossil fuels in supplying the remaining energy demand in buildings. This is particularly difficult since the currently most dominant form of renewable energy used in buildings is biomass, which is limited in its availability and which is also much sought after in other sectors. Therefore, ambient heat made available through heat pumps as well as solar thermal energy are important renewable energy carriers in this low-carbon scenario. A highly decarbonised electricity supply (incl. the use of electricity-based novel fuels) in combination with also highly decarbonised district heating complete the low-carbon energy carrier supply for buildings in 2050.

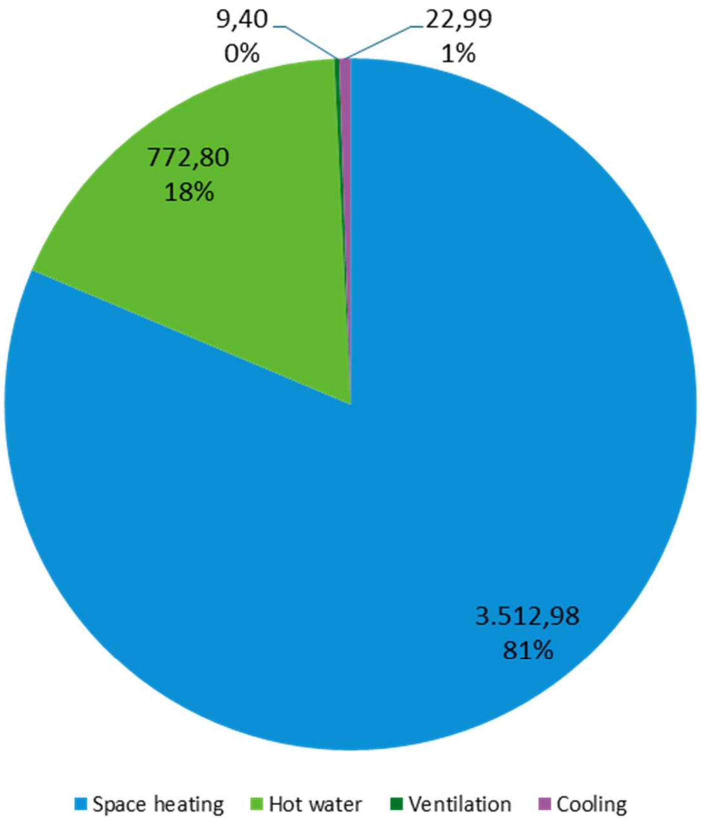
E.2 Status quo

Figure E 1 shows final energy demand (FED) in TWh per year for space heating, hot water, ventilation and cooling for the EU28 in 2015 (status quo). The data are based on a combination of sources. Space heating FED is based on the latest available data from the EU Building Stock

Observatory[9] for floor area specific energy consumption and relevant floor areas in the EU28 MS. These data are from 2013. The space heating data for 2015 shown in Figure E 1are therefore already a modelling result. Hot water FED in 2015 is based on a generic 25 kWh/(m²a) across the entire EU28 without any country-specific adjustments. The FED for ventilation and space cooling are also modelling results. Space heating dominates the final energy demand with more than 80% followed by hot water with 18%, whilst ventilation and cooling together take up about 1%.

The combined FED for 2015 as modelled here differs from the EU's official energy balance for 2015 due to the fact that 2015 was an unusually warm year, which means the official (not climate-adjusted) energy balance has a space heating FED about 10-15% lower than the modelling results.

Figure E 1: Modelling results of the final energy demand in TWh per year for space heating, hot water, ventilation and cooling in the EU-28 in 2015



Source: own calculation (Oeko-Institut and Fraunhofer ISI)

Looking in more detail into the status quo of space heating and hot water usage, Figure E 2 displays the distribution of energy carriers in 2015 based on the Heat Roadmap Europe project (EU COM 2016a). Gas clearly dominates with a share of more than 40%, with oil taking up about 15% and district heating 10%. Biomass is more commonly used for space heating (more than

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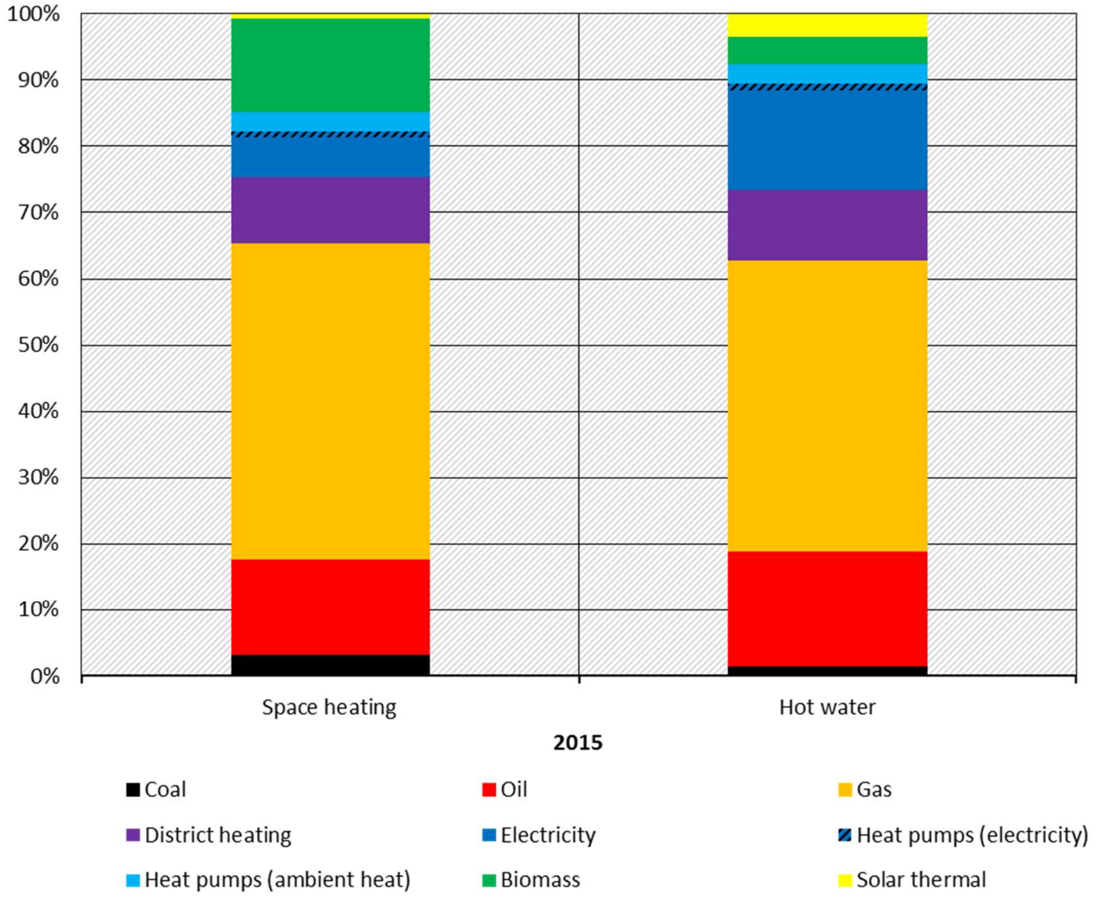
[9] See https://ec.europa.eu/energy/en/eubuildings

13%) and less for hot water (less than 5%). The opposite is true for both electricity and solar thermal energy, which have a bigger share in the hot water energy carrier distribution compared to the distribution for space heating. The overall share of renewable energy carriers is still comparatively low for both forms of energy usage.

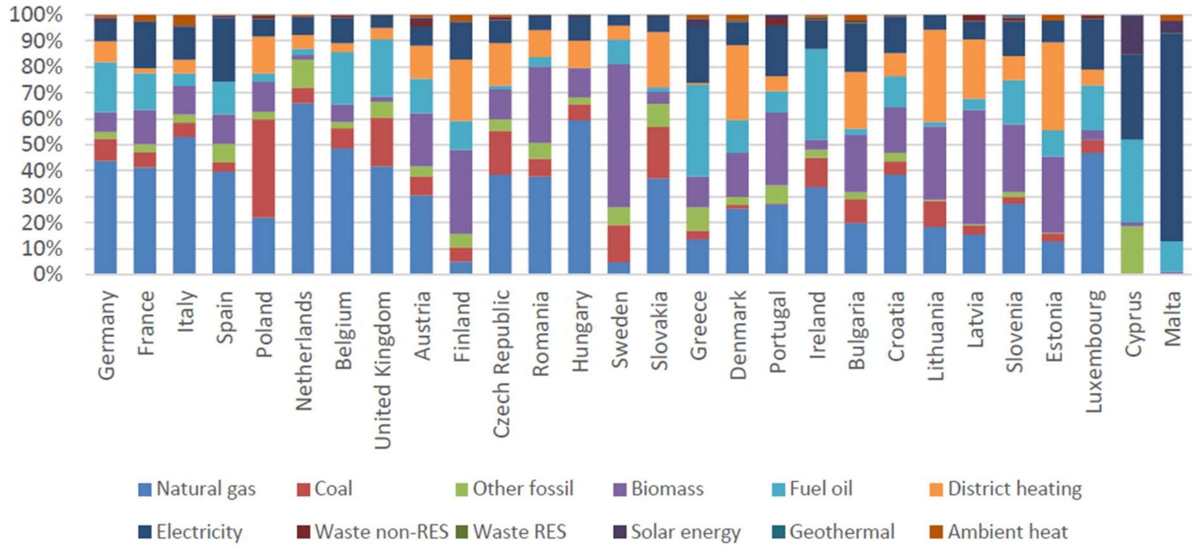
Figure E 2: Energy carrier distribution for space heating and hot water in the EU-28 in 2015



Source: Heat Roadmap Europe (2018)

For a more detailed look into the energy carrier distribution in the various EU-28 countries see Figure E 3, which shows data for 2012. There are big differences in the energy carrier distributions within the EU-28 with some countries using lots of biomass whilst others have a high share of natural gas, fuel oil or district heating.

Figure E 3: Energy carrier distribution for heating and cooling in the EU-28 MS in 2012



Source: EU Strategy on Heating and Cooling (EU COM 2016b)

E.3 Methodology, assumptions and underlying data set for 2050 scenario

E.3.1 Modelling approach

The energy demand for heating and cooling is calculated by means of a simplified stock exchange accounting model. Various drivers such as the rate of newly-built buildings, the demolition rate, the refurbishment rate as well as energy consumption levels of existing, new and refurbished buildings are implemented in the model and change over time (for details see below).

The overall aim is to reduce the total final energy demand (FED) by 60% in 2050 with respect to 2008. This aim was derived from two studies[10] that look in detail into the German buildings sector and which found that -60% is the maximum possible reduction in FED by 2050. As can be seen below, we struggled to achieve such a reduction and achieved only about -50%. Therefore, the remaining energy demand has to be covered by even more renewable energy sources in order to reach GHG-neutrality.

In order to take account of the differences in energy carrier distributions in the various EU-28 countries, yet at the same time not going into too detailed a modelling approach, we decided to form six country clusters. The building sector therefore is modelled in slightly more detail taking into account regional differences within the EU-28. The clusters contain countries that share similar characteristics such as e.g. a traditionally high use of biomass or a broadly developed district heating infrastructure. The various characteristics were used for the modelling to specifically set the 2050 energy carrier distributions taking into account the historical energy use per cluster. Figure E 4 and Table E 2 give an overview of the six clusters.

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[10] Energieeffizienzstrategie Gebäude (Thamling et al. 2015) and Klimaneutraler Gebäudebestand 2050 (Bürger et al. 2016)

Figure E 4: Cluster overview

Source: own representation (Oeko-Institut)

Table E 2: Cluster definitions

	Country 1	Country 2	Country 3	Country 4	Country 5	Country 6	Country 7
North	Denmark	Finland	Sweden				
Northeast	Estonia	Latvia	Lithuania				
East	Bulgaria	Czeck Republic	Hungary	Poland	Romania	Slovakia	Slovenia
South	Croatia	Cyprus	Greece	Italy	Malta	Portugal	Spain
West	Belgium	France	Irland	Netherlands	United Kingdom		
Central	Austria	Germany	Luxemburg				

Source: own representation (Oeko-Institut and Fraunhofer ISI)

E.3.2 Data sources

The status quo is based on publicly available data from the EU Building Stock Observatory[11] for each member state: floor areas for residential and non-residential buildings as well as climate-adjusted heating consumption per floor area. Here we used the latest available complete dataset,

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[11] https://ec.europa.eu/energy/en/data-analysis/building-stock-observatory

which is from 2013. The data were used to calculate the total final energy consumption in residential and non-residential buildings.

Data sources for the main drivers in the model (see below) are the population and GDP developments from the EU's reference scenario (EU COM 2016a).

The status quo for the energy carrier distributions for each country were taken from the Heat Roadmap Europe project (Heat Roadmap Europe 2018).

E.3.3 Main assumptions and drivers

The following Table E 3 gives an overview of the main drivers and assumptions made in model calculations for the buildings sector. Each driver is being introduced in more detail below.

Table E 3: Main drivers

	Unit	2015	2050
Population	Million	505	522
GDP	Billion EUR	13,427	22,526
Demolition rate residential	%/a	0.15	0. 50 (linear increase)
Demolition rate non-residential	%/a	0.20	1.0 (linear increase)
Rate of newly-built buildings, residential	%/a	based on population growth in year t-2	based on population growth in year t-2
Rate of newly-built buildings, non-residential	%/a	based on GDP growth	based on GDP growth
Refurbishment rate residential	%/a	1.0	2.75
Refurbishment rate non-residential	%/a	1.0	2.5
Equipment rate cooling systems residential	%	0.1	0.1
Equipment rate cooling systems non-residential	%	0.5	0.5

Source: own representation (Oeko-Institut and Fraunhofer ISI)

Demolition rate: the demolition rate is increasing over time – for residential buildings it starts at 0.15% per year in 2015 (broadly modelled on statistical data from Germany, cf. destatis, 2018) and reaches 0.50% per year by 2050, for non-residential buildings it starts at 0.30% per year in 2015 and reaches 1.00% per year by 2050 (cf. Table E 4). Due to increased migration away from countries of the country clusters Northeast and East, the demolition rates for residential buildings for these two clusters were specifically controlled and increase more than for the remaining clusters.

Table E 4: Demolition rates

	2015	2020	2025	2030	2035	2040	2045	2050
Residential	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
Residential (Cluster Northeast + East)	0.20	0.30	0.35	0.40	0.45	0.50	0.55	0.60
Non-residential	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00

Source: own representation (Oeko-Institut and Fraunhofer ISI)

Rate of newly-built buildings: the rate of newly-built buildings is based on a regression analysis for the entire EU (historical data from 2000 to 2014), both for residential and non-residential buildings. For residential buildings, the rate of newly-built buildings in each country is calculated according to $y = 0.81\ x + 1.0$ where y is the rate of newly-built buildings and x is the change in population growth two years previously (i.e. the rate in e.g. 2020 is based on the population change in 2018). For non-residential buildings, the rate is based on $y = 0.62\ x + 1.1$ where y is the rate of newly built buildings and x is the change in GDP with respect to the previous year.

Refurbishment rate: the refurbishment rate increases gradually and more or less linearly from 2015 to 2050. There are slightly different rates for residential and non-residential buildings – see Table E 5. The starting value of 1% per year in 2015 is based on historical data for Germany (cf. Cischinsky & Diefenbach, 2018).

Table E 5: Refurbishment rates

	2015	2020	2025	2030	2035	2040	2045	2050
Residential	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75
Non-residential	1.00	1.15	1.30	1.50	1.75	2.00	2.25	2.50

Source: own representation (Oeko-Institut and Fraunhofer ISI)

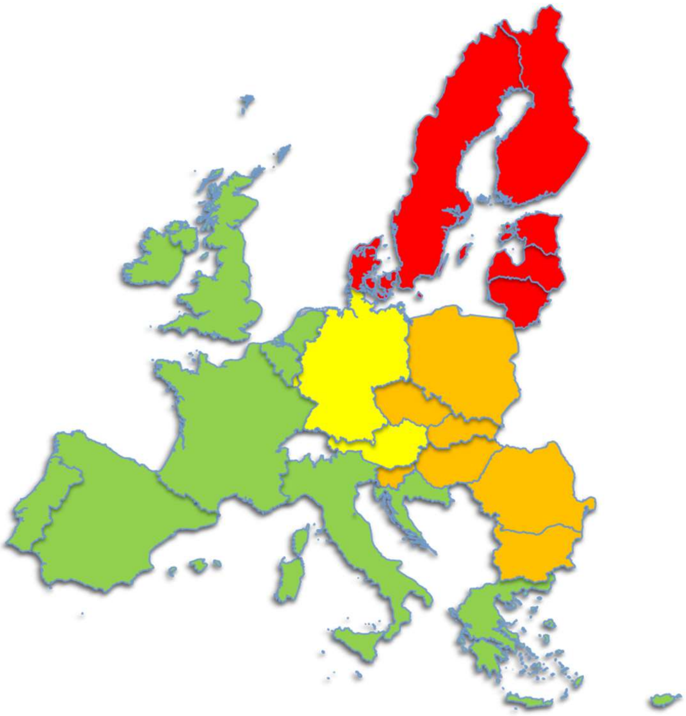
Energy standard of new buildings: In new buildings (residential as well as non-residential) the final energy demand (FED) for space heating is lowered by 25% every five years, starting from 2020. From 2040 onwards all new buildings achieve a “passive house” space heating demand of 15 kWh/(m^2a). All countries with space heating FED greater than 60 kWh/(m^2a) for the existing building stock (residential and non-residential) start with a space heating FED for new buildings of 60 kWh/(m^2a) in 2015. Those with existing building stock space heating FED below 60 kWh/(m^2a) start with a 20% reduced FED of the existing building stock FED in 2015.

Energy standard of refurbished buildings: Refurbished buildings follow a similar pattern: here the refurbishment standard for newly refurbished buildings starts with 80 kWh/(m^2a) in 2015 and is reduced by 25% every five years starting in 2020. Countries with space heating FED greater than 80 kWh/(m^2a) for the existing building stock (residential and non-residential) start with a space heating FED for newly refurbished buildings of 80 kWh/(m^2a) in 2015. Those with existing building stock space heating FED below 80 kWh/(m^2a) start with a 10% reduced FED of the existing building stock FED in 2015.

Equipment rate cooling systems: the equipment rate for cooling systems is kept constant over time – for residential buildings at 0.1%, for non-residential buildings at 0.5%.

Energy carrier distributions: Based on the status quo energy carrier distributions in the different country clusters we defined energy carrier distributions for each cluster for 2050. The main differences between country clusters relate to the use of biomass and district heating (shown in the figures below). The Nordic and eastern countries traditionally have a high share of district heating, which we tried to emulate in the Scenario GHG-neutral EU2050 (c.f. Figure E 5). Biomass being a much sought-after energy carrier with a limited availability is reduced substantially in its use in buildings – nonetheless it is still in use in 2050, especially in country clusters that have traditionally shown a strong reliance on biomass (c.f. Figure E 6).

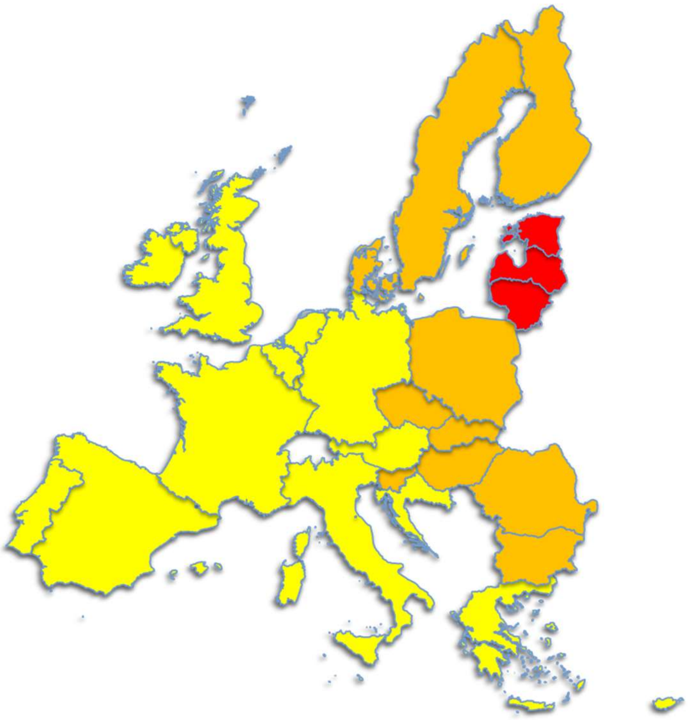
Figure E 5: District heating share of the final energy demand in space heating in 2050



Colour coding: red: 30%, orange: 25%, yellow: 20%, green: 15%

Source: own representation (Oeko-Institut)

Figure E 6: **Biomass share of the final energy demand in space heating in 2050**



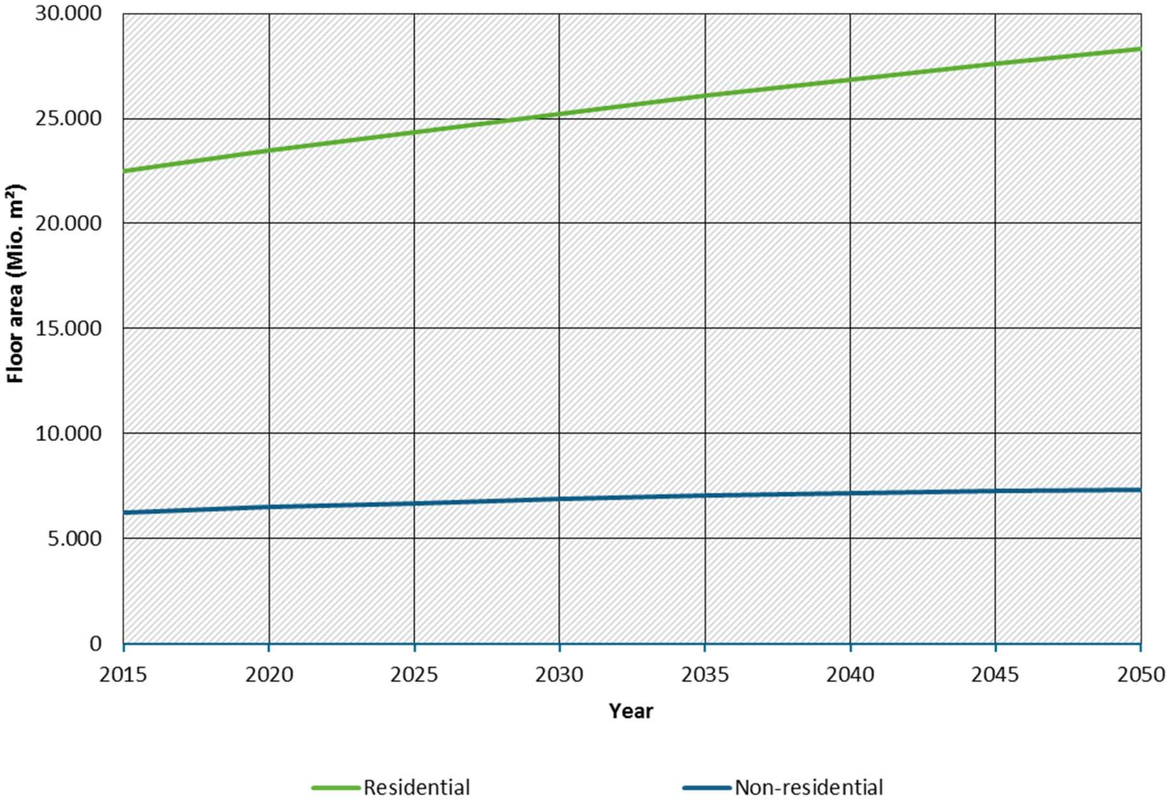
Colour coding: red: above 10%, orange: 10%, yellow: no biomass use at all

Source: own representation (Oeko-Institut)

E.4 Scenario GHG-neutral EU2050

The following Figure E 7 shows the evolution of residential and non-residential floor areas. The residential floor area increases from 22.5 billion m^2 in 2015 to 28.3 billion m^2 in 2050 (+26%). The floor area in non-residential buildings also increases: from 6.3 billion m^2 in 2015 to 7.3 billion m^2 in 2050 (+17%). The main drivers behind the increase in floor area are the increase in population, and the fact that more new buildings are being built than old buildings are being demolished (see above).

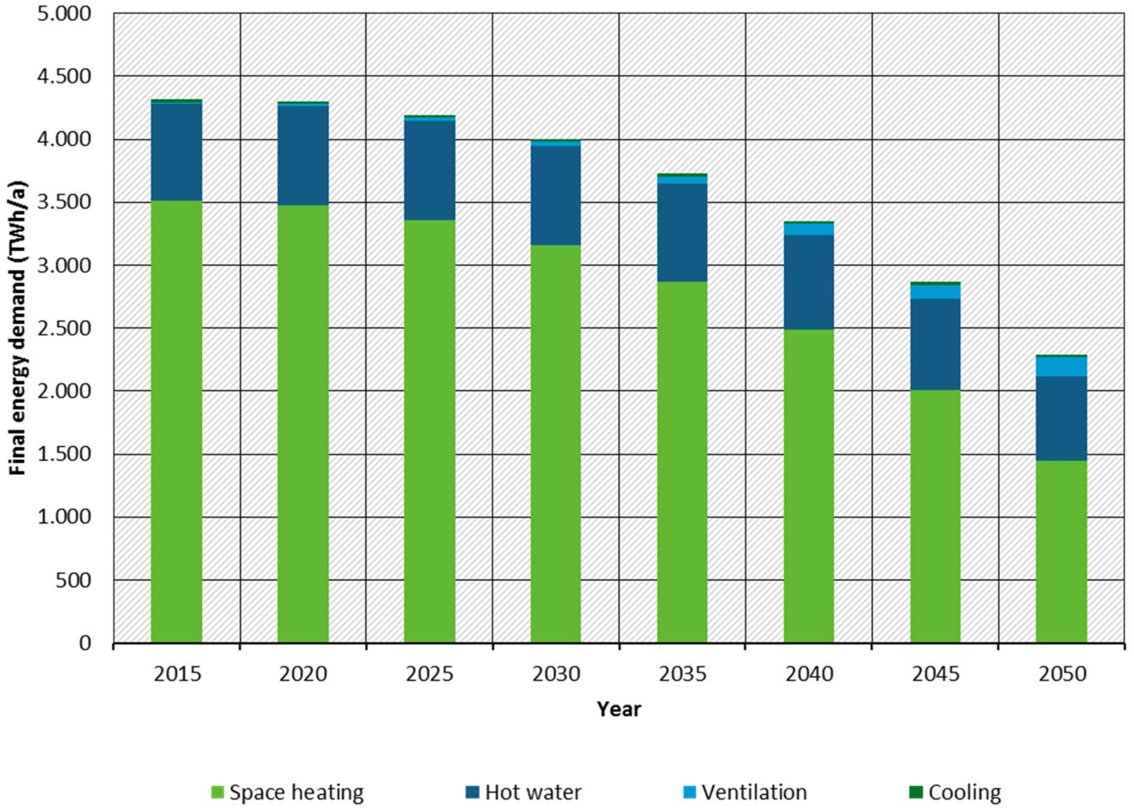
Figure E 7: Development of floor area in residential and non-residential buildings in the EU-28



Source: own calculation (Oeko-Institut, Fraunhofer ISI)

Figure E 8 and Table E 6 show the results of the scenario calculations for the EU-28. Overall a reduction in final energy demand (FED) of -47% is achieved for the combined FED for space heating, hot water, ventilation and space cooling. While demand for space heating is reduced by almost 60% in 2050 compared to 2015, hot water FED is only reduced by 13%. Ventilation demand, however, increases considerably: starting from a low base of 9 TWh per year in 2015, it increases fifteen-fold by 2050. Demand for space cooling is lowered by 5% over the same time period. Since space heating has such a high share of the overall FED (more than four times higher than the FED for hot water in 2015 and still more than twice as high as that for hot water in 2050), the overall reduction in FED for all energy applications is dominated by the FED for space heating.

Figure E 8: Development of final energy demand in EU-28



Source: own calculation (Oeko-Institut, Fraunhofer ISI)

Table E 6: Overview final energy demand in EU-28

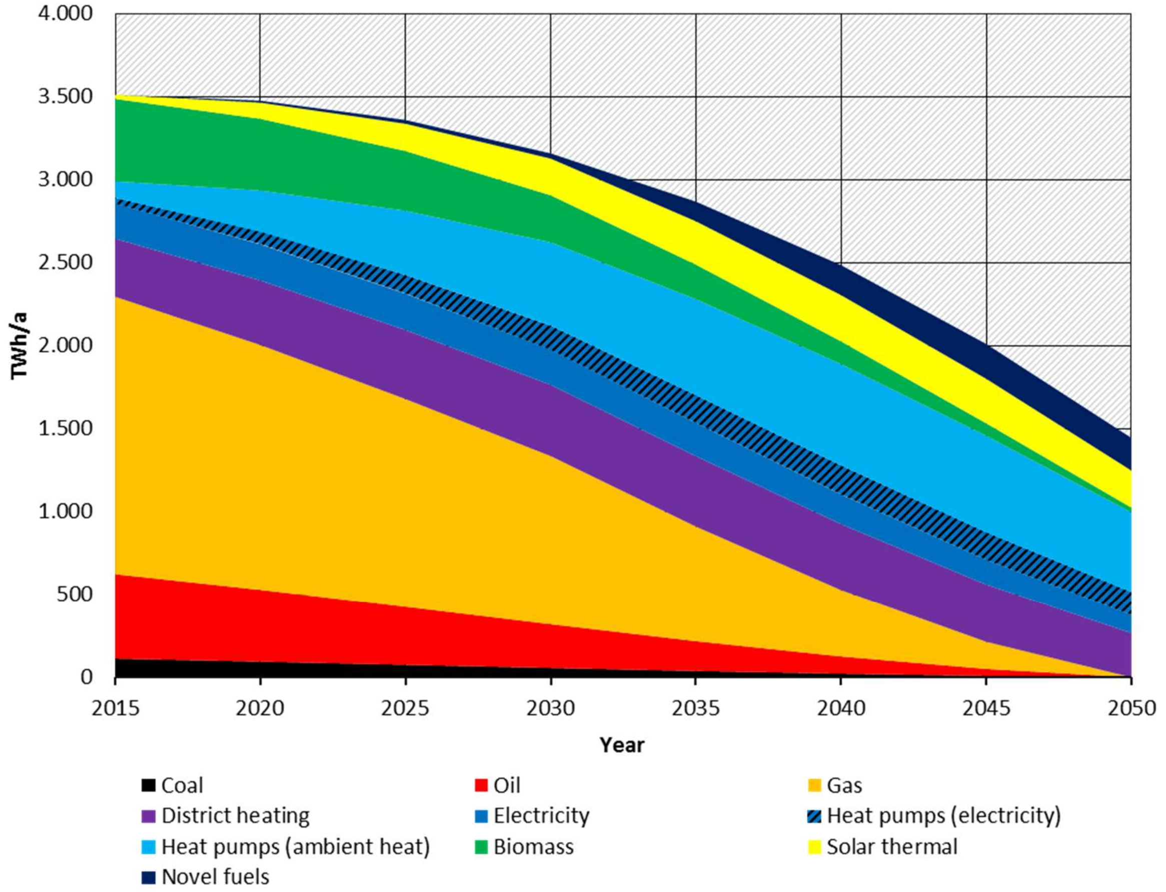
Final energy demand	Unit	2015	2050	% change
Space heating	TWh/a	3.513	1.443	-59
Hot water	TWh/a	773	675	-13
Ventilation	TWh/a	9	152	1513
Space cooling	TWh/a	23	22	-5
TOTAL	**TWh/a**	**4.318**	**2.292**	**-47**

Source: own calculation (Oeko-Institut, Fraunhofer ISI)

Figure E 9 and

Table E 7 below show the energy carrier distribution for the FED for space heating. While in 2015 gas is still the most dominant energy carrier for space heating with a FED of 1,672 TWh per year, its share is reduced by 100% to zero in 2050. The amount of biomass used for space heating is also reduced substantially by more than 90% in the same time period. The same is true for direct electrical heating systems and district heating which are lowered by 48% and 24%, respectively. The use of solar thermal energy, ambient heat (made available via heat pumps) as well as the share of electricity needed for heat pumps increase markedly: solar thermal jumps from a mere 25 TWh per year in 2015 to 223 TWh in 2050 (+794%), and the FED for heat pumps increases by 382%. The space heating made available via heat pumps is the dominant energy carrier by 2050 covering a third of the total space heating FED. Energy carriers based on novel fuel technologies such as synthesised hydrogen or methane (as well as longer chained synthetic hydro carbonates) cover close to 200 TWh in 2050, which is a share of about 14% of the total final energy demand for space heating.

Figure E 9: Final energy demand for space heating in EU-28



Source: own calculation (Oeko-Institut, Fraunhofer ISI)

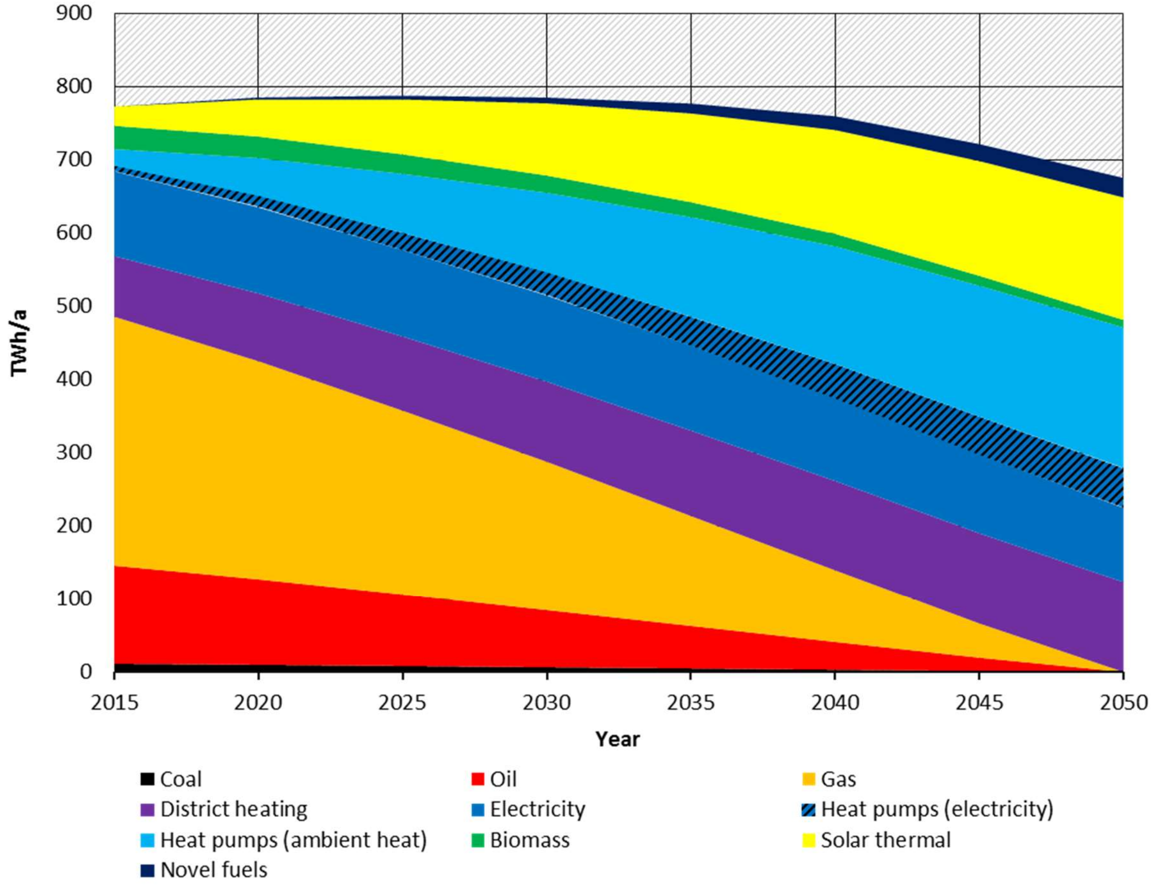
Table E 7: Final energy demand for space heating in the EU-28

Energy carrier	Unit	2015	2050	%-change
Coal	TWh/a	112	0	-100
Oil	TWh/a	510	0	-100
Gas	TWh/a	1,672	0	-100
District heating	TWh/a	351	266	-24
Electricity	TWh/a	212	110	-48
Heat pumps (electricity)	TWh/a	33	138	313
Heat pumps (ambient heat)	TWh/a	100	481	382
Biomass	TWh/a	497	29	-94
Solar thermal	TWh/a	25	223	794
Novel fuels	TWh/a	0	197	NA
Total	**TWh/a**	**3,512**	**1,443**	**-60**

Source: own calculation (Oeko-Institut, Fraunhofer ISI)

The distribution of energy carriers for the FED for hot water is shown in Figure E 10 and Table E 8 below. Generally speaking, the calculated changes for the different energy carriers are similar to those for the FED for space heating. While fossil fuel energy carriers cover 63% of the FED for hot water in 2015, their usage has all but disappeared in 2050. At the same time novel fuels such as synthesised hydrogen or methane increase their share in 2050 to just under 10%. The share of renewable energy carriers increases substantially: solar thermal covers 167 TWh of hot water FED per year in 2050, an increase by 534%. Ambient heat made available via heat pumps even increases by 739% to 192 TWh per year in 2050. District heating for hot water increases by nearly 50% whilst biomass usage falls by 68%.

Figure E 10: Final energy demand for hot water in EU-28



Source: own calculation (Oeko-Institut, Fraunhofer ISI)

Table E 8: Final energy demand for hot water in the EU-28

Energy carrier	Unit	2015	2050	%-change
Coal	TWh/a	11	0	-100
Oil	TWh/a	134	0	-100
Gas	TWh/a	340	0	-100
District heating	TWh/a	83	123	49
Electricity	TWh/a	116	101	-12
Heat pumps (electricity)	TWh/a	8	55	619
Heat pumps (ambient heat)	TWh/a	23	192	739
Biomass	TWh/a	32	10	-68
Solar thermal	TWh/a	26	167	534
Novel fuels	TWh/a	0	27	NA
Total	**TWh/a**	**773**	**675**	**-13**

Source: own calculation (Oeko-Institut, Fraunhofer ISI)

As is shown in Figure E 8 above the ventilation demand increases considerably from 9 TWh per year in 2015 to 152 TWh per year in 2050. This development is mostly driven by the need to ventilate buildings with high energy efficiency standards, of which there is a high share in 2050. Space cooling does not play a major role in the low-carbon scenario. Since possible consequences of climate change such as periods of severe heat during the summer months are not considered in this study, electricity demand for space cooling remains nearly constant over the years (cf. Table E 6 above). The overall increase in floor area (and therefore higher demand for cooling) is compensated for by the higher energy efficiency standards of the buildings.

The direct CO_2 emissions of the residential sector, the tertiary and the agricultural sector in the EU amounted to 636 Mt CO_2 in 2015 (UNFCCC 2019), with 620 Mt CO_2-eq. coming from the energy demand of buildings. The direct emissions almost completely result from heating and cooling of buildings (512 Mt CO_2). Due to the complete replacement of fossil fuels, these emissions are fully mitigated in the scenario GHG-neutral EU2050 (see Table E 9).

Table E 9: Overview GHG emission development in EU-28

GHG emissions	Unit	2015	2050	% change
Space heating & cooling	Mt CO_2/a	512	0	-100%
Hot water	Mt CO_2/a	108	0	-100%
Ventilation	Mt CO_2/a	0	0	N/A
TOTAL	Mt **CO_2/a**	620	0	-100%
Memo item: indirect emissions	Mt CO_2/a	91	0	-100%

Source: own calculation (Oeko-Institut, Fraunhofer ISI)

Currently, there are also indirect CO_2 from the use of electricity for space heating and hot water preparation, which amounted to 360 TWh in 2015. Based on the country-wise specific emissions of public electricity generation, the indirect emissions can be estimated to 91 Mt CO_2 in 2015. This is comparably low, as some of the most relevant countries like France and Sweden have a power mix with low specific carbon emissions. As electricity is carbon-neutral in the scenario GHG-neutral EU2050, there are also no indirect GHG emissions anymore.

E.5 Challenges

During the calculations for the scenario several challenges arose:

- The progression of building energy standards (for new buildings as well as refurbished ones) is very ambitious in the current calculation (-20% every 5 years), nonetheless the final energy demand for space heating is only reduced by about 50%.
- The model results show that, on the one hand, the per head floor area increases dramatically in countries that experience population decreases. In other countries, on the other hand, population increases cause more pressure on the housing market. Consequently, the construction industry faces quite different challenges in different countries – the need for new buildings might be very limited in some countries and exacerbated in others.
- When it comes to the energy carrier distribution it is difficult to project relatively new technologies into the future. The debate about novel fuels (PtG/PtL) is in full flow at the moment with new studies making very different forecasts as to how important these novel

fuels are going to be in the future (and in which sector they are going to be used). Since their deployment depends a lot on real developments over time, we followed a more cautious approach in this scenario with an only limited use of novel fuels in buildings. Furthermore, novel fuels are more likely to be used in other sectors such as industry and mobility first, since these have fewer options to fully decarbonise. In the Scenario GHG-neutral EU2050 for 2050 they contribute about 10% of the energy needed for space heating and hot water.

E.6 List of references

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F Appliances and process heat in the residential and the tertiary sector

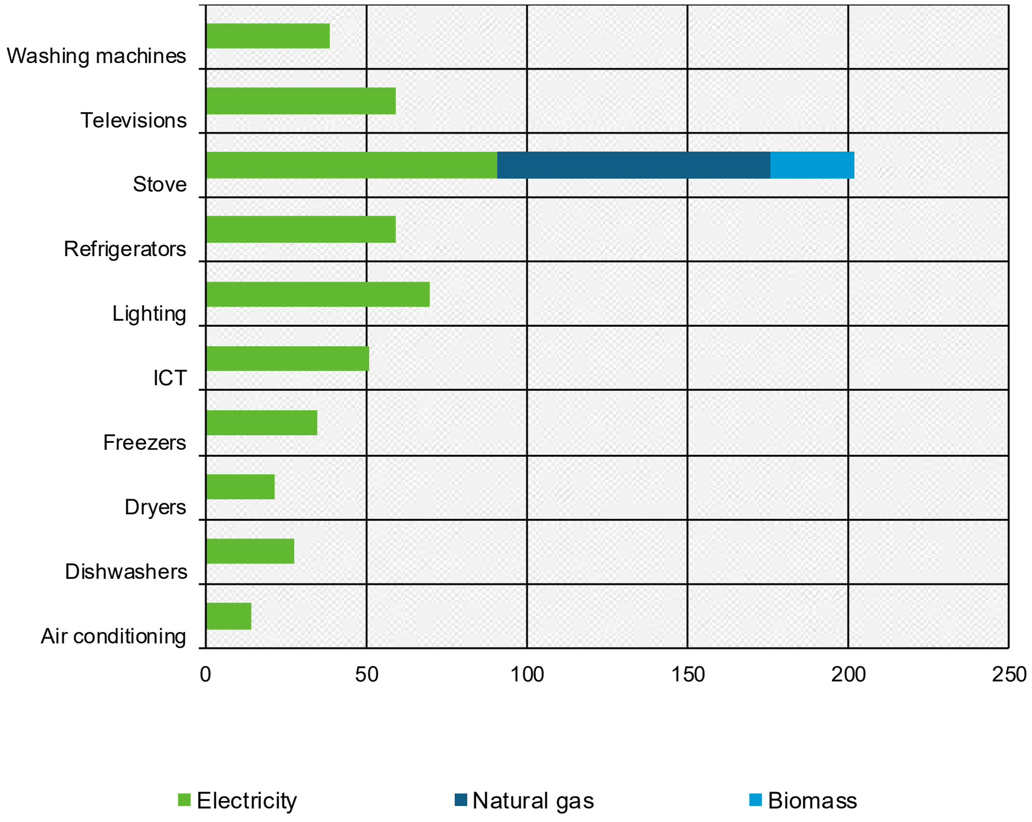
F.1 Introduction

In this chapter, the final energy demand of the residential and tertiary sector for appliances and process heat (mainly cooking) is analysed. The main contributors for the electricity demand of private households are white goods like refrigerators, freezers, washing machines, information and communication technology (ICT) applications like TVs, laptops and periphery, and lighting. For stoves, the main energy source is electricity, with gas and biomass as secondary sources. In the tertiary sector lighting, ICT and process heating and cooling are dominant. The energy demand for building technologies like space heating purposes and sanitary hot water are not included in this section and will be discussed in Section E.

F.2 Status quo

In Figure F 1, the final energy demand for the residential sector is depicted, which is in total 580 TWh in 2015, distributed by the different appliances. Besides stoves that make up a large share of final energy demand, all technologies are based on electricity. The energy carrier share for residential cooking differs among the European countries, depending on available technologies and user preferences.

Figure F 1: EU28 residential final energy demand for appliances and lighting in TWh (2015)



Source: FORECAST based on Eurostat

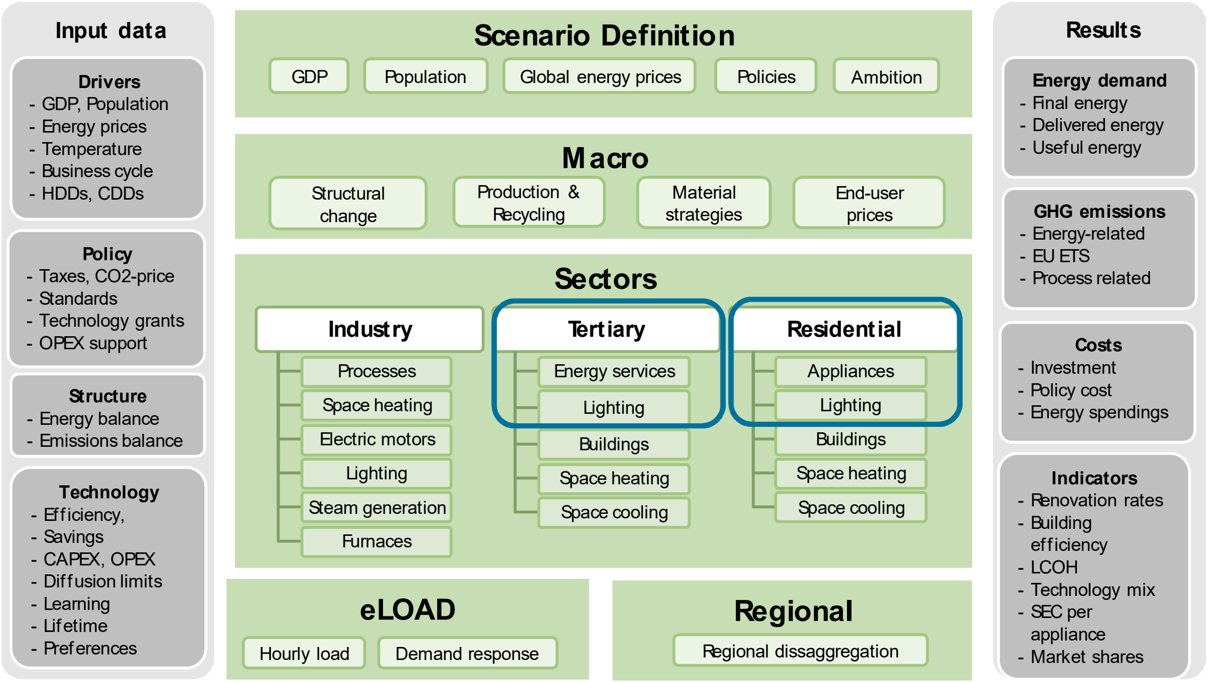
The final energy demand of the tertiary sector accounts to 618 TWh, which is similar to the residential sector. The main loads in the tertiary sector, depending on the branch, are on the one side electric appliances like lighting, ICT, gears like elevators and process technologies like refrigeration (mostly in the wholesale and retail trade branch). On the other side, process heat, mainly cooking in the education, gastronomy and health branch, has a share of 8% of the tertiary final energy demand. In 2015, the electricity demand of households for appliances accounts for 18%, for the tertiary sector 24% of the total electricity demand in the EU.

F.3 Methodology, assumptions and underlying data set for 2050 scenario

F.3.1 Simulations of the residential and tertiary sector

The FORECAST platform comprises three individual modules (see Figure F 2), each representing one sector according to the Eurostat (or national) energy balances: industry, services/tertiary and residential. While all sector modules follow a similar bottom-up methodology, they also consider the particularities of each sector like technology structure, heterogeneity of actors and data availability. For the Scenario GHG-neutral EU2050 FORECAST has been used for evaluating the future electricity demand of appliances and process heat developments up to 2050 in the residential and service sector. The model calculates the technology stock based on socio-economic drivers and on assumptions of lifetime, future ownership rate and costs. With further assumptions on the electricity demand per appliance, annual running time and market share of efficient technologies, the total electricity demand for appliances is then calculated.

Figure F 2: FORECAST model overview



Source: FORECAST

F.3.2 Scenario GHG-neutral EU2050

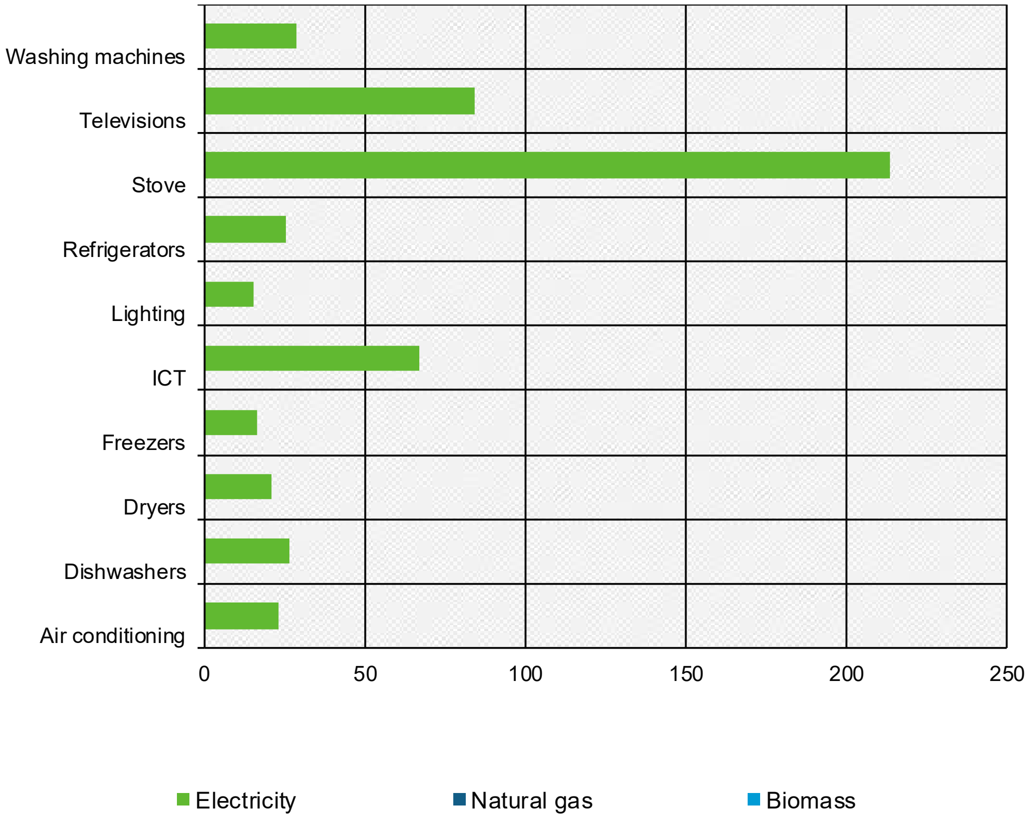
The main exogenous model inputs include the development of economic and demographic parameters, e.g. the gross domestic product, the population growth and the number of households, which have been taken from the European Reference Scenario 2016 (EU COM 2016). Population in the EU Reference Scenario is remaining mostly stable in the EU average, while the number of households is increasing by 10% until 2050. This reflects the trend to more single households and smaller families. The GDP per capita shows an annual growth of 2% per year. For details, see European Commission (2016). Other input data include the sectoral value added for the service sector, space per employee per subsector and the ownership rate of appliances.

F.4 Scenario GHG-neutral EU2050

The scenario GHG-neutral EU2050 shows an ambitious development of final energy demand in the tertiary and residential sector. In terms of appliances, this means that the European Ecodesign Directive is applied and tightened. New efficiency classes and labels are introduced and more efficient technologies are expected to enter the market. The lighting technology market shares in the private and tertiary sector are undergoing a major change; with the LED technology having a market share of about 80% in 2050.

Final energy demand for appliances and lighting in the residential sector decreases by 10% from 2015 (580 TWh) to 2050 (523 TWh) due to higher efficiency of appliances and the ongoing efficiency leap in lighting technologies due to LEDs (Figure F 3). Consequently, the EU28 electricity demand for lighting strongly decreases by 77% from 2015 (70 TWh) to 2050 (16 TWh).

Figure F 3: **EU28 residential final energy demand for appliances and lighting in TWh in the scenario GHG-neutral EU2050**

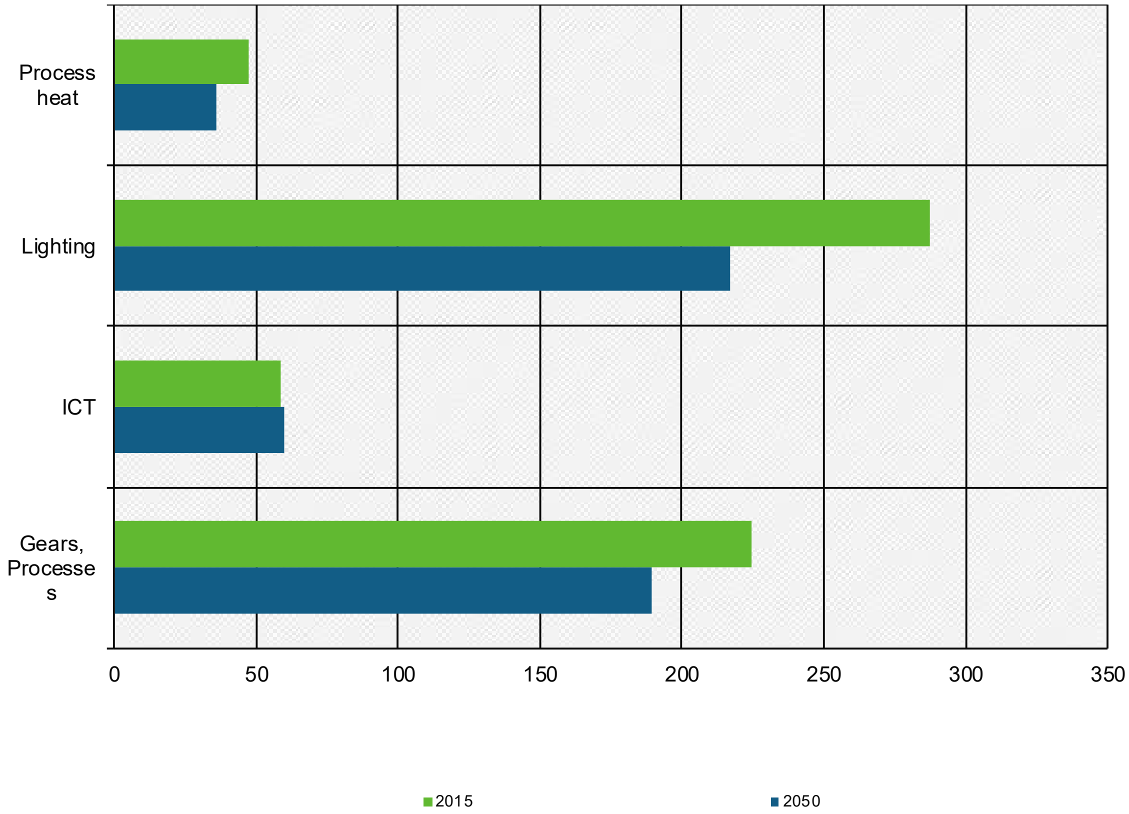


Source: FORECAST

For ICT equipment, on the other hand, further increases in equipment rates are expected for most of the equipment groups considered. This applies in particular to laptops and small ICT appliances, where significant increases in inventory are expected. Demand for ICT devices is expected to increase until 2050 from 51 TWh in 2015 to 67 TWh in 2050 (+30%). The energy demand for cooking slightly increases from 202 TWh in 2015 to 214 TWh in 2050 (+11%) due to the increasing number of households. Gas-fired stoves are fully replaced by electric stoves.

The main applications in the tertiary sector are gears and process technologies as well as lighting. Efficiency gains in lighting and other cross-sectional technologies in particular lead to a decrease in electricity demand, overcompensating the economic growth in the tertiary sector, in the scenario GHG-neutral EU2050 of 19% from 618 TWh in 2015 to 502 TWh in 2050. The electricity demand for gears and processes in the tertiary sector decreases by 16% from 2015 (224 TWh) to 2050 (189 TWh). The demand for lighting decreases by 25% from 288 TWh in 2015 to 217 TWh in 2050 caused by the same reasons as stated for the residential sector. Process heat demand for electricity will decrease by 24% in the tertiary sector from 48 TWh in 2015 to 36 TWh in 2050. The demand for ICT devices is also increasing in the tertiary sector - however much less significant than in the residential sector - by 2% (from 58.5 TWh to 59.6 TWh; Figure F 4).

Figure F 4: **EU28 tertiary final electricity demand for appliances and lighting in TWh in 2015 and in the scenario GHG-neutral EU2050**



Source: FORECAST

F.5 Challenges

Apart from buildings-related challenges treated in Section E, an additional challenge to mitigate all GHG emissions in the residential and the tertiary sector is the increasing number of households and ownership rates for some of the appliances in the residential sector. However, this challenge is minor compared to the other sectors, as there are no obstacles to a full electrification. Nevertheless, in order to limit electricity demand, the energy consumption of appliances, lighting and cooking has to be reduced on an ongoing basis. This can be achieved by intensifying the current policies - in particular minimum energy performance standards (MEPS) for newly sold appliances through the Ecodesign Directive, which has proven to be the most effective instrument. In addition, improved labelling also contributes to more energy-conscious purchasing behavior.

F.6 List of references

EU COM (2016): European Commission, “EU Reference Scenario 2016. Energy, transport and GHG emissions. Trends to 2050”. Online available at: https://ec.europa.eu/energy/en/data-analysis/energy-modelling, last accessed 27 Feb 2019.

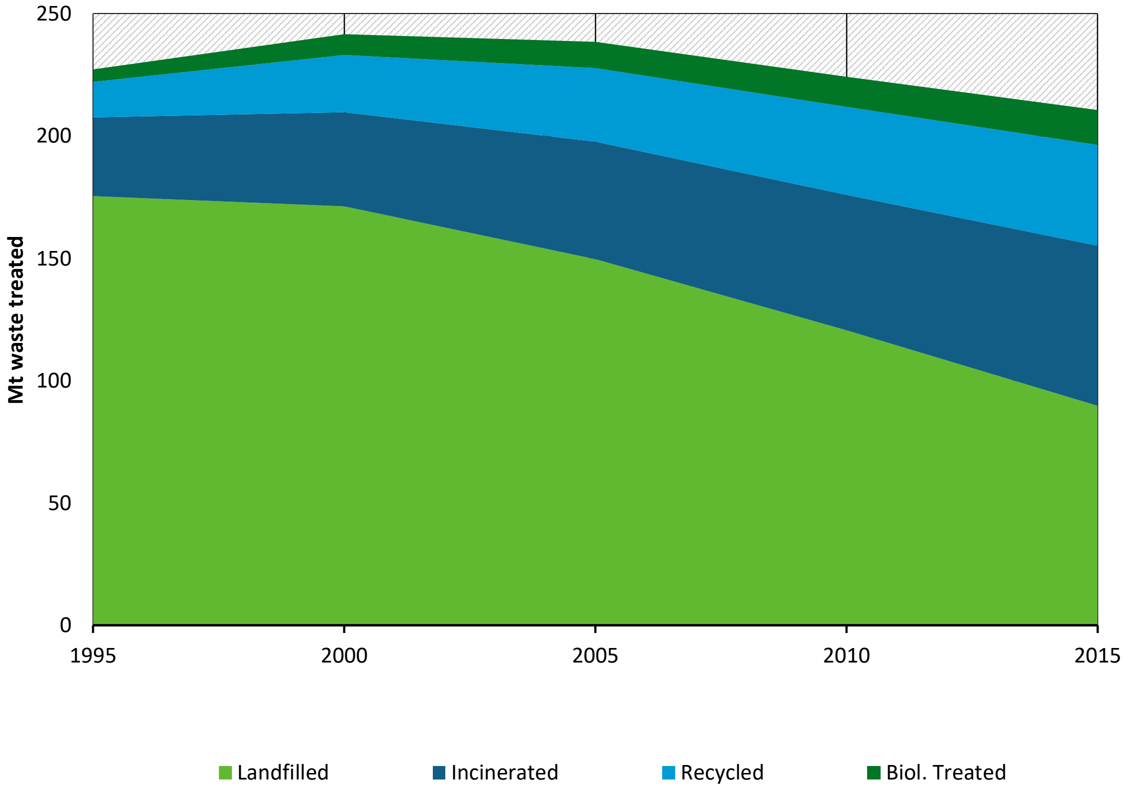
G Waste and waste water treatment

G.1 Introduction

According to EU “Roadmap for moving to a competitive low carbon economy in 2050” (EU COM 2011) other non-CO_2 emissions, which mainly refer to the waste sector shall be reduced by 70-78% until 2050.

GHG emissions in the waste sector are generated from the treatment and disposal of liquid and solid waste. For solid and liquid waste, there are different routes for treatment available. Solid waste can be recycled, landfilled, incinerated and biological treated. The decrease of total GHG emissions in the waste sector is mainly driven by the development of the different waste treatment routes, which are shown in Figure G 1.

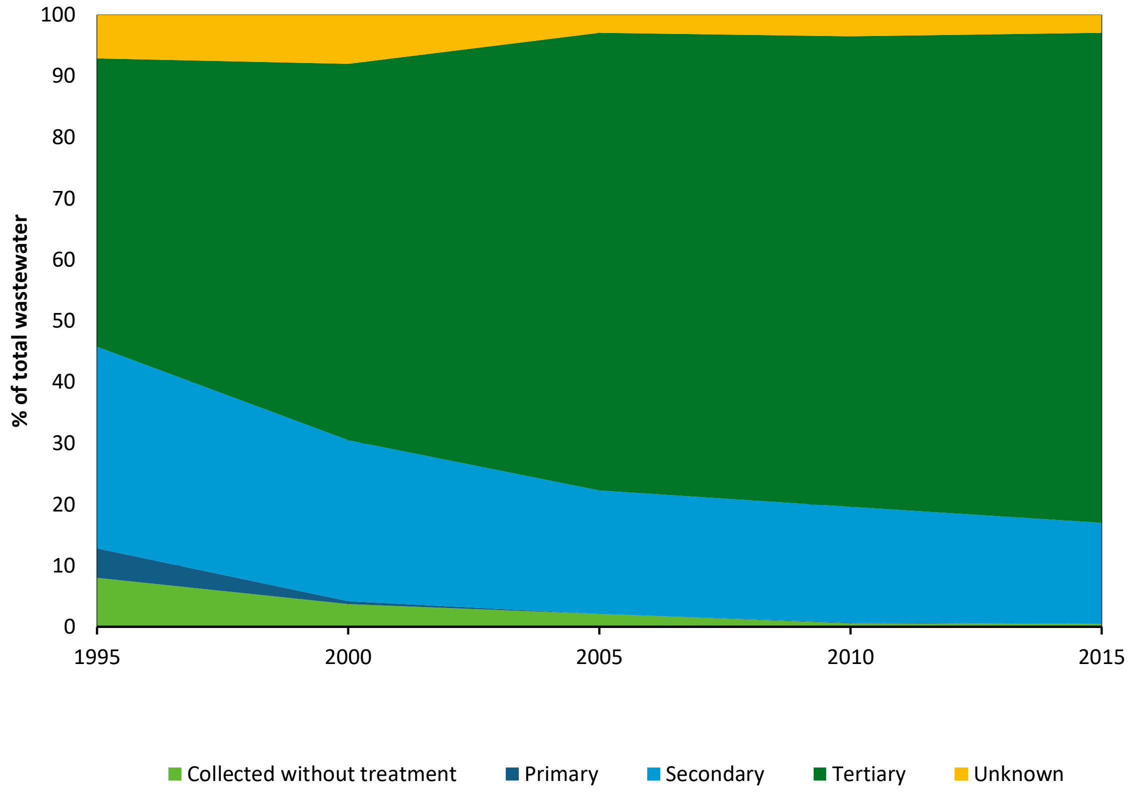
Figure G 1: Development of solid waste treatment in the EU



Source: Eurostat 2017 (en-wasmun)

Treatment routes for wastewater (liquid waste) also influence GHG emissions from the waste sector. Official waste statistics differentiate between primary treatment (settled or floating material will be removed), secondary treatment (reduce the amount of dissolved and suspended organic material) and tertiary treatment of wastewater (nutrient removal). Figure G 2 shows the improvement in collection and level of treatment of sewage over time for central Europe. An increase in tertiary treatment leads to reduced emissions from wastewater treatment.

Figure G 2: Changes in urban wastewater treatment in Central Europe



Source: EEA 2017

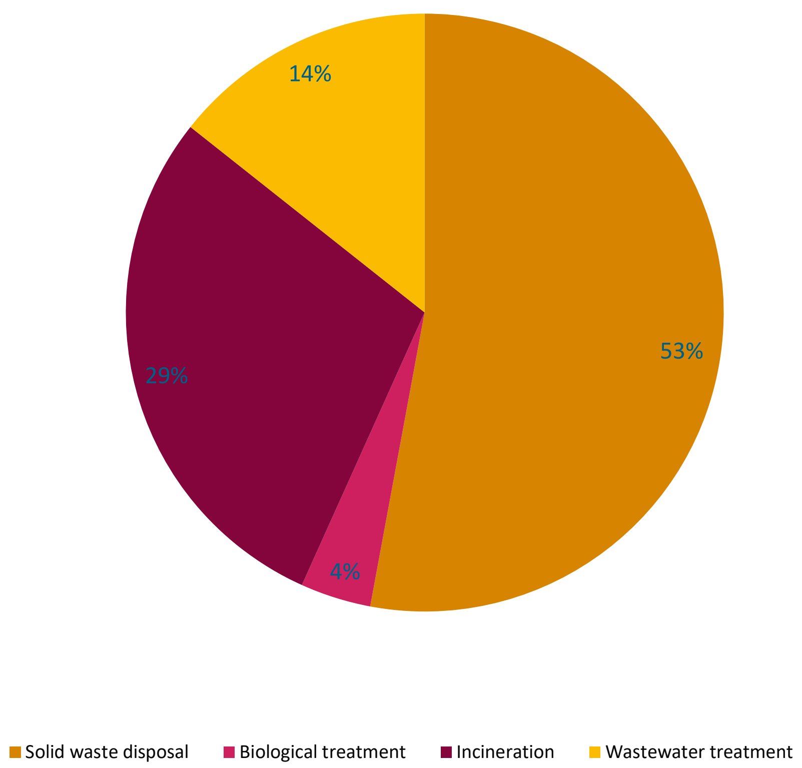
G.2 Status quo

GHG emissions

In 2015, GHG emissions from the waste sector (CRF sector 5) contributed with 3% to EU total emissions (without LULUCF). Since 1990 total emissions from the waste sector decreased by 42% from 240 Mt in 1990 to 138 Mt in 2015. Taken into account GHG emissions from waste incineration with energy recovery (which are reported under the energy sector), GHG emissions decreased only by 26% from 255 Mt CO2-eq. to 189 Mt. CO2-eq. between 1990 and 2015 because the amount of waste incinerated increased (see also Figure G 1).

In 2015, 53% of waste related emissions are CH_4 emissions from waste disposal on landfills, while waste incineration (with and without energy recovery) contributes 29% to total emissions from waste treatment (see Figure G 3).

Figure G 3: Share of waste emissions in the waste sector in 2015



Source: UNFCCC 2017

G.3 Methodology, assumptions and underlying data set for 2050 scenario

According to the definition of the IPCC 2006 Guidelines, GHG emissions from the waste sector are reported in the GHG inventory under CRF category 5. This category includes CH_4 emissions from solid waste disposal on landfills, CH_4 and N_2O emissions from biological treatment of waste (composting and anaerobic digestion), CO_2, CH_4 and N_2O emissions from waste incineration (without energy recovery) and CH_4 and N_2O emissions from domestic and industrial wastewater handling. Emissions that are related to waste recycling are reported in the industry sector, while emissions from burning of waste with energy recovery are reported under the energy sector. In 2050, emissions from waste incineration will be relevant in the energy sector, as all other energy sources in the energy sector are renewable. Thus, these emissions will also be considered in the scenario GHG-neutral EU2050 in the waste sector.

An assessment including all individual MS would require very detailed data sets and models for all countries. The scope of the project does not allow for such a detailed handling of countries, as it would require additional information on observed trends and other additional information for building country-specific scenarios. To calculate a first mitigation scenario for the year 2050 for the EU waste sector, available activity data for the period 1990-2015 is aggregated for the EU-28 and used to calculate GHG emissions in the year 2050. There are no Member State specific assumptions included.

However, in a second step a more detailed analysis for the most important MS will be set up, including country-specific scenarios.

Data sources

According to the Waste Statistics Regulation (EC) No 2150/2002 and its amendment in 2010 (EU) 849/2010 waste generation, waste treatment and waste classification are reported by all EU MS. According to the IPCC 2006 Guidelines, the definition of waste is not defined in detail and includes municipal waste as well as industrial waste, sewage sludge and other waste. Differences between the waste data reported in the inventory and the waste data reported under Eurostat are due to different waste definitions and reporting requirements.

Waste generation and treatment

In the year 2014[12], total waste generation in the EU-28 is about 1137 kg of waste per capita (Eurostat 2018).[13] Out of this, 20% of the waste is landfilled, 6% incinerated, 55% recycled and 18% burned with energy recovery. The treatment of the different waste categories is shown in Table G 1.

Table G 1: Waste treatment in the EU per capita (2014)

in kg/capita/year

Waste categories	Waste treatment	Landfilling	Incineration	Energy recovery (not part of CRF sector 5)	Recycling (not part of CRF sector 5)
Animal and vegetal waste	143	5	2	9	126
Mixed ordinary waste	476	198	52	134	91
Common sludge	39	4	3	3	14
Recyclable waste	398	4	1	52	342
Chemical and medical waste	59	14	8	10	27
Equipment	22	0	0	0	21
Total waste without mineral waste	**1,137**	**225**	**66**	**208**	**621**
Share of treatment in total waste		**20%**	**6%**	**18%**	**55%**

Source: Eurostat (env-wastrt) 2018

According to Eurostat data for the year 2014, almost 90% of the waste (without mineral waste) landfilled and incinerated is mixed ordinary waste. For this type of waste more detailed information is available in the Eurostat data base, which refers to municipal waste (env-wasmun). The amount of waste reported under Eurostat data for municipal waste treatment correlates in most MS with data reported in the UNFCCC GHG inventories of the MS. The assumptions on waste management for the year 2050 are therefore derived from the data on waste reported in the UNFCCC Inventory 2015 (2017 submission) and the data reported under Eurostat (env-wasmun).

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[12] Waste statistic is only available every two years. The year 2015 is not reported under the waste statistic.

[13] This does not include mineral waste, which at 3500 kg/cap represents about 2/3 of the total waste generation. Waste treatment of mineral waste is not included in the following analysis, as it does not lead to emissions reported under the CRF category 5.

One main driving factor of emissions from the waste sector is the waste composition, as this influences the amount of degradable organic carbon and fossil carbon. However, composition of municipal waste varies widely in different regions and countries and there is no official statistic on waste composition of municipal waste on EU level available. Therefore, data for waste composition is taken from the IPCC waste model for Western European countries and is shown in Table G 2.

Table G 2: Share of waste categories reported under municipal waste

In %

Food	Garden	Paper	Wood	Textiles	Plastic
24%	7%	14%	7%	10%	37%

Source: IPCC Waste model

For the development of waste generation and waste treatment the following general assumptions are taken into account:

- Reduction of waste generation per capita by 25% until 2050 in comparison to 2015
- All waste generated is treated
- Increase recycling share to 90% for all recyclable materials in comparison to 2015 (paper, textiles, plastics etc.)
- Reduction of food waste by 70% in comparison to 2015
- Stop of waste disposal in landfills until 2050

The following Table G 3 shows activity data that is reported under the GHG inventory or in the Eurostat data for the year 2015 and the assumptions for the year 2050.

Table G 3: Waste treatment in the EU per capita according to UNFCCC inventory data for the year 2015 and assumptions for 2050

In kg/cap/year

	Waste generated	Recycling	Landfilling	Composting	Anaerobic digestion	Incineration, Energy Recovery
UNFCCC/Eurostat 2015	476	91	181	79	31	92
Assumptions 2050	359	193	-	94	51	21

Note: There are small differences between Table G 1 and Table G 3, because Table G 3 refers to data that is reported under UNFCCC inventory and includes biological treatment of waste and the reporting year is 2015. The amount of waste incinerated is calculated as the difference between total waste treated and all other waste treatments

Source: Eurostat (2018a/b), UNFCCC 2017, own calculation (Oeko-Institut)

Table G 3 shows that the reduction of waste being landfilled leads to increased amounts of waste in other treatment routes. The amount of waste with biological treatment increases, as the share of organic waste landfilled and organic waste incinerated is now biologically treated. Also increased amount of plastic, paper and textiles are now recycled instead of incinerated or landfilled. In total, 52 Mt of plastics will be recycled in 2050, which enables a reduction of the plastics produced by the chemical industry.

G.3.1 Solid waste disposal on landfills

To calculate CH_4 emissions from solid waste disposal on landfills the IPCC waste model is used. Within this project an EU waste model has been set up, using available data on waste disposal from the EU inventory. The historic time series on waste disposal between 1950 and 1990 was extrapolated as there is no data for all MS available. Further model parameter where adapted to calibrate the model to meet historic CH_4 emissions. However, some uncertainties still occur.

Further mitigation measures to reduce CH_4 emissions from landfilling are CH_4 recovery and landfill ventilation. Therefore, the following assumptions are taken into account:

- As the proportion of organic material deposited in landfills decreases, so does the proportion of biogas potential. An evaluation of the EU MS shows methane recovery rates between 70% (in Great Britain) and 4% (in Croatia). For the calculation of emissions from waste deposition, a recovery rate of 40% is assumed for the EU as a whole.
- With declining biogas potential, landfill stabilization through ventilation to reduce methane emissions is gaining in importance. For the calculation of emissions in 2050, it is assumed that 30% of methane emissions in the EU 28 as a whole can be reduced by landfill ventilation.

G.3.2 Biological treatment of waste

Since there will be no landfilling and only reduced incineration of waste in 2050, all organic waste will be treated biologically. Assuming a reduction of food waste by 70% until 2050 approx. 145 kg of organic waste per inhabitant will be generated, which must be digested or composted.

For the scenario GHG-neutral EU2050, it is assumed that the treatment of biological waste is carried out with the best available technology. To calculate CH_4 and N_2O emissions the emission factors of the German GHG inventory are therefore applied for the calculation.

G.3.3 Waste incineration

So far, a large proportion of municipal waste has been used to generate energy. In some MS, waste incineration is still practiced without energy recovery, but with a declining trend. For the scenario GHG-neutral EU2050, it is assumed that waste incineration with energy recovery still takes place. The total amount of non-biogenic waste incinerated decreases by 77% until 2050 from 554,230 TJ in 2015 to 128,190 TJ in 2050.

Furthermore, 23.3 Mt of wood waste were used as a source of bioenergy, which corresponds to roughly 360,000 TJ of thermal energy. The total amount of wood waste used for energy purposes is assumed to remain stable. As non-energy use of wood increases, total wood waste should also increase so that the assumption implies an implicitly higher recycling rate for wood waste.

G.3.4 Wastewater

G.3.5 Methane emissions from domestic wastewater treatment

Methane emissions from wastewater treatment are calculated in accordance with the IPCC 2006 Guidelines. It is assumed that 95% of the total wastewater volume is aerobically treated and therefore does not lead to methane emissions. The remaining 5% is divided between other wastewater treatment pathways (septic tanks, anaerobic sludge treatment, etc.). It is assumed that biogas is obtained during sewage sludge treatment.

G.3.6 Nitrous oxide emissions from domestic wastewater treatment

The nitrous oxide emissions from wastewater treatment are also calculated in accordance with the IPCC 2006 Guidelines. For the year 2050, it is assumed that the protein supply per inhabitant is on average 50 g/cap/day. This corresponds approximately to the recommendations of the DGE.[14] In addition, it is assumed that 90% of the wastewater produced is treated in wastewater treatment plants with denitrification stages.

G.3.7 Industrial wastewater

According to current reporting under UNFCCC, high methane emissions from industrial anaerobic wastewater treatment are still being reported. According to EU waste experts, this is unrealistic. Anaerobic wastewater treatment plants are too expensive and are usually only operated with biogas generation. For the calculations in the Scenario GHG-neutral EU2050, it was therefore assumed that by switching to aerobic wastewater treatment or increased biogas production, approx. 80% of methane emissions from industrial wastewater treatment can be avoided.

The nitrous oxide emissions from industrial wastewater were calculated according to the IPCC 2006 Guidelines under municipal wastewater by including the FIND-COM factor (Factor for industrial and commercial co-discharged).

G.4 Scenario GHG-neutral EU2050

G.4.1 Scenario settings

The implementation of a Scenario GHG-neutral EU2050 requires far-reaching efforts in all areas of the waste sector. Table G 4 summarizes all measures and targets that need to be taken into account for a further reduction of GHG emissions in the waste sector.

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[14] http://www.dge.de/wissenschaft/referenzwerte/protein/

Table G 4: Overview of specific scenario settings

Category	Description of measure	Source
Waste generation	Reduction of waste generation per capita by 25%	Own assumption
Recycling	Increase of recycling quotes for plastic, paper, textiles to 90%	Own assumption
Amount of waste landfilled	Reduction of waste landfilled to 10% until 2030 and linear reduction to 0 until 2050	EU target 2030[15]
Landfill gas	CH_4 recovery of 40% of CH_4 produced in landfills	Own assumption
Landfill stabilization through ventilation	Installation of ventilation systems in 60% of landfills, with reduction of 50% of total CH_4 produced	GHG-neutral Germany (UBA 2014)
Food waste reduction	Reduction of food waste by 50% compared to 2015	Own assumptions
CH_4 wastewater	95% of wastewater is treated in well managed aerobic systems, other 5% in other systems	Own assumption
Protein consumption	Reduction of protein consumption to 50 g/cap/day	DGE-recommendation
Wastewater plants with denitrification steps	90% of wastewater is treated in wastewater plants with nitrogen removal	Own assumption
CH_4 Industrial wastewater	Switch to aerobic wastewater plants, or installation of CH_4 recovery (sewage gas)	Own assumption

Source: Own assumptions

G.4.2 Results

In order to achieve far-reaching emission reductions in the waste sector in 2050, waste treatment routes have to change. In the scenario GHG-neutral EU2050, landfilling of waste is decreased to zero, while the amount of waste recycled increases. Also waste incineration decreases drastically as most of waste incinerated will be biologically treated or recycled. Many MS experienced a reduction of waste landfilled and an increase of recycling, composting and landfill gas recovery already until 2015. However, the further reduction of solid waste disposal in landfills assumes an ongoing trend until 2030 and a reduction to zero until 2050.

In comparison to 1990, GHG emissions from the waste sector (including emissions from incineration with energy recovery) will be reduced by 85% in 2050. Emissions from biological degradation processes in the waste sector are similar to those in the agricultural sector, which so far cannot be completely reduced by technical measures. Therefore, a reduction in emissions by -95% compared to 1990 is not possible in the waste sector, or would require more far-reaching changes with regard to the reduction of waste generation.

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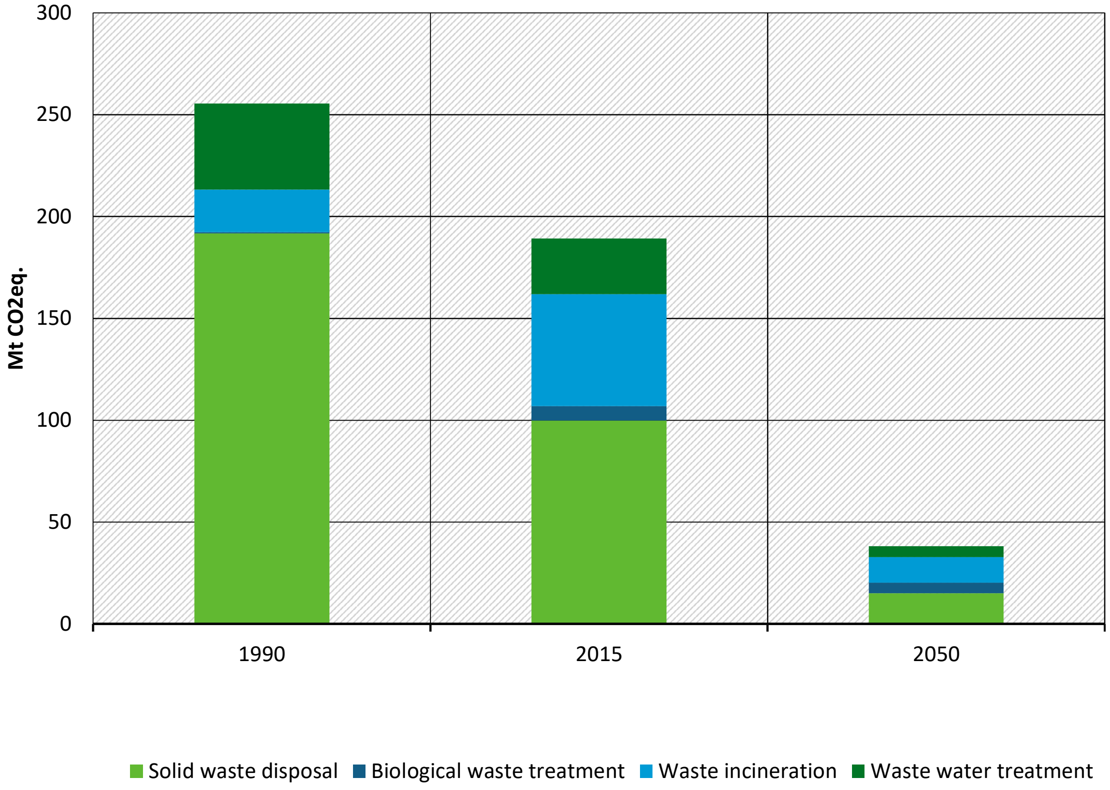
[15] http://ec.europa.eu/environment/waste/target_review.htm

Figure G 4 shows that large emission reductions already took place until 2015. Especially big MS like Germany and the United Kingdom contributed to this large emission reduction until 2015. Further mitigation potential in these MS is therefore lower as in other MS.

Figure G 4: Emissions from the waste sector in 2050



Source: UNFCCC 2017, own calculation (Oeko-Institut)

In comparison to the year 1990, large mitigation potential exist in the category of solid waste disposal and for waste water treatment. For both categories emissions can be reduced by ca. 90% until 2050 (Table G 5). Biological treatment of waste becomes more relevant in 2050, but emissions can be reduced by applying appropriate technologies for anaerobic digestion and composting. Even in 2050, a small amount of waste that cannot be completely sorted will still be incinerated. More details about how to achieve the emission reductions related to waste disposal on the level of MS can be found in Section J.

Table G 5: GHG emissions in the waste sector until 2050 in Mt CO2-eq.

Category	1990	2015	2050	Change since 1990	Change since 2015
Solid waste disposal	191,6	99,8	15,1	-92%	-85%
Biological waste treatment	0,7	7,3	5,2	646%	-28%
Waste incineration	20,8	54,9	12,7	-39%	-77%
Waste water treatment	42,2	27,2	5,3	-88%	-81%
Total	**255,5**	**189,1**	**38,4**	**-85%**	**-80%**

Source: UNFCCC 2017, own calculation (Oeko-Institut)

G.5 Challenges

The technical mitigation options to reduce emissions from the waste sector are available and already in place in countries like Germany. The implementation is therefore primarily dependent on strengthening the political targets, adaptation of implementation strategies and costs. Some options might not be cost efficient in small MS with smaller landfills or small wastewater treatment plants (e.g. landfill ventilation systems, equipment of all wastewater plants with denitrification stages). Thus EU subsidies or possible cheaper options need to be available to overcome these barriers.

The reduction of CH_4 emissions from landfills strongly depends on a fast reduction of waste disposal on landfills. Until the year 2030 only 10% of municipal waste can be landfilled to achieve the reduction target in 2050.

In addition to the technical options, the reduction of waste volume, food waste and dietary changes in protein intake are important drivers for further emission reduction in the waste sector. This requires changes in behaviour, which can be achieved through educational measures and information campaigns.

G.6 List of references

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H Agriculture

H.1 Introduction

The level of emissions from the agricultural sector is strongly linked to the agricultural production level by the underlying biological processes. Technical options for reducing greenhouse gases from agriculture are limited and a reduction of -95% compared to 1990 is not possible in this sector without a large-scale abandonment of production and a reduction in livestock numbers. According to the EU Roadmap 2011, emissions from the agricultural sector are to be reduced by 42% – 49% compared with 1990 levels in order to achieve an overall reduction of -80% compared with 1990 levels[16]. With an overall target of 95%, the agricultural sector would also have to further reduce its emissions, otherwise the agricultural sector would account for the majority (more than 90%) of the remaining total budget. A further reduction in emissions from agriculture that goes beyond halving 1990 levels will only be possible through two mechanisms. On the one hand, a drastic change in dietary patterns and, on the other hand, fewer exports of agricultural goods (especially products of animal origin) due to reduced agricultural production in Europe.

H.2 Status quo

In 2015 emissions from the agricultural sector contributed with 10% to EU total emissions (without LULUCF). Since 1990, total emissions from the agricultural sector decreased by 20% from 549 Mt to 438 Mt of CO_2-eq in 2015, showing an increasing emission trend from 2010 onwards. Main drivers for GHG emissions are nitrogen inputs in agricultural soils and livestock numbers.

Figure H 1 shows the development of nitrogen inputs to agricultural soils between 1990 and 2015. After a strong decrease between 1990 and 1995 nitrogen inputs remain almost stable until 2010 and show an increasing trend after 2010.

Figure H 2 shows the development of cattle, swine and sheep in the EU 28 calculated in livestock units. A strong decline of animal numbers in the EU 28 took place between 1990 and 1995 in consequence of the upheaval after the end of the Soviet Union. After 2010, the number of cattle shows a slight increase due to the cancellation of the milk quota.

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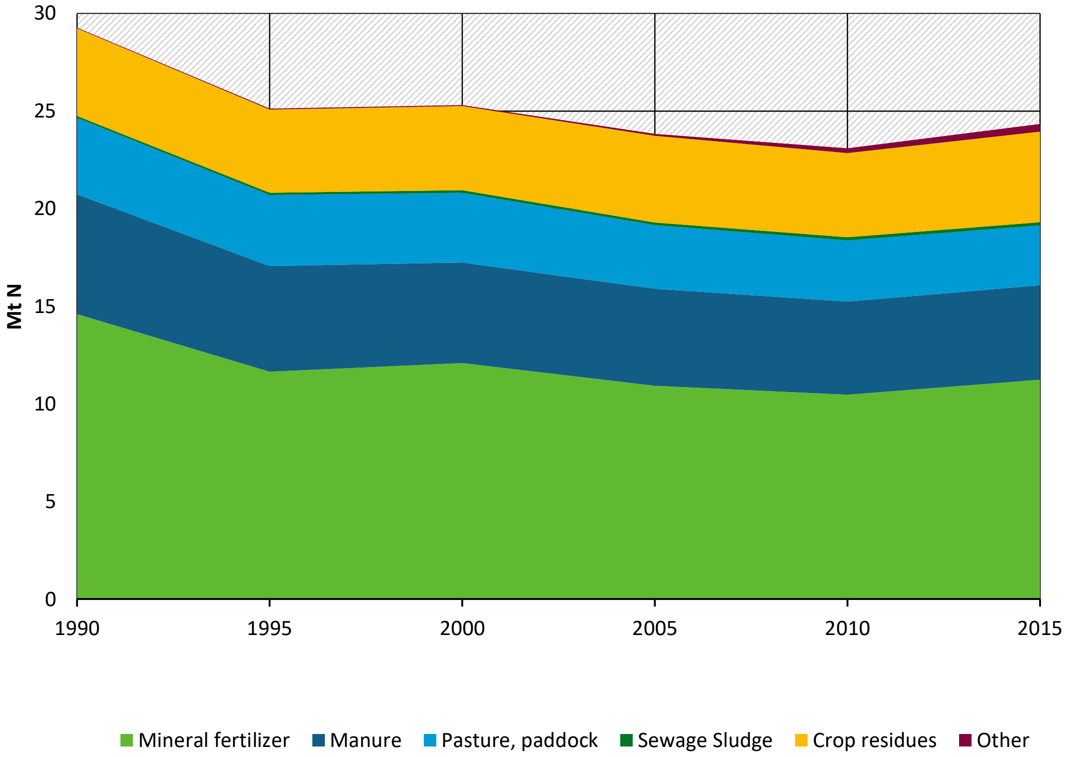
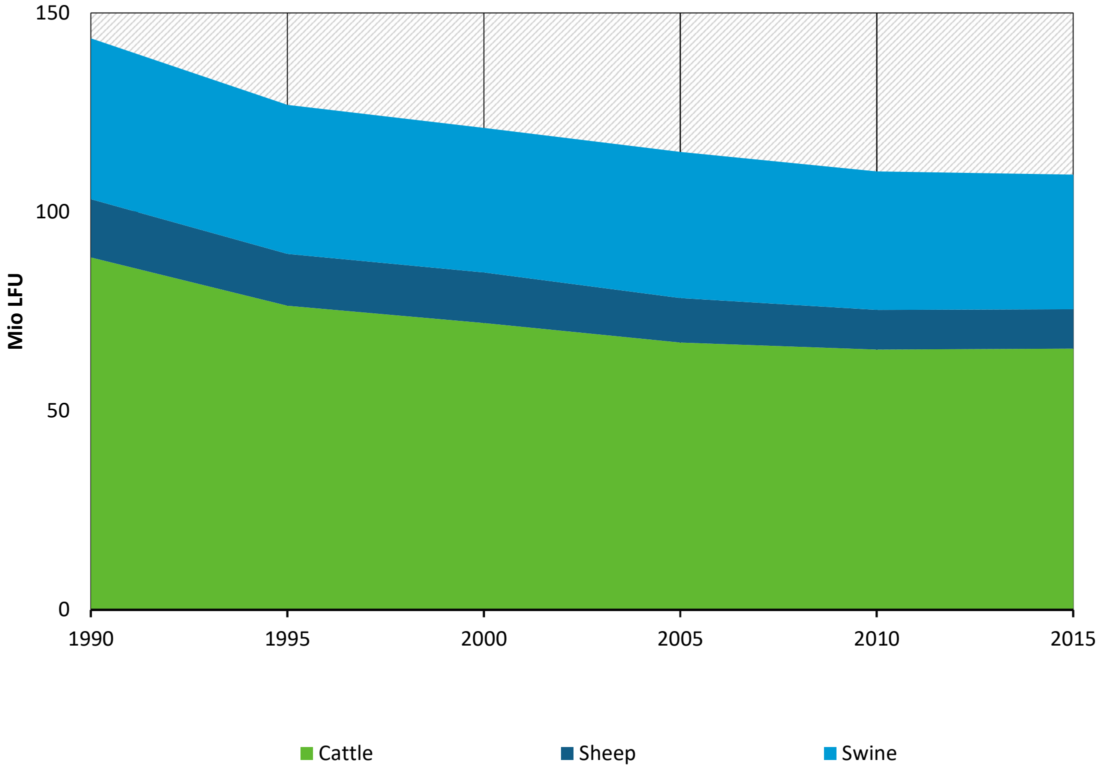
[16] http://www.europarl.europa.eu/meetdocs/2009_2014/documents/com/com_com(2011)0112_/com_com(2011)0112_en.pdf

Figure H 1: Development of nitrogen input into agricultural soils



Source: UNFCCC (2017)

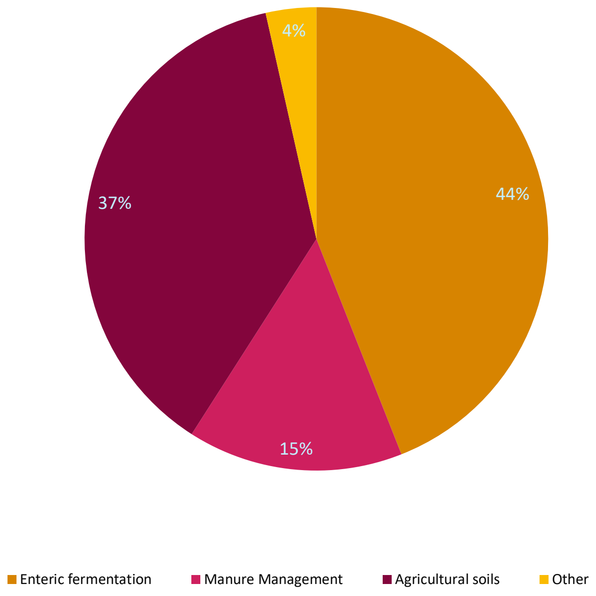
Figure H 2: Development of animal numbers in EU 28



Source: UNFCCC (2017), Eurostat (2018)

In 2015 44% of emission in the agricultural sector are CH_4 emissions from enteric fermentation from ruminants, 37% are N_2O emissions from agricultural soils while CH_4 and N_2O emissions from manure management contribute 15% to total emissions from agriculture (see Figure H 3).

Figure H 3: Share of emission sources in the agricultural sector in 2015



Source: UNFCCC 2017

H.3 Methodology, assumption and underlying datasets

H.3.1 Data sources

The calculation for the year 2050 is based on historic data sources from national and EU 28 CRF (common reporting format)-tables submitted by MS under the obligation of the Kyoto Protocol of the UNFCCC. These tables include reviewed annual values (“activity data”) and emission factors for all animals and categories. For more detailed information, the Eurostat database on agriculture is used. The following Table H 1 provides an overview of data sources used for the calculation.

Table H 1: Overview of data sources used for calculation

Category	Data sources
Agricultural area	Eurostat database
Nitrogen balance surplus	Eurostat database
Area of organic farming	Eurostat database
Management of slurry	Eurostat database
Area of agricultural use of organic soils	UNFCCC inventory submission
Nitrogen input to agricultural soils	UNFCCC inventory submission
Animal numbers	UNFCCC inventory submission (conversion in Livestock units based on Eurostat factor)

Source: own compilation (Oeko-Institut)

H.3.2 Agricultural land

Main drivers are changes in agricultural land use patterns (which entails changes in the area of grassland, arable land and cultivated organic soils) and the expansion of organic farming.

H.3.3 Agricultural soils

N_2O emissions from agricultural soils are calculated according to the Tier 1 method of the IPCC 2006 Guidelines (IPCC 2006). Direct N_2O emissions from agricultural soils are based on the nitrogen input from mineral-fertilizer, manure, sewage sludge other organic nitrogen inputs, crop residues, nitrogen inputs from urine and grazing and from N-mineralization. The indirect nitrous oxide emissions resulting from the leaching of nitrogen into the soil or the release into the atmosphere are determined from the direct nitrogen inputs. Further direct N_2O emission appear from drained organic soils used for agricultural production.

Nitrogen surplus

Reduced nitrogen inputs are decisive for future arable farming strategies and will lead to reduced N_2O emissions from agricultural soils. One main driving factor is to reduce nitrogen surpluses to a minimum. For developing a Scenario GHG-neutral EU2050 it is assumed that in 2050 nitrogen surpluses will be reduced to 30 kg nitrogen per hectare in all MS. The value is derived from the current nitrogen surpluses of the individual MS on the basis of the area balance and is determined via the difference to the target value and the agricultural area in the corresponding MS. According to Eurostat data most MS have to reduce their nitrogen inputs drastically in order to achieve the low nitrogen surpluses.

The total amount of nitrogen that needs to be reduced is determined by using MS specific nitrogen inputs and recent nitrogen surpluses.

Organic farming

In 2015 about 11 million hectares are farmed by the principles of organic farming, which corresponds to about 6%to the total agricultural area in the European Union. For the year 2050 it is assumed that the area of organic farming will increase to 25 million hectare which makes up 20% of total agricultural area. Due to its lower production level[17] combined with lower inputs of nutrients and pesticides and an equilibrated humus balance, organic farming has lower GHG emissions per hectare.

The calculation of emission reductions from organic farming refers only to reduced mineral fertilizer inputs,[18] as other factors such as carbon sequestration from humus formation are not reported.

Rewetting of cultivated areas

Drained organic soils lead to CO_2 and N_2O emissions. CO_2 emissions are part of the reporting requirement of the LULUCF sector, while N_2O emissions from drained organic soils are reported in the agricultural sector. By raising the water level, emissions from organic soils can be lowered or completely reduced.

In 2015, ca. 4 million[19] hectare of organic soils are farmed, which results in large CO_2 and N_2O emissions. For the year 2050, it is assumed that 50% of the farmed organic soils will be rewetted and not used for agriculture anymore.

H.3.4 Animal stocks

The main driver for GHG emissions from enteric fermentation and manure management is the size of animal stock. Technical abatement measures (anaerobic digestion, covering of slurry tanks) still exist for the latter, but not for emissions from enteric fermentation. Since 44% of all agricultural GHG emissions result from enteric fermentation, one of the most important mitigation measures is the reduction of ruminants. Furthermore, swine and poultry will be reduced as well.

Starting point is a change of human dietary in the EU: Today the average protein intake is 82.5 g per day an capita (unweighted average across all MS, range from 57,5 g to 96,7 g) of which 58% origin from animal products. Whereas WHO (World Health Organisation) recommendations for protein intake are merely about 50g/d/cap. Hence, a halved animal protein intake against today is possible without health risk for the European population.

To reach the final figures for lifestock, a step-wise approach was taken. In a first approach, the livestock stock of ruminants was reduced to 1 LU (Livestock Unit) per hectare grassland which would lead to reduction of about 30% compared to 2015. But this number of animals was still too large to hit the agricultural emission target for the year 2050. Therefore, the following approach was chosen:

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[17] An increase in organic farming area should be accompanied by dietary changes in particular by lower consumption of animal products with high land consumption.

[18] In organic farming, nitrogen requirements are covered by organic fertilizers and legumes. According to the IPCC 2006 Guidelines, the emission factor 0 is used for the cultivation of legumes. Therefore, in this scenario it is assumed that nitrous oxide emissions from agricultural soils will decrease by the same amount as the reduced use of mineral fertilizers.

[19] There are differences in the area for organic soils reported under LULUCF and agriculture. The area reported under agriculture is smaller as it contains only farmed area, while under LULUCF also organic soils on bushy grassland etc. is included.

1. Almost 80% of the GHG emissions from enteric fermentation result from 7 MS (MS)[20]. For these MS a reduction of 45% of their ruminants was assumed. This was chosen as a kind of burden sharing. Exception is Romania for which a reduction of 30% was assumed since this country shows the lowest supply from animal proteins today and simultaneously a significant potential for milk increase for the future.
2. For the other MS the ruminants were reduced by 45%, 35% or 30% depending on the number of heads above >1LU in each MS.
3. Furthermore, a reduction for total lifestock density is assumed to be <0.5 ha land per LU. This is applied to swine and poultry. Depending on the overhang of this limit, it is assumed that livestock will be reduced by 30%, 40% or 50%.

These assumptions show the importance of simultaneous measures (reduction of food waste esp. of meat and milk products as well as awareness rising, education of kitchen staff, price instruments etc.), which are not in the focus of the Low-Carbon-Europe Project. Furthermore, exports of animal products in non-EU countries might to be reduced in order to achieve the ambitious reduction of animal stock. If livestock reduction falls faster than demand, there is a risk of leakage effects from necessary milk and meat imports into the EU from third countries. More details about the implications for meat and dairy consumption on the level of MS can be found in Section K.

CH_4 emissions from enteric fermentation are calculated according to the Tier 1 method of the IPCC 2006 Guidelines.

The integrated emission factors (IEF) depend mainly on average milk yields in the single MS. In this analysis, IEF stayed stable since two contrary developments are assumed: yield increase in MS with low production levels and extensification resp. increase of organic agriculture with lower yields in MS with a current high production level.

H.3.5 Technical measures

In the field of manure management, future mitigation measures are assumed, such as anaerobic digestion or covering of slurry tanks. This depends on the amount of manure management systems, which distributions vary widely within each MS. Based on Eurostat data on manure storage, the CH4 reduction potential from 2015 to 2050 has been estimated. It was assumed that the technical abatement measures in the field of slurry management will be implemented to a level of 80% for all farms with a slurry system in 2050.

H.3.6 Scenario Settings

Table H 2 summarizes all measures and targets that need to be taken into account for a further reduction of GHG emissions in the agricultural sector.

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[20] France, Germany, United Kingdom, Ireland, Italy, Netherlands, Poland and Spain

Table H 2: Overview of specific scenario settings

Category	Description of measure	Source
Agricultural area	Agricultural area decreases by 11% until 2050 following the results of the LULUCF model, including rewetting of organic soils	Own assumption
Nitrogen balance surplus	Reduction N-Inputs to 30 kg/ ha nitrogen balance	Own assumption
Organic farming	Increase share of organic farming to 20% in total agricultural area	Own assumption
Digestion of energy crops	In 2050, digestion of energy crops is no longer practiced.	Own assumption
Rewetting of organic soils	In 2050, 50% of organic soils that is used as agricultural land will be rewetted.	Own assumption
Reduction of animal stock (in grazing livestock units)	Overall Livestock units will be reduced by 42% in 2050 differentiated by MS and ruminants and non-ruminants.	Own assumption
Share of covered slurry resp. of manure anaerobic digested	80% of slurry based systems – amount of liquid and solid manure management systems varies by MS. 90% of N_2O emissions can be reduced and 85% of CH_4 Emissions.	Own assumption

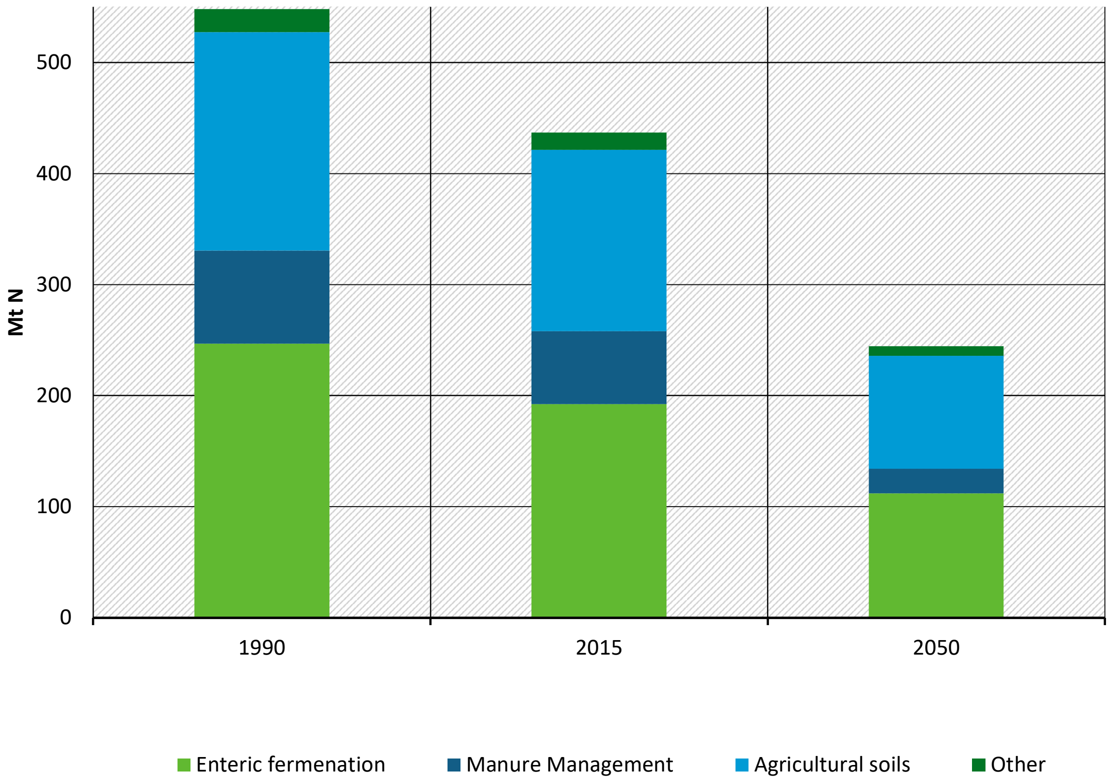
Source: Own assumptions (Oeko-Institut)

H.4 Scenario GHG-neutral EU2050

H.4.1 Results

In comparison to 1990 emissions from the agricultural sector will be reduced by 55% in 2050, see Figure H 4. Due to biological processes that are immanent in the agricultural production process emissions cannot be completely reduced by technical measures. Therefore, a reduction in emissions to – 95% compared to 1990 is not possible in the agricultural sector, or would require more far-reaching changes with regard to further reduction in dairy product and meat consumption.

Figure H 4: Emissions from agriculture



Source: UNFCCC (2017), Own calculation (Oeko-Institut)

Under those assumptions, the emissions from enteric fermentation will be reduced by 42% from 2015 to 2050. Those from manure management even go down by 65% due to the combination of technical options and the reduction of livestock, see Table H 3.

Reducing N_2O emissions from agricultural soils is combined with an optimal utilization of the nitrogen available in the plants and the rewetting of farmed organic soils.

Table H 3: GHG emissions in the agricultural sector until 2050 in Mt CO2-eq.

Category	1990	2015	2050	Reduction to 1990	Reduction to 2015
Enteric fermentation	246.7	192.2	112.2	-55%	-42%
Manure Management	83.8	65.7	23.0	-73%	-65%
Agricultural soils	196.8	163.4	101.5	-48%	-38%
Other	20.9	15.4	8.7	-59%	-44%
Total	**548.3**	**436.7**	**245.3**	**-55%**	**-44%**

Source: UNFCCC (2017), own calculation (Oeko-Institut)

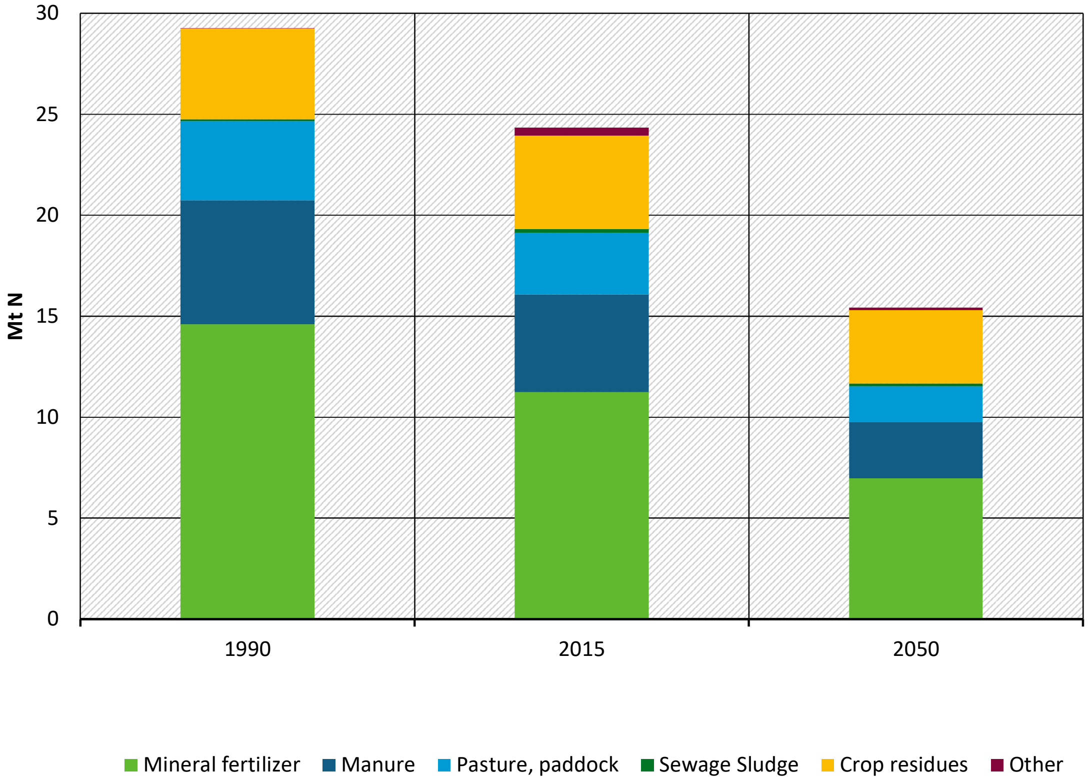
Agricultural land

Based on results from the LULUCF model total agricultural area decreases by -11% until 2050. 2/3 of the reduction is based on declining cropland area, while 1/3 is based on declining grassland area. Parts of organic soils that were farmed are now rewetted and reported under wetlands, while the LULUCF model assumes afforestation and new area for settlements on the rest of the area.

Agricultural soils

Until 2050, nitrogen inputs in agricultural soils will be reduced by about 37% in comparison to 2015. The drop is caused by reduced nitrogen surpluses and an expansion of organic farming area and a declining agricultural area. In comparison to 1990, nitrogen input decrease by 13.8 Mt with the largest reduction in nitrogen inputs from animal manure and mineral fertilizer until 2050 (see Figure H 5).

Figure H 5: Nitrogen input to agricultural soils

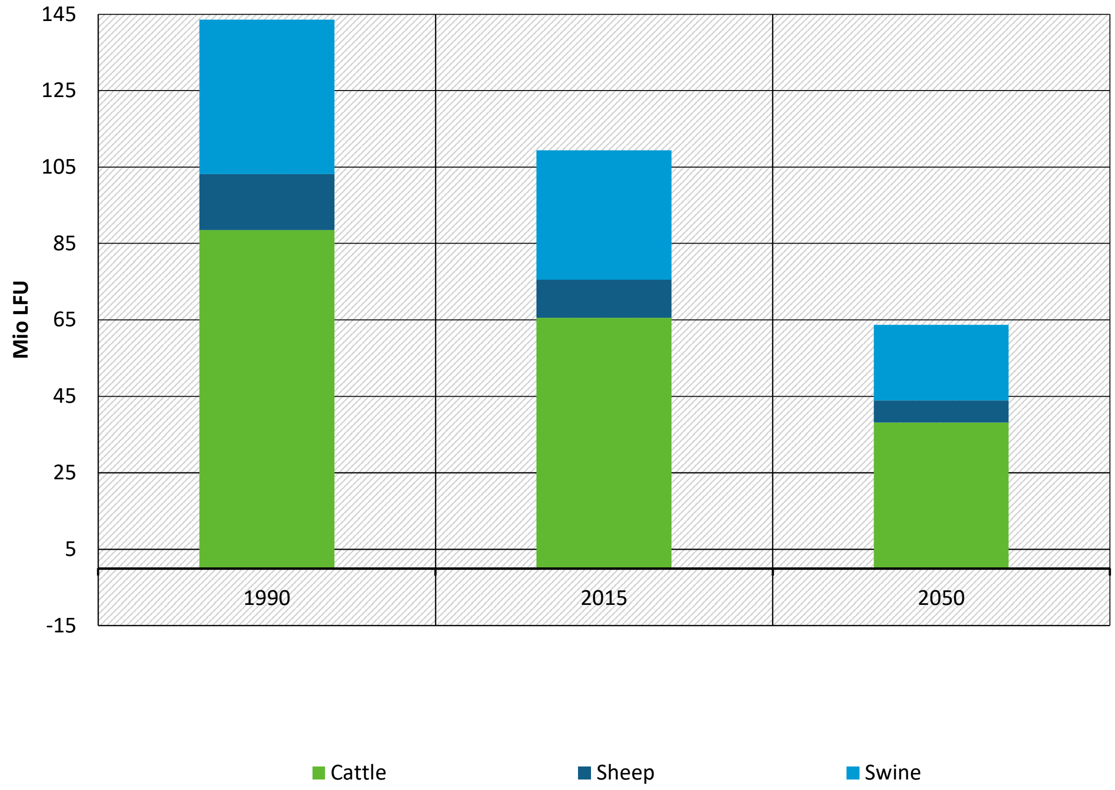


Source: UNFCCC (2017), own calculation (Oeko-Institut)

Animal stocks

In comparison to the year 2015, large emission reductions will be achieved by a further reduction of livestock units by 42% until 2050. Emissions from manure management can be further reduced by technical measures like covering and using slurry for anaerobic digestion (Figure H 6).

Figure H 6: Animal stocks



Source: UNFCCC (2017), own calculation (Oeko-Institut)

H.5 Challenges

One main driving force for emissions but also for the production of agricultural goods is the agricultural area. According to LULUCF model results, it is assumed that until 2050 agricultural area decreases by -11%, which is a loss of about 20 Mio ha in total, which is more than the agricultural area of Germany. In praxis there are many demands to extensify the agricultural area and establish more fallow land for biodiversity purposes. As the Scenario GHG-neutral EU2050 is a climate protection scenario, large parts of the agricultural area that is lost is used for afforestation to increase the carbon sink of the LULUCF sector. Due to the strong reduction of animal numbers less agricultural area is needed for fodder production and can be used for afforestation or fallow land to conserve biodiversity. However, the assumed GHG-reduction from livestock reduction is vague since this requires analogue reduced consumption of milk and meat. Otherwise, indirect effects will occur due to increased imports of those products.

Other studies for agriculture include also mitigation options that are related to feed additives (nitrate and tannins) to reduce rumen CH_4 emission. These mitigation options are not included in the Scenario GHG-neutral EU2050, due to big concerns regarding animal welfare and food safety restrictions.

The use of nitrification inhibitors is playing an increasing role in the agricultural sector. However, there are major uncertainties with regard to the environmental impacts and there is no evidence of a lasting reduction effect either. Thus this option is not considered for the calculation of the scenario GHG-neutral EU2050.

However, it is likely that in the year 2050 further innocuous mitigation options for a further reduction of CH_4 emissions from enteric fermentation and N_2O emissions from soils will be available. This could further reduce emissions from the agricultural sector and reduce total EU emissions by -95% compared with 1990 levels.

Besides the necessity to meet climate protection targets a reduction in nitrogen surpluses and livestock numbers is also necessary in order to meet other environmental goals (Nitrate Directive, National Emission Ceiling Directive, Water Framework Directive, Habitats Directive).

H.6 List of references

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I Land use, land use change and forestry

I.1 Introduction

The land use sector, formally Land use, land use change and forestry (LULUCF), is special. This is because land use activities can result in emissions and removals of CO_2. Growing forests, the establishment of new forests and intact wetlands typically store more carbon that they emit. Agricultural lands are often emitters of carbon, especially when they have been converted from forests or wetlands. The EU reported emissions and removals from LULUCF reflect these different sources and sinks. In 2015, the EU LULUCF sector represented a net reported carbon sink of about 309 Mt CO_2. This sink was dominated by CO_2 absorbed from existing and new forests. The largest source was land conversion, especially from forests to other land uses and emissions from organic soils under cropland.

In July 2016, the EU Commission published a proposal to include the sector in the EU climate target for 2030, including new projections for the LULUCF sector. The proposal was adopted by Parliament and Council in 2018 ("LULUCF Regulation", European Commission, 2018). The LULUCF Regulation sets the rules and principles for accounting of land in the sector. It makes accounting for most land categories mandatory leading to a rather wide coverage of emissions and removals from the sector that MS will be held accountable for until 2030. The core rule included in the Regulation is the "no debit" rule. MS need to ensure that debits from accounting do not exceed credits for the periods from 2021 to 2025 and from 2026 to 2030 for the whole sector. This rule is meant to ensure that the EU, as a whole, maintains the currently observed sink or at least minimizes its reduction.

For 2050, the European Commission low-carbon economy roadmap ("Energy roadmap 2050", European Commission, 2011) suggests that the EU should cut greenhouse gas emissions to 80% below 1990 levels with all sectors contributing to the reduction. For the LULUCF sector there is currently no target suggested for 2050 but there have been estimates of the development of emissions and removals from the sector (e.g. included in the EU Reference scenario ("EU Reference Scenario 2016", European Commission, 2016).

Decarbonisation of the EU economy will require a large quantity of biomass for heat, electricity and transport. It is assumed that the biomass needed for energy will mostly come from wastes and residues, and to a limited amount from agricultural land. This is contrast to assumptions set in the Reference scenario, where biomass production on agricultural land (i.e. short rotation coppice) and forest biomass play a larger role (European Commission, 2011). Looking at the target of net zero emissions requested by the Paris Agreement, the decarbonisation of the EU economy would leave significant emissions in Europe which would have to be offset by negative emissions, i.e. the expansion of CO_2 sinks. Negative emission technologies involving biomass production, such as BECCS (Bioenergy Carbon capture and Storage) will increase the competition for land. Also the Special Report of the IPCC on Global Warming of 1.5° C (IPCC, 2018) shows that nearly all global scenarios achieving the target rely on negative emission technologies. To a limited extent, such technologies can be integrated into the use cascades of sustainable biomass provision, but the corresponding potentials are limited. It can thus be expected that the LULUCF sector will be impacted by policies and measures to achieve emission reductions in other sectors.

The EU Reference scenario expects that forest harvest will increase from 516 Mm^3 in 2005 to 603 Mm^3 in 2050 due to growing demand for wood for energy production but also material use. With forest increments remaining relatively stable or declining slightly, the carbon sink in EU forests is expected to decline. However, also opposing trends can be observed. With rising demand for wood additional afforestation will take place as forestry becomes more competitive compared to other land uses. At the same time the scenario foresees that short rotation coppices will provide 53 Mm^3 of biomass annually for energy production, by 2050.

In general it can be assumed that an intensification of agricultural and forestry production will limit the opportunities for sink enhancement and emission reduction in the sector. There are only few examples where increased biomass production can be achieved hand in hand with mitigation in the LULUCF sector. Short rotation coppice plantations on marginal/abandoned cropland can help to increase soil carbon and provide biomass for bioenergy. This can also support biodiversity on the land. However, yields on these sites are typically relatively low and the option competes with afforestation for what the area could be used instead.

I.2 Status quo

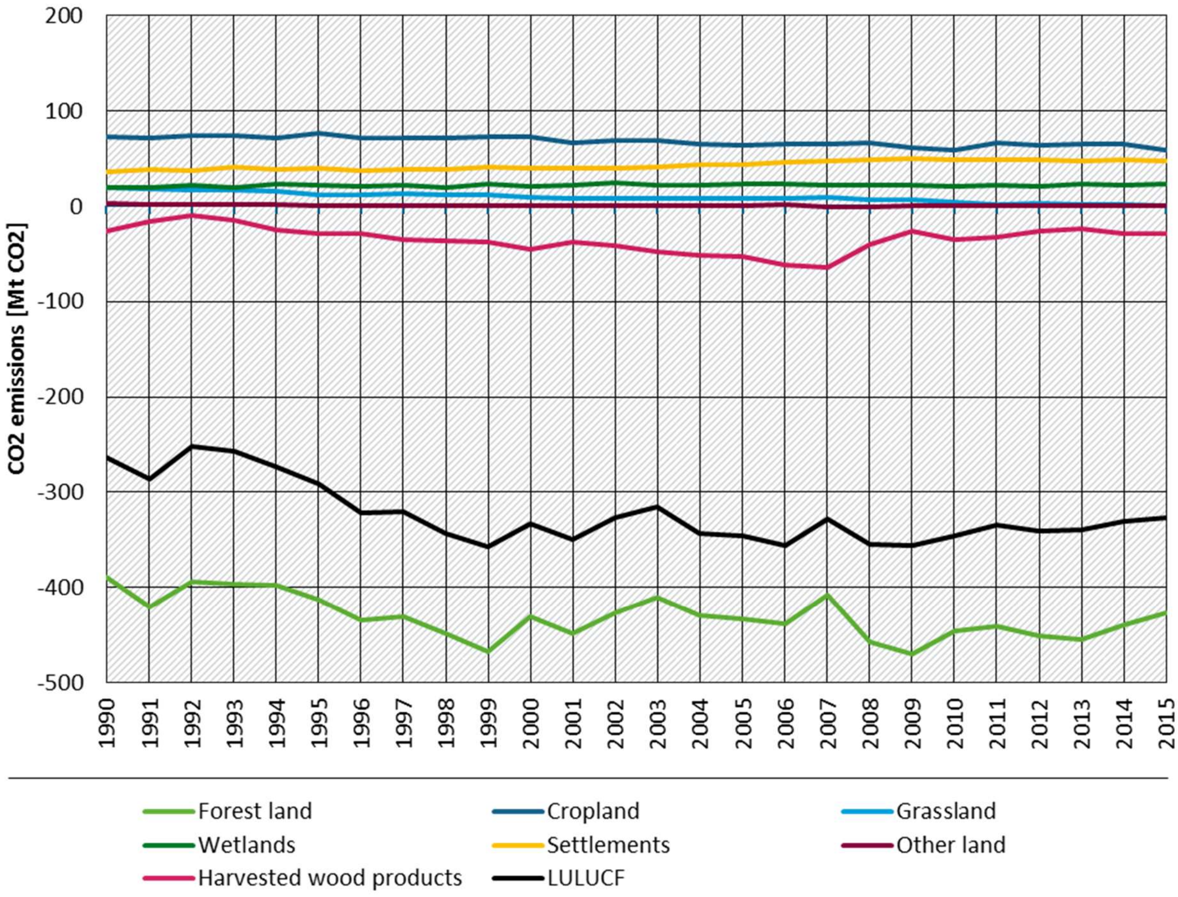
The LULUCF sector represented a net sink of 309 Mt CO_2 in the EU in 2015, i.e. more carbon was sequestered than emitted from this sector (see Table I 1 and Figure I 1). In particular, managed forests in the EU-28, which cover about one third of the land area (about 166 Mha), absorbed CO_2. In contrast, cropland, grassland and the conversion of forests to other land uses represented a net CO_2 source. Overall, in 2015 the sector compensated for about 7% of emissions from all other sectors.

Table I 1: Reported area and emissions from LULUCF main categories in 1990 and 2015

	Area 1990 in 1000ha	Area 2015 in 1000ha	Emissions 1990 in 1000t CO2	Emissions 2015 in 1000t CO2
A. Total forest land	159.839	166.371	-388.560	-426.964
B. Total cropland	134.316	126.982	73.077	58.361
C. Total grassland	93.045	88.112	19.731	821
D. Total wetlands	23.614	23.964	19.892	23.336
E. Total settlements	23.550	29.440	36.047	46.911
F. Total other land	13.358	12.854	2.551	20
G. Harvested wood products	-	-	-26.224	-29.130
Total	447.723	447.723	-263.485	-326.644

Source: UNFCCC (2017)

Figure I 1: **Historic reported CO_2 emissions and removals 1990 – 2015 for different categories of the LULUCF sector for EU-28**



Source: UNFCCC CRF tables of EU MS.

I.2.1 Forests

The forest sink is the largest contributor to the sector's carbon balance and also the most dynamic one. Since the 1990s around 400 Mt CO_2 were removed annually from the atmosphere through forests in the EU. This is due to the fact that the growth of trees clearly outweighed the felling rate. Moreover, new forests were established that store additional carbon. More than in other sectors, natural disturbances and climatic influences cause seasonal fluctuations of the flows of CO_2 between atmosphere, vegetation and soils. In some countries forest fires result in net emissions from forests in years with high fire intensity. For example, storms in Central Western Europe in 2000, 2005 and 2007 and forest fires in the Mediterranean countries in 1990, 2003 and 2007 led to reductions in the sink performance.

It is expected that due to intensification of forest management but also forest ageing there will be a reduction of the forest sink by 2050 if no additional measures are taken (European Commission, 2016). This development will also reduce the overall net sink of the sector. However, if new forests will be established at a similar rate as in the past, the CO_2 removals from these will compensate the sink reduction to some degree. Deforestation rates are already at a relatively low level in EU-28. Nevertheless, a reduction of gross forest area loss has the potential for emission reductions and also will help to maintain the forest sink.

Harvested wood products (HWP) are a category included under LULUCF. They form a carbon pool that is closely connected to the pool in living forest biomass. Harvest of biomass reduces the living biomass pool but moves carbon partly to HWP carbon pools. The amount of carbon stored in HWPs depends on the allocation pattern of the harvested wood to wood product types. The HWP carbon stock increased since 1990 with an average rate of 35 Mt CO_2 per year. If more long-living wood products are produced, such as construction and furniture wood, the harvested carbon can be held back from being emitted to the atmosphere again. Wood harvested for energy purposes instead leads to instant emissions of the CO_2 stored in wood. Also trees not being harvested further store the carbon. Moreover, trees not being harvested can further sequester carbon from the atmosphere. By the means of reduced harvest the sink capacity can thus be enhanced. However, effects of reduced harvest can be increased imports and increased intensification of management abroad if not measures of efficiency and sufficiency of wood use are put in place in parallel.

I.2.2 Agricultural soils

Cropland in the EU historically had the largest net emissions within the LULUCF sector. Emissions decrease from 75 Mt CO_2 in 1990 to 58 Mt CO_2 in 2015. Also for the future a further decrease of the emissions is expected, partly due to the effect of carbon depletion in the organic soils. Of about 127 Mha cropland reported under UNFCCC, only 1.7 Mha were on organic soils in 2015. However, these drained former wetlands and now cultivated areas are responsible for more than 50% of the emissions from cropland (32 Mt CO_2).

Another important category of agricultural lands are grasslands that cover 88 Mha in EU-28. Also grasslands have been established on drained organic soils. In 2015 these were reported to amount to 2.4 Mha. While grasslands on mineral soils formed a net sink of CO_2 of 37 Mt CO_2, grasslands on organic soils emitted in total 38 Mt CO_2. Both figures, emissions from grassland and cropland stress the importance of organic soils for measures of emission reduction in the LULUCF sector.

I.2.3 Settlements and other categories

One category that reports increasing emissions at the EU-28 level are settlements. In 1990 emissions from settlements and conversion of other land categories to this category caused emissions of 36 Mt CO_2. In 2015 these increased to 47 Mt CO_2. Since 1990 the category of settlements increased by 2.5 Mha to 29.4 Mha in 2015.

I.3 Methodology

I.3.1 System boundaries and modelling approach

The Excel-based LULUCF-model developed by Oeko-Institut was used to project emissions and removals resulting from the LULUCF sector. The analysis covers the following categories:

- Forest (management of the existing forest, afforestation);
- Cropland (short rotation plantations, other arable land);
- Grassland;

- Harvested wood products (HWP);
- Settlements.

Emissions are estimated by combining area information with category-specific emission factors, both derived from CRF (common reporting format) reporting tables submitted by EU MS and the EU. The area information describes the transition of area between different land use categories, e.g. from cropland to forests. These are combined with area-specific GHG emissions that are either derived as emission factors from national GHG inventory data, such as the CRF reporting tables submitted by MS and the EU under the UNFCCC KP, default values for specific land use categories provided by the IPCC guidelines or estimates calculated from the comparison of estimated carbon stocks over time. The historic data cover the period 1990 to 2015, for which both, the area and area change data and emission factors are available. This approach is equivalent to a Tier1 approach (in case of international default values) or Tier 2 approach (in case of national data).

Based on the reported data prior to 2015, area change and emission factors are extrapolated using the average of a five year period (2011-2015). As a first approximation it is assumed that the observed trends in this time period are continuing into the future. The assumed policies need to be translated into concrete changes of areas and emission factors. Any measures that are assumed to change future land use and emissions in EU are either formulated as deviations from these basic trends (e.g. percentage change of the observed rate of forest conversion to other land uses) and/or as target values for the years 2030 and 2050 (e.g. cropland on organic soils to be reduced to 80% of value in 2015 in 2030). The LULUCF-model tracks all areas consistently and manages the transitions between categories. For example, if arable land is re-wetted on organic soils, the corresponding area size is transferred to the category of re-wetted wetland areas. Measures can thus work through changes of areas (e.g. as a ban of grassland conversion to cropland) and/or address emission factors (e.g. as a prolonged mean residence time of carbon stored in harvested wood products).

The LULUCF-model is built for the analysis of individual countries. There is detailed information on historic emission available for all 28 EU MS. However, the calculation of the GHG-neutral EU2050 scenario is based on aggregate numbers for the entire EU 28. This is for the following reasons

- An assessment including all individual MS would require a detailed description of the anticipated policies and measures for all countries. The scope of the project does not allow for such a detailed handling of countries as it would require additional information on planned policies, observed trends and other additional information for building country-specific scenarios;
- Assumptions under the GHG-neutral EU2050 scenario have a rather broad-brush character. Applying the tool to the whole of EU 28 allows for a more flexible interpretation of the numbers as there is no allocation of policies and measures to individual countries. Given the current negotiations on adequate mitigation measures within EU MS a general EU-estimate allows for a less political discussion of options for mitigation in the LULUCF sector.
- Nevertheless, the individual country data serve as an information basis for constructing the GHG-neutral EU2050 scenario and assessing the general potential for specific measures for the EU.

The model outputs are trajectories of area development and aggregated emissions and removals for main categories up to the year 2050. GHG-neutral EU2050 assesses the target year 2050 and does not look at trajectories towards the target. However, modelling GHG emissions and removals for the year 2050 from the LULUCF sector requires tracking areas over the transition time because specific emissions for certain categories change over time. This is different in other sectors. Especially, the modelling of emissions and removals from existing and new forests is subject to dynamic changes. The emission factor of the forests strongly depends on the forest increment and forest harvest rates, both driven by forest age.

I.3.2 Data sources

All data sources used for constructing a Scenario GHG-neutral EU2050 for the LULUCF sector and estimating resulting emissions and removals from land use, land use change and forestry in EU are readily available from public data sources. As laid out in the methodology section above, there are different types of data necessary for the analysis: area data, emission factor data, information on policies, information on comparable scenario analyses and driver data.

Area and emission factor data

The main data source for historic estimates of the allocation of land area to different categories and reported changes over time are the national and EU CRF (common reporting format)-tables submitted by MS under the obligation of the Kyoto Protocol of the UNFCCC. These tables include reviewed annual values (“activity data”) of areas covered by certain land use categories and sub-categories and a land use matrix showing the transition of areas between categories.

The tables further include “implied carbon stock change factors” and “implied emission factors”. They describe the specific emissions or removals occurring in a certain land use category in CO_2 per ha. Multiplied with the area information the emission factors are turned into total emissions. This information is reported for the entire EU and was used to construct the Scenario GHG-neutral EU2050 for the LULUCF sector.

Information on policies

The GHG-neutral EU2050 scenario explores the implications of different mitigation options that are simulated as policies and measures. For the characterization of policies and measures different data sources are used. These range from information extracted from reported data and submitted inventory reports to data provided by peer-reviewed and grey literature that is publically available.

Information on comparable scenarios

A number of scenarios for the EU LULUCF sector have recently been published. In the following we present selected scenarios that were used to inform the setting for the Scenario GHG-neutral EU2050. Due to the fact that the sector does not have concrete emission reduction targets apart from a net zero target after accounting, the information was used as a reference for formulating specific targets for the sector, e.g. for the development of forest area, reduction of deforestation emissions, reduction of area converted to settlements and others.

In 2016 the European Commission published an update of the EU Reference scenario that was first published in 2013 (EU COM 2016). The scenario also includes estimates of GHG emissions from the LULUCF sector. It focuses on the EU energy system, transport and GHG emission developments, including the LULUCF sector, covering all 28 EU MS. It serves as a benchmark of current policy and market trends and provides a model-derived simulation of one of its possible future states given certain conditions. The EU Reference scenario results are used to interpret the model output of the Scenario GHG-neutral EU2050 and put the results into perspective.

Another set of EU scenarios was published 2016 as a product of the EC project ClimWood2030 (Rüter et al. 2016). A limitation of the scenarios is that they were restricted to the year 2030. The authors conducted longer running scenario runs but these were not published. However, the results can still serve as a basis for comparison as also for the LCE 2050 scenario estimates for 2030 are produced. The scenarios constructed in the project include:

- Increase forest carbon stock in existing EU forests: exploring the consequences of a decision to focus policy on increasing the carbon stock in EU-28 forest, notably by reducing domestic harvest rates;
- Cascade use – increase recovery of solid wood products: exploring the consequences of decisions to encourage cascade use by improving the recovery of solid wood products, for material and energy purposes;
- Cascade use – prevent first use of biomass for energy: exploring the consequences of decisions to encourage cascade use by ensuring that wood of sufficient quality and dimensions harvested in EU-28 forests is first used as raw material, and only subsequently as a source of energy;
- Strongly increase material wood use: exploring the consequences of success in increasing wood consumption in its major markets, especially the construction sector, by innovation, investment and promotion.

In September 2018, results of the Carbon Transparency Initiative (CTI) 2050 Roadmap Tool project were published (Climact 2018). This project used a simulation model[21] for describing and analyzing European emissions and available mitigation options as possible pathways to reach net-zero GHG emissions in 2050. The analysis included all sectors of the economy (power production, industry, buildings, transportation, and Agriculture, Forestry and Land-Use (AFOLU). The project resulted in three core scenarios:

- “Shared-efforts” scenario: exploring the situation where a comparable level of effort is maintained across sectors and levers, i.e., there is no emphasis on any specific mitigation option;
- “Technology” scenario: exploring implications of emphasising efficiency and innovative technological options by raising their ambition to the highest levels (e.g., energy efficiency, electrification, hydrogen, carbon capture, and storage (CCS));
- “Demand-focus” scenario: exploring the option where demand-side levers are used to reduce the overall demand.

I.3.3 Considered mitigation measures

Due to the dynamics ("slow in, fast out"), the reduction of emissions from LULUCF should primarily aim at reducing emissions from deforestation and organic soils. In Germany, for

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[21] The webtool can be found at: https://stakeholder.netzero2050.eu

example, managed organic soils occupy only a relatively small area, but are responsible for a disproportionate share of emissions. A further strategy for GHG reduction in the LULUCF sector is to increase the sink capacity of forests and wood products. Emissions caused by natural disturbances can also be potentially reduced by changes in management. This requires measures that are strongly adapted to the natural conditions in member countries.

Table I 2: Overview of measures considered and description of the technical implementation

Category	Description of measure	Comment on the theoretical potential
Forests	Reduction of deforestation emissions	Deforestation emissions in 2015 were reported to be 33 Mt CO_2/year. This is the maximum potential that can be avoided.
	Afforestation	Potential is difficult to assess as it depends on availability of land. Estimates range from + 10 Mha (EU Reference scenario) to + 94 Mha (Demand-focus scenario, CTI 2050 Roadmap Tool), resulting in a GHG removal range of -77 to -210 Mt CO_2/year in 2050.
	Increase carbon stocks in existing forest	Potential depends on how close countries are already to the maximum sustainable level of wood harvest. The theoretical potential can be very high. However, tradeoffs regarding reduced wood harvest need to be considered. Increased forest carbon stocks can have co-benefits with nature conservation targets but also reduced stability of stands for certain ecosystems. A study by Oeko-Institut (Oeko-Institut 2018) estimated a potential of about 50 Mt CO_2/year.
Harvested wood products	Increase the share of longer-living wood products	The potential is rather limited and has medium- to long-term effects. The ClimWood2030 project estimated a potential of 11 Mt CO_2/year for 2030.
	Increased cascade use of wood	Estimates of the ClimWood2030 project expect that there are probably no positive net effects of increased cascade use of wood due to the fact that temporarily reduced availability of biomass needs to be compensated by increased biomass production or imports.
Cropland and grassland	Rewetting of organic soils	According to reported data in 2015 there are about 2.4 Mha of organic soils under grassland and 1.7 Mha under cropland. Even higher area potential for rewetting exists for forests (12.5 Mha). Emissions from these areas amount to more than 80 MtCO_2/year.
	Reduction of grassland conversion	Emissions from grassland converted to cropland in 2015 were reported to be 35.8 Mt CO_2/year. Annually 9 Mha were converted in 2015. This is the maximum potential that can be avoided. Conversion of grassland to cropland also has impacts on biodiversity.
Settlements	Reduction of land consumption due to increase of area used for settlements	In 2015, 6.5 Mha of other land categories were included in the category of land converted to settlements, this is equivalent to an average annual rate of 0.325 Mha converted into settlements. At the same time about 0.08 Mha of settlements turned into other land uses. The EU Roadmap to a Resource Efficient Europe (EU COM 2011) formulates the aim to achieve no net land take of infrastructure and settlements by 2050.

Source: own compilation (Oeko-Institut)

Theoretically all land use categories reported by EU MS could be included in an assessment of potential mitigation policies and measures. There are, however, technical limitations of the model and also constraints on what algorithms can be used to translate the measures. Further, for efficiency reasons a focus on the largest emission sources and removal sinks makes sense. Table I 2 below lists the selected policies and measures, the respective land use categories, and provides a short general assessment of the theoretical mitigation potential of measures. The list serves as a basis for the specification the Scenario GHG-neutral EU2050.

I.3.4 Important general assumptions and limitations

There are a number of limitations and constraints that need to be mentioned. These restrictions need to be considered when results are interpreted:

- No consideration of the impact of climate change on the sector. We did not assume any negative nor positive feedback of climate change happening until 2050and impacting biomass or soil. It is expected that changes in temperature and precipitation patterns and amounts will be present by 2050. The likely impacts on photosynthesis, plant growth, decomposition of organic matter and soil respiration can be very different, from reduced growth due to drought and flooding events, increased carbon accumulation due to enhanced growing season and increased average temperatures, increased emissions from fire and storm events etc. The projection of regional changes of climate has recently advanced and the robustness of estimates increased. However, the complex potential responses of vegetation and soil can only be considered with sophisticated modelling tools, such as process-based plant growth models. The application of such a model is beyond the effort that could be spent in this study.
- It is assumed that production levels and import/export volumes will remain constant until 2050, i.e. there will be no relocation of production abroad. This is an important assumption as it puts constraints on the availability of goods and materials. This assumption affects consuming sectors much more than the producing sector LULUCF.
- In this study no consideration is given to feedback or rebound effects, e.g. increased consumption of biomass products through possible price shifts, more cascade use and effects on the availability of wood resources. The model used does not consider economic drivers but translates policies into direct area and emission changes. It therefore assumes that policies and measures take care of economic affects they might cause and compensate e.g. for reduced income of farmers or foresters if production levels are reduced.
- There is limited feedback considered between land use in LULUCF sector and activities in the agriculture sector. In order to satisfy the demand for fodder to livestock under conditions of increased organic farming with reduced outputs per ha, it is assumed, that a minimum amount of additional grassland area will be available for feed production in 2050 to ensure the livestock held in 2050 can be fed without increased imports.

- It is assumed that the demand for biomass for energy use does not increase above the current level. This means that neither the area for biofuel crops increases, nor increases the amount of biomass harvested from forests for energy. Forest harvest levels in general remain constant, indicating that also for material use no additional wood extraction is assumed. Therefore, the harvest rate stays at a level of around 70% of the annual increment, leaving scope for increasing carbon stocks in EU forests.
- Emissions from forest fires, biomass burning and non-CO_2 greenhouse gases are not taken into account.

I.3.5 Specific scenario settings

The implementation of the Scenario GHG-neutral EU2050 involves mitigation measures and policies related to a number of land use categories, namely forests, harvested wood products, cropland and grassland, settlements and others. The details of the scenario specification including target values and reference years are presented in Table I 3. The selection of measures reflects technical capabilities of the modelling tool on the one hand and the relevance of the amount of emissions and removals of the categories and the theoretical potential for mitigation (see Table I 2).

Table I 3: Overview of specific scenario settings

Category	Description of measure	Target value and reference year	Source
Forests	Reduction of deforestation emissions	50% of emissions reported in 2015	Own assumption
	Afforestation	Increase forest area through new forest plantations by 10%, i.e. 16 Mha by 2050 compared to 2015	EU Reference scenario
	Increase carbon stocks in existing forests	Maintain the forest sink compared to 2015 by stabilizing the harvest rate at about 70% of increment	Own assumption
Harvested wood products	Increase the share of longer-living wood products	Increase the carbon residence time in HWP by 25% compared to 2015	Own assumption informed by ClimWood2030 results
	Increased cascade use of wood	See above	See above
Cropland and grassland	Rewetting of organic soils	Conversion of 50% of cropland on organic soils in 2015 to wetlands (70%), forest (10%) or grassland (20%) Conversion of 50% of grassland on organic soils in 2015 to wetlands (65%) or forest (35%) Conversion of 50% of forests on organic soils in 2015 to wetlands	Own assumptions

Category	Description of measure	Target value and reference year	Source
	Reduction of grassland conversion	Reduction of grassland conversion to cropland in 2015 by 100% for organic and by 50% on mineral soils	Own assumptions
Settlements	Reduction of land consumption due to increase of area used for settlements	No net land take of infrastructure and settlements by 2050	EU Roadmap to a Resource Efficient Europe

Source: own assumptions (Oeko-Institut)

I.4 Scenario GHG-neutral EU2050

The settings chosen for the description of the Scenario GHG-neutral EU2050 affect the area distributions between the different area categories (Figure I 2). Most strongly affected is the forest area that increases from 160 Mha in 1990 to more than 182 Mha in 2050. This is at the expense of cropland and grassland that are both decreasing. Increasing are also the categories settlements and wetlands.

These area changes result in changes in emissions and removals from the LULUCF sector. Table I 4 lists main and sub-categories of emissions and removals. Categories including new and old forests show increasing removals until 2050. Cropland and grassland categories on the other hand show decreasing emissions. This is especially true for the lands with organic soils that are partly converted into wetlands. In this category emissions remain roughly the same as it is assumed that intact wetlands do not emit GHGs but also do not sequester carbon. The main mitigation effect results from the areas being transferred other categories and emissions therefore being reduced.

In total the LULUCF sink can be increased until 2050 from 335 Mt CO_2 in 2015 to 517 Mt CO_2 in 2050 (Figure I 3, Table I 4).

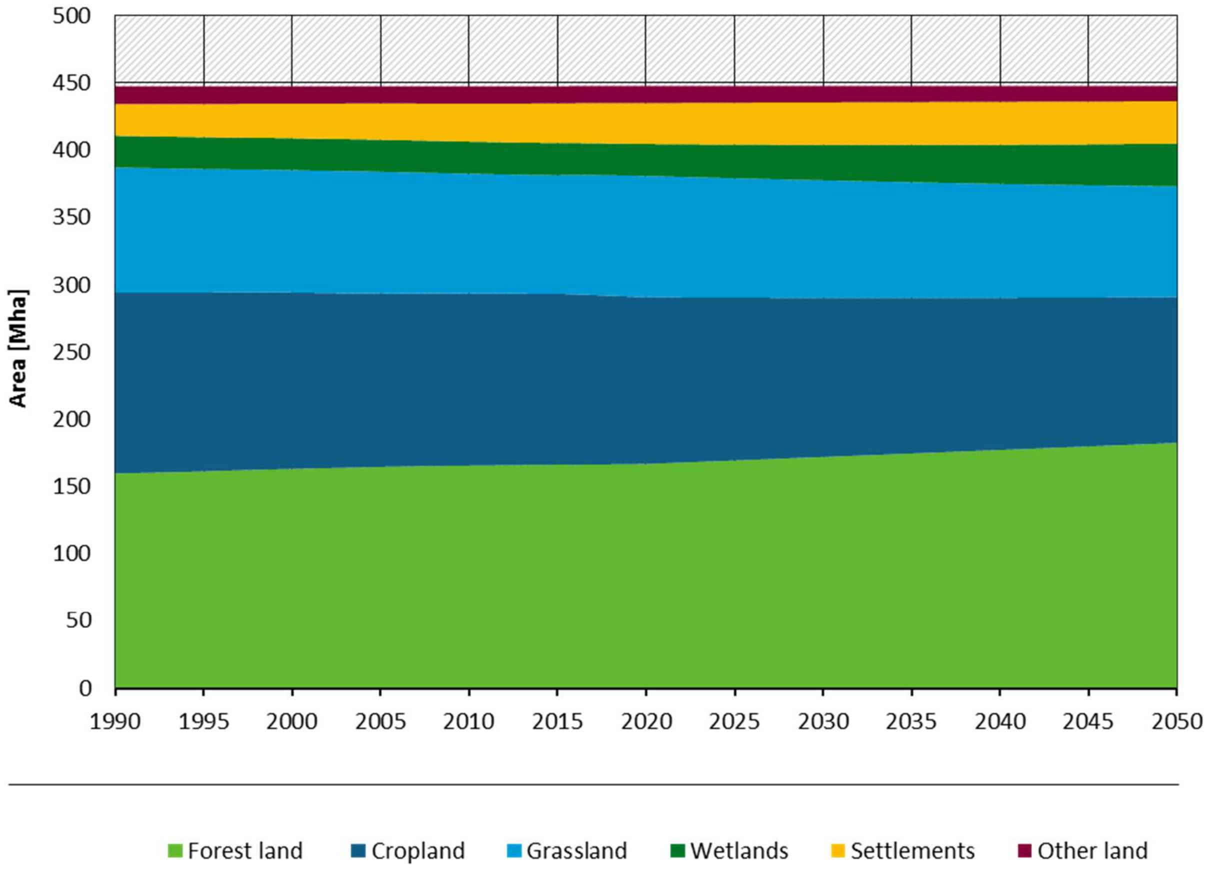
Table I 4: Historic (1990 and 2015) and projected (2030 and 2050) emissions and removals of the main categories of the LULUCF sector in 1000t CO_2

Category	1990	2015	2030	2050
A. Total forest land	-388.560	-426.964	-472.421	-506.379
Existing forests	-362.689	-373.535	-404.176	-404.554
New forests	-25.871	-53.429	-68.245	-101.825
B. Total cropland	73.077	58.361	36.085	22.548
Mineral soils	42.929	26.563	13.264	12.428
Organic soils	30.148	31.799	22.821	10.120
C. Total grassland	19.731	821	-10.979	-29.295
Mineral soils	-24.144	-37.376	-39.897	-41.106
Organic soils	43.875	38.197	28.918	11.811

Category	1990	2015	2030	2050
D. Total wetlands	12.829	14.473	15.593	16.143
E. Total settlements	36.047	46.911	36.555	17.388
F. Total other land	2.551	20	-1.036	-1.199
G. Harvested wood products	-26.224	-29.130	-33.586	-36.507
Total	-263.485	-326.644	-424.097	-517.676

Source: Historic data from UNFCCC CRF tables for EU MS, projection by own calculations (Oeko-Institut)

Figure I 2: Area development until 2050 for different land use categories for EU-28



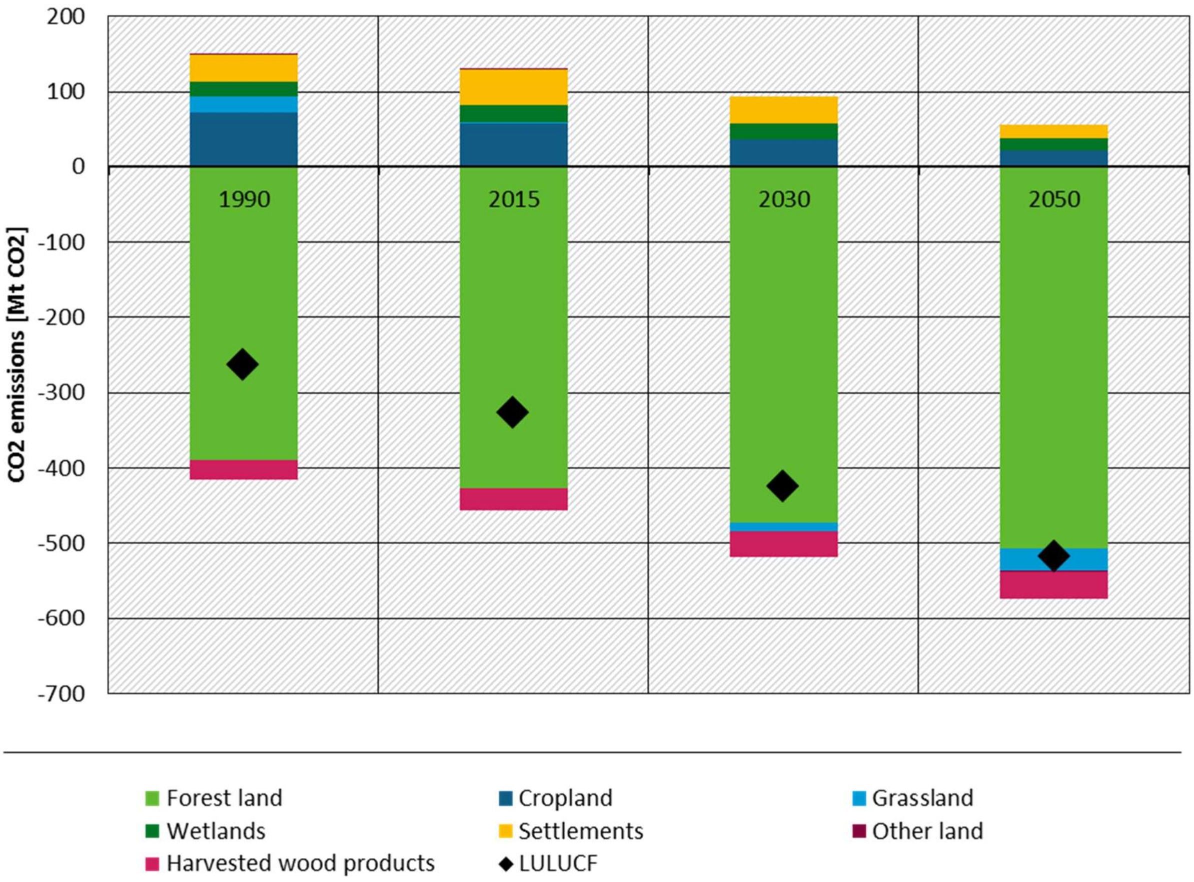
Source: Own projection (Oeko-Institut) based on UNFCCC reported CRF tables for EU MS until 2015.

Table I 5: Projection of area development under the LCE scenario in 1000ha

Category	2030	2050	Change
A. Total forest land	172.058	182.581	16.209
B. Total cropland	118.328	108.376	-18.606
C. Total grassland	87.274	82.216	-5.896
D. Total wetlands	26.394	31.768	7.804
E. Total settlements	31.566	31.521	2.081
F. Total other land	12.102	11.260	-1.593
Total	447.723	447.723	0

Source: Historic data from UNFCCC CRF tables for EU MS, projection by own calculations (Oeko-Institut)

Figure I 3: CO_2 emissions and removals for different categories of the LULUCF sector: historic values for 1990 and 2015 and projections for 2030 and 2050 for EU-28.



Source: UNFCCC CRF tables for EU MS, own projection (Oeko-Institut).

I.5 Challenges

The Scenario Low-Carbon Europe considers significant area transitions between different land use categories. Between 2015 and 2050 more than 25 Mha of land are affected (see Table I 3). The largest changes occur in the forest and cropland categories with a reduction of cropland area by 18 Mha, area largely converted into forest area (increase of 16 Mha). These transitions are small compared to other existing mitigation scenarios, such as the Carbon Transparency Initiative (CTI) 2050 Roadmap scenarios where area turnovers of more than 100 Mha are assumed.

Nevertheless, the area transitions can have impacts on the supply of ecosystem services from these areas, especially the amount and type of biomass. Newly established forests are expected to supply only limited amounts of wood for timber as the majority of trees will not mature during the simulation period. Biomass from early thinning operations is likely to materialize during this period but has not been quantified in this study.

The reduction of cropland area will reduce the production of agricultural products in EU. Similarly, a reduction is expected from the conversion of farming practices to organic farming (see Agriculture chapter). In case the demand for agricultural products remains constant there is the risk of indirect land use effects for areas outside EU. Therefore demand-side measures for increased efficiency and sufficiency need to accompany mitigation in the land use sector, not only for measures affecting cropland area. The issues related to land availability for afforestation apply similarly for the measure of rewetting organic soils.

Forest management under the LCE scenario results in assumed constant harvest amounts of about 520 Mm^3 per year. This is in contrast to the EU Reference scenario (European Commission, 2016) that assumes harvest from forests in 2050 to increase to more than 600 Mm^3/year. This increase results in a reduction of the forest carbon sink in the EU Reference scenario from 340 Mt CO_2 in 2015 to 150 $MtCO_2$ per year in 2050. In the LCE scenario the sink of existing forests increases to 400 Mt CO_2. The increase in wood demand assumed in the EU Reference scenario is to a large degree due to increases in demand for bioenergy. In the LCE scenario the use of bioenergy has been constrained, leaving room for the considered land conversions.

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J Detailed analysis of emissions from landfilled waste

J.1 Introduction

According to EU-28 inventory data for the year 2015 (UNFCCC 2017) CH_4 emissions from landfills have a share of 71% of total emissions from the waste sector (excluding emissions from incineration which are reported in the energy sector). Emissions from managed landfills are reported at 86.5 Mt. CO_2-eq., while 12.9 Mt CO_2-eq. are from unmanaged landfills (UNFCCC 2017). As shown in Table G 5, the largest emission reduction potential in the waste sector until 2050 is expected due to a reduction of CH_4 emissions from solid waste disposal in landfills. According to the scenario GHG-neutral EU2050, CH_4 emissions are reduced by 85 Mt CO_2-eq. in 2050, which represents a reduction of 85% in comparison to 2015 emissions. The amount of waste, especially of biodegradable waste going to landfills is the main driving force of CH_4 emissions from waste disposal. Because organic components decay slowly over decades, the current waste management practices have an effect on the amount of CH_4 emissions from landfills in 2050. Even if landfilling of organic waste were to be stopped immediately, emissions from the landfill of today's waste will still occur in 2050. Thus, whether emissions from landfilling of solid waste can be reduced by 85% until 2050 depends strongly on changing waste treatment routes in specific MS. The waste sector in the EU MS is very heterogeneous and differs greatly from region to region in terms of waste generation, waste composition and waste treatment (see Table J 1and Figure J 1). To better reflect the heterogeneous conditions in the MS a more detailed analysis of MS was carried out. The results indicate in which regions a change in waste management is essential to achieve the 2050 targets.

To carry out the detailed analysis, we developed a set of scenarios for selected MS or groups to show the effects of landfill stops in different years on emission reduction in 2050. The scenario settings reflect, amongst other things, the current EU waste policy that introduced a target for the maximum amount of waste disposal on landfills for the year 2035.

Table J 1: Municipal waste generation and waste treatment in the EU-28 countries for the year 2015

Country	Waste generation in kg/capita/year	Landfilled	Incinerated	Recycled	Biologically treated
Belgium	412	1%	44%	35%	20%
Bulgaria	419	67%	3%	19%	11%
Czechia	316	53%	18%	26%	4%
Denmark	789	1%	53%	27%	19%
Germany	632	0%	32%	49%	19%
Estonia	359	8%	59%	28%	4%
Ireland	581	42%	18%	34%	6%
Greece	488	81%	0%	16%	4%
Spain	456	55%	12%	17%	16%
France	515	26%	35%	22%	17%

Country	Waste generation in kg/capita/year	Landfilled	Incinerated	Recycled	Biologically treated
Croatia	393	82%	0%	17%	2%
Italy	486	30%	21%	29%	20%
Cyprus	638	81%	0%	14%	5%
Latvia	404	68%	0%	25%	7%
Lithuania	448	55%	12%	23%	10%
Luxembourg	607	18%	34%	28%	20%
Hungary	377	54%	14%	26%	6%
Malta	606	93%	0%	7%	0%
Netherlands	523	1%	47%	25%	27%
Austria	560	3%	39%	26%	32%
Poland	286	44%	13%	26%	16%
Portugal	460	49%	21%	16%	14%
Romania	247	82%	3%	6%	9%
Slovenia	449	24%	18%	49%	8%
Slovakia	329	73%	11%	8%	8%
Finland	500	12%	48%	28%	12%
Sweden	447	1%	51%	32%	16%
United Kindgom	483	23%	32%	28%	17%

Source: Eurostat (en-wasmun) 2017, municipal waste by waste operation, waste generated

J.2 Methodology and assumptions

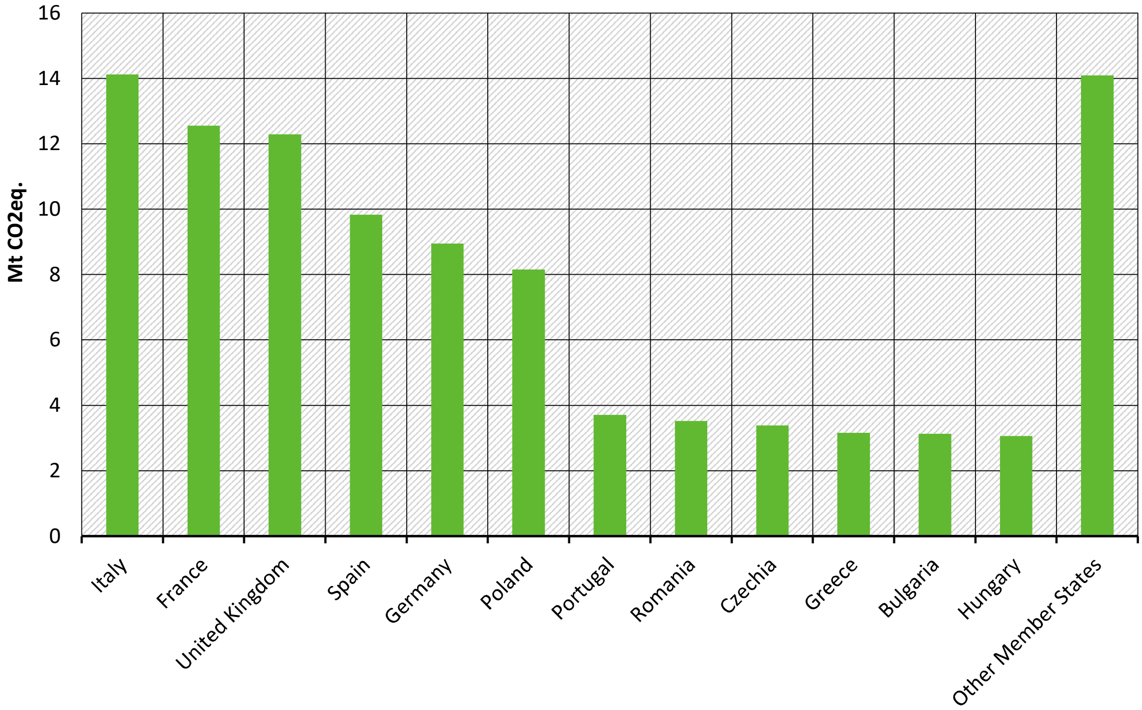
The analysis is based on five steps, which are described in this subsection:

1. Identify MS with highest CH_4 emissions from managed landfills in 2015
2. Select data on waste composition and historic waste disposal in the selected MS based on inventory report for the year 2015 (2017 submission) and related data.
3. Set up waste models for selected MS or groups.
4. Define different scenario settings considering amongst others EU waste policies.
5. Group selected MS into 4 representative groups depending on share of solid waste disposal in recent years and on amount of organic waste disposal per capita.

1. Identification of MS

EU-28 CH_4 emissions from solid waste disposal are dominated by seven MS. Italy, France, the United Kingdom, Spain, Germany, Poland and Portugal reported the highest emissions from landfills in 2015 (see Figure J 1). These seven MS accounted for 69% of total emissions from managed and unmanaged landfills in 2015 in the EU. Emissions from the waste sector in 2050 will thus be largely determined by developments in these MS. Besides these seven MS, high CH_4 emissions from landfills are reported in Romania, Czechia, Bulgaria, Greece and Hungary in 2015. Together these twelve MS have a share of 86% in total EU CH_4 emissions from solid waste disposal on landfills and will therefore be part of the analysis. The detailed analysis for CH_4 emissions from landfills will only focus on managed landfills. Since in 2015 waste disposal on unmanaged landfills was only practiced in seven MS (BG, CY, GR, HR, LT, RO, SK) and make up only 2% of total waste disposed (CRF 2017, Table 5.A).

Figure J 1: CH_4 emissions from solid waste disposal 2015



Source: Based on UNFCCC 2017 data

2. Selection of data on waste composition and historic data

Since methane emissions from the landfilling of waste arise over several years, IPCC 2006 Guidelines require the use of waste data related to waste generation, waste composition and waste treatment over the last 50 years. These data are not available for all MS as they are neither reported in the CRF tables nor described in all inventory reports. The CRF tables report the proportion of waste landfilled from 1990 onwards for managed and unmanaged waste disposal sites. For waste disposal in managed landfills inventory data from 1990 has been used and extrapolated back to 1950, if no further information on historic amounts of waste disposed in managed landfills was available.

Depending on the quality of the inventory report, more detailed information on current and historical waste composition etc. is available and used in the waste models. Waste composition has large effects on the development of CH_4 emissions, due to different organic carbon contents and different performances of the special waste type (wood, food waste, etc.) that influence the decomposition of the degradable organic carbon over time.

Table J 2 shows the share of different organic waste categories as reported in the National Inventory Reports (NIRs) 2017 or related reports to the UNFCCC. This data is used as input data for the waste models. For calculating CH_4 emissions from solid waste disposal we assume that the share of the organic waste categories remains constant until 2050. The reduction of total waste disposed on landfills leads to a reduction of organic waste over time.

Table J 2: Share of waste categories reported under municipal waste for 2015 in %

Country	Food	Garden	Paper	Wood	Textiles/ Nappies	Other organic	Source
Spain	36%	7%	17%	2%	11%	0%	Spain 2017
Greece	42%	0%	24%	1%	3%	0%	UNFCCC 2017, p. 377
Czechia	35%	7%	16%	7%	8%	0%	UNFCCC 2017, p. 293 (wood and straw are divided by 2 and attributed to wood and garden)
Romania	49%	6%	10%	2%	0%	0%	UNFCCC 2017, p. 702
Portugal	38%	0%	13%	1%	3%	14%	UNFCCC 2017, p. 7-12
Bulgaria	17%	10%	11%	2%	4%	0%	UNFCCC 2017, p. 352, (mean value)
France	19%	4%	11%	3%	3%	7%	UNFCCC 2017, p. 463
Italy	22%	6%	24%	2%	3%	5%	UNFCCC 2017, p. 276
United Kingdom	21%	4%	11%	5%	9%	0%	UNFCCC 2017, Annex 3, p. 763
Hungary	25%	0%	17%	2%	10%	0%	UNFCCC 2017, p. 366
Poland	36%	0%	15%	1%	4%	0%	UNFCCC 2017, p. 230
Germany	26%	5%	8%	1%	16%	0%	UNFCCC 2017, p. 656

Source: Based on Spain 2017 and UNFCCC 2017 data

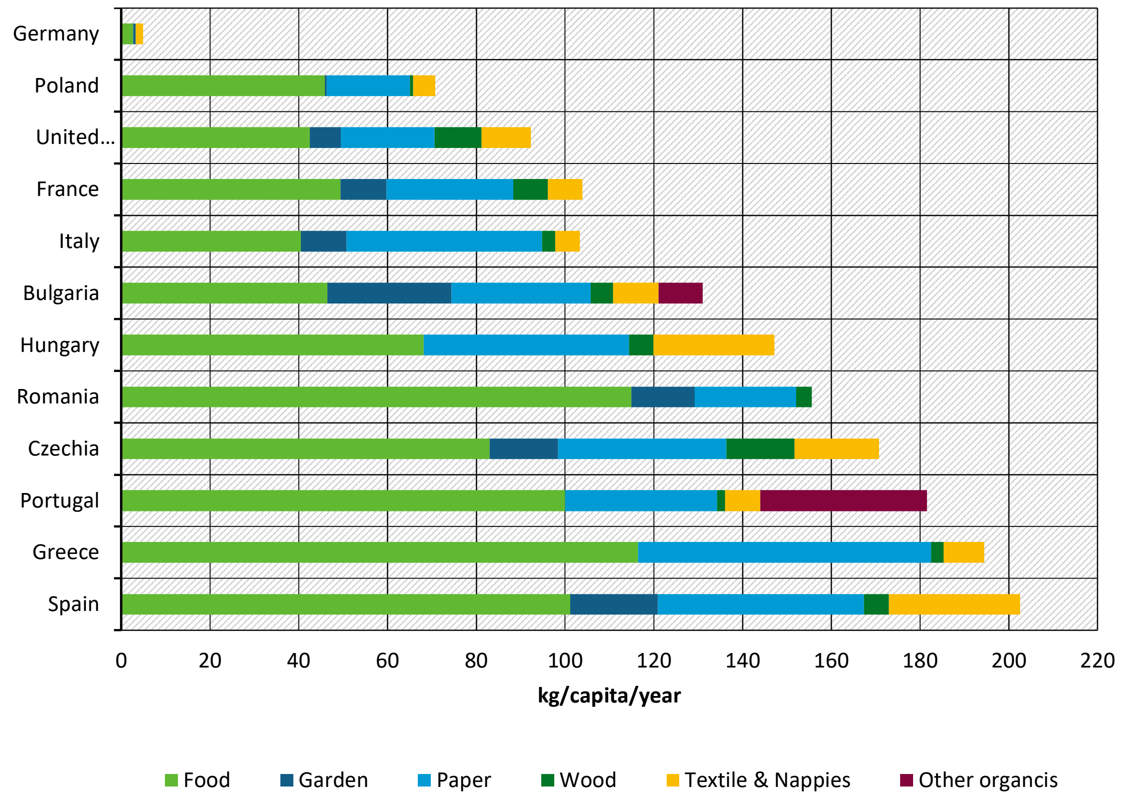
Figure J 2 shows the disposal of food waste, garden, paper, wood, textiles and nappies on managed landfills in the year 2015 in kg per capita. Data is calculated from total amount of waste disposed on landfills and information from the NIR 2017 on waste composition and total population. It shows that the disposal of organic waste in landfills per capita is still very high in some MS in 2015. Main waste fractions disposed are food waste and paper.

3. Set-up of waste models

Individual waste models were set up to estimate future emissions resulting from the historic and recent landfilling of solid waste. For setting up country specific waste models the IPCC 2006 waste model was used, which is available as an Excel model. Input data was derived from country specific data of the selected MS as available in the 2017 inventory submission for waste composition, amount of waste disposal and CH_4 recovery and flaring data. For all other parameters (DOC, K-value, OX) we used IPCC default values, which is the common practice in most MS. The IPCC model differentiates the parameters based on the climatic conditions in the MS. Under dry climatic conditions organic material takes longer to degrade as under wet climatic conditions, which influences the amount of CH_4 emissions in 2050. This was taken into account by choosing the related climatic condition in the waste model for the selected MS.

For all MS analyzed it was possible to calibrate the waste model in a way that the difference between CH_4 emissions for the year 2015 from inventory data and CH_4 emissions for the year 2015 in models used for calculating scenarios, was below 10%.

Figure J 2: Disposal of organic waste in kg/Capita/year 2015



Source: Based on UNFCCC 2017 data

4. EU waste policy and scenario settings

For the detailed analysis we developed a set of scenarios for the selected MS to show the effects of landfill stops in different years on the emission reduction in 2050. The scenario settings also reflect the current EU waste policy.

Directive (EU) 2018/850 of the European Parliament and of the Council of 30 May 2018 amending Directive 1999/31/EC on the landfill of waste, sets up new targets for the amount of waste landfilled. Until the year 2035 only 10% of total municipal waste generated is allowed to be disposed on landfills (EU COM 2018a).[22] Thus, the new targets of the landfill directive will have a significant impact on the development of CH_4 emissions from landfills until 2050. Furthermore, the landfill directive sets no specific target for the amount of organic waste landfilled until 2035. The Waste Framework Directive requires MS to collect paper, metal, plastics, glass, textile and bio-waste separately. The introduction of a separate collection system for bio-waste and textiles is mandatory respectively, from 2024 and 2025 onwards. As it is not allowed to landfill separately collected waste fractions, this will lead to reduced amounts of organic waste landfilled. The landfill directive also requires MS to set up a comprehensive strategy following the waste hierarchy principles to avoid a shift from landfill to incineration and to promote recycling and reuse of waste. In this regard, the Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste sets new and more stringent recycling targets for the coming years. By 2035, 65% of municipal waste is to be recycled (EU COM 2018b).

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[22] MS with high waste disposal rates in 2013 (>60%) do not have to reach the target before 2040.

The new targets in the directive of the landfill of waste are reflected in one scenario setting. As there is no specific target for the amount of organic waste, waste composition is assumed to be constant until 2050 and organic waste is decreasing due to reduced total amounts of waste landfilled. Table J 3 includes a description of the scenario settings.

Table J 3: Overview of specific scenario settings

Scenario	Description of scenario	Timing for the reduction of landfilled waste	Source
Business as usual (BAU)	- No reduction of landfilled waste until 2035 in comparison to 2015 - Reduction of 50% until 2050.	Start after 2035	Own assumption
2035_2050	- MS reach their EU target in 2035 and dispose only 10% of their municipal waste[23], - Extension for MS with high disposal rates in 2013 until 2040, - No further reduction in landfilled waste until 2050 compared to 2035/2040.	Immediate start	EU target 2035, own assumption
2035_25%	- All MS do not reach the target of 10% municipal waste landfilled and landfill 25% of waste in 2035. - No organic waste is disposed on landfills in 2050.	Immediate start, delay	Own assumption
2035_10%	- All MS reach their EU target of only 10% municipal waste in 2035. - No organic waste is disposed on landfills in 2050.	Immediate start	EU target 2035, own assumption
2030	- MS reach their EU target of 10% municipal waste disposal already in 2030. - No organic waste is disposed on landfills in 2050.	Immediate start, early achievement	Own assumption based on recommendation for EU target

Source: Own assumptions (Oeko-Institut)

5. Identification of representative groups

The twelve selected MS have a share of 86% in total EU-28 CH_4 emissions from managed landfills. For a better presentation of results and a more focused discussion on the differences, selected MS are grouped into representative groups. The grouping is based on information from Table J 1 and Figure J 1, depending on the share of landfilled waste, waste composition, CH_4 recovery rates and amount of landfilled organic waste per capita (see

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[23] For MS with differences between municipal waste disposal data reported under Eurostat (env-wasmun) and UNFCCC Inventory data (2017 submission) it is assumed that the amount of non-municipal waste disposed is also reduced to 10% in comparison to 2015 amounts.

Table J 4).

Table J 4: Cluster definitions

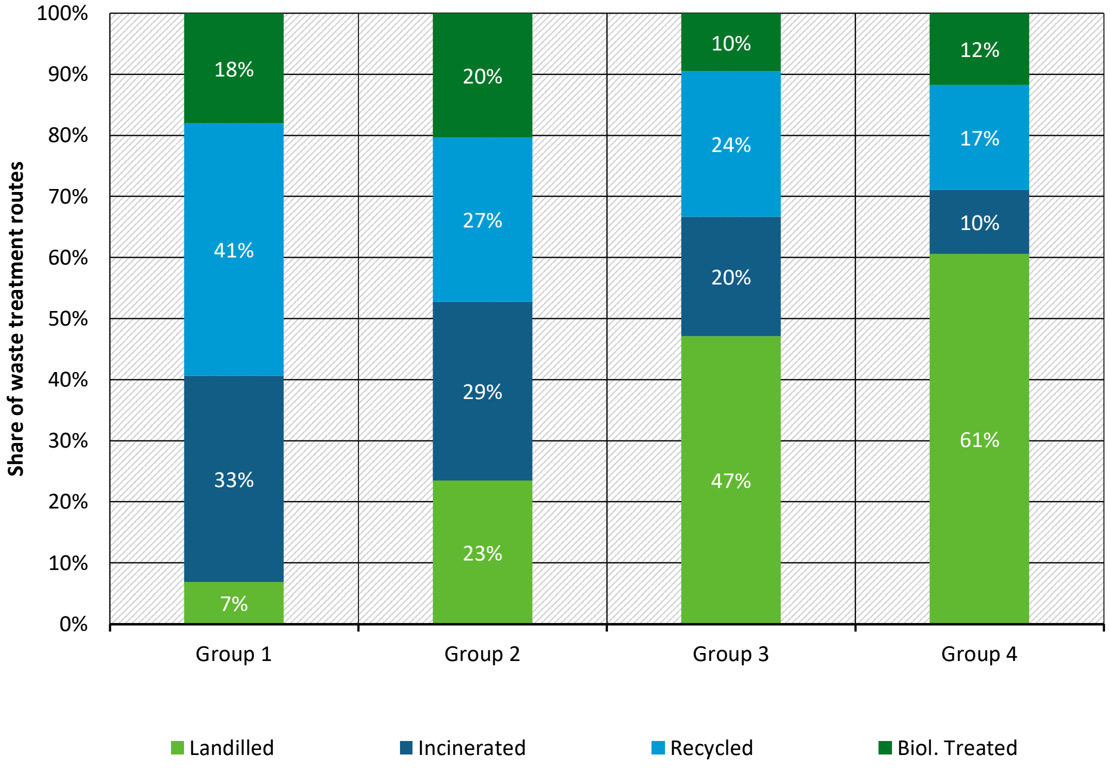
	Country 1	Country 2	Country 3	Country 4	Characterization
1.Group	Germany	United Kingdom			Very low emissions from waste disposal due to ban of organic waste disposal (Germany) and high amount of CH_4 recovery (UK)
2. Group	France	Italy			Similar share of landfilled waste and organic waste disposal per capita
3.Group	Poland	Portugal	Hungary	Bulgaria	Similar share of solid waste disposal, low CH_4 recovery rates
4.Group	Spain	Greece	Romania	Czechia	High landfill rates per capita, dry climate* (except Czechia)

*In MS with dry climate conditions organic waste degrades slower, which effects 2050 emissions from waste disposal

Source: own presentation (Oeko-Institut)

Figure J 3 shows the waste treatment routes in the representative groups. There are large differences in the treatment routes and reaching recycling goals of 55% in 2025, 60% in 2030 and 65% in 2035 requires very fast and focused action in many MS especially in those of Group 3 and Group 4.

Figure J 3: Share of solid waste treatment routes in 2017



Source: Eurostat 2017 (en-wasmun)

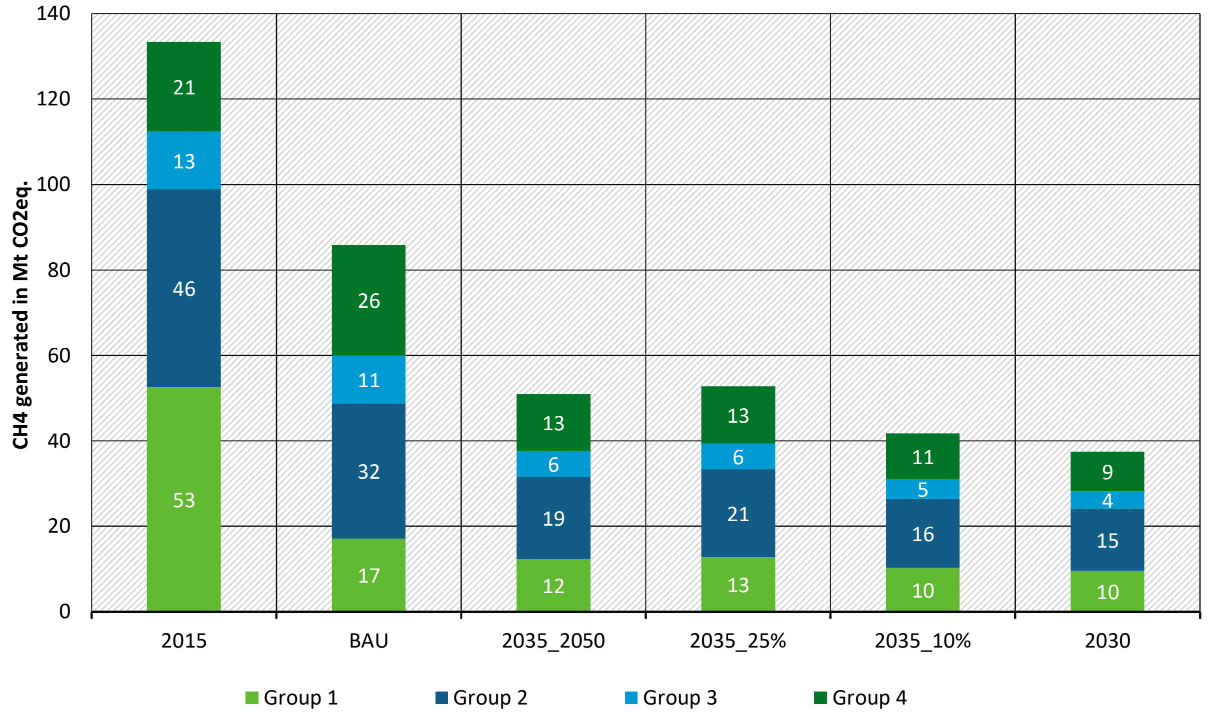
J.3 Scenarios and results

J.3.1 CH_4 generated

Figure J 4 shows the results of the different scenarios for CH_4 generated in landfills in 2050. This includes all the CH_4 which is produced by landfilling organic waste and is different from net CH_4 emissions from landfills.

As expected CH_4 generated in the BAU scenario is very high, because there is no reduction in waste disposal on landfills until 2035. Still, in comparison to 2015 a large reduction can be observed, given that solid waste disposal on landfills has been declining in many MS already since 1990. Even if the current waste disposal rate is not reduced in comparison to 2015, there would be a reduction of almost 50 Mt CO_2-eq. in CH_4 generated in the BAU scenario for 2050. Most CH_4 is generated in landfills from MS of Group 1 and Group 2 in all scenarios.

Figure J 4: CH_4 generated from waste disposal on managed landfills in different scenarios in 2050



Source: UNFCCC 2017, own calculation (Oeko-Institut)

Table J 5 shows the reduction in CH_4 generation by the representative groups of MS. Due to the historic and the current waste disposal practices there are large differences in the reduction rates of CH_4 generation in 2050. Highest reductions take place in group 1 with -82% in CH_4 generated in comparison to 2015. Group 2 and 3 would show a reduction of -69% of CH_4 generation in comparison to 2015 and the reduction of CH_4 generation would show only a maximum of -56% in Group 4, while CH_4 generation would still increase in the BAU scenario. Thus in the groups with high disposal rates of organic material per capita in 2015, reduction potential in 2050 is lower in comparison to other groups. Besides relatively high organic waste disposal rates per capita, MS of Group 4 are located in the Mediterranean region, where the main climate conditions are dry temperate. In regions with a dry temperate climate, degradation of organic waste takes longer than in wet temperate climates because of missing moisture. This is another reason why reduction in CH_4 generation in 2050 in comparison to 2015 is lower in Group 4 than in other groups.

Table J 5: Reduction in CH_4 generation in 2050 in comparison to 2015

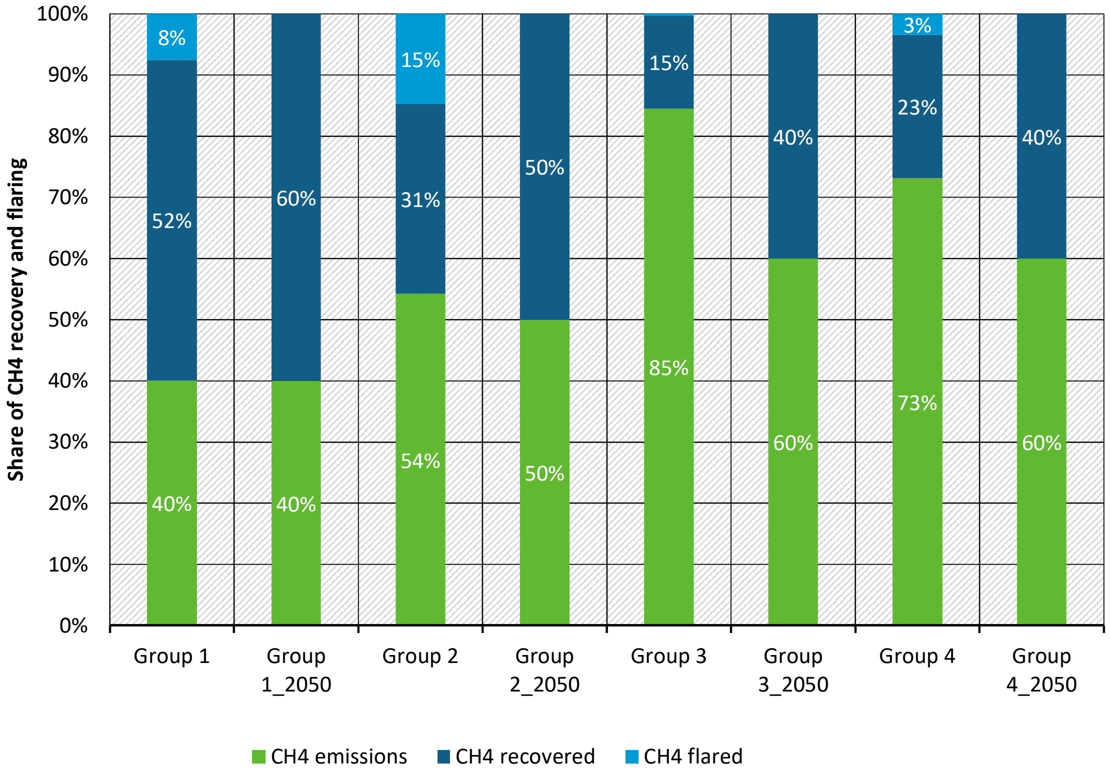
	Group 1	Group 2	Group 3	Group 4
BAU	-67%	-32%	-16%	23%
2035_2050	-77%	-58%	-55%	-36%
2035_25%	-76%	-56%	-56%	-36%
2035_10%	-80%	-65%	-66%	-49%
2030	-82%	-69%	-69%	-56%

Source: Own calculation (Oeko-Institut)

J.3.2 CH_4 recovery and flaring

CH_4 emissions from landfills are not the same as CH_4 generated because about 10% of CH_4 generated is oxidized and does not result in CH_4 emissions. Additionally, CH_4 generated can be reduced by installing technologies for flaring and recovering of CH_4. The recovered CH_4 is the amount of CH_4 that is captured for energy use and is a country-specific value which has significant influence on the emission level. Because MS have implemented technologies on landfills to flare and recover methane, CH_4 emissions are already 61 Mt CO_2-eq. lower than total CH_4 produced on the landfills. The percentage of CH_4 recovered and flared in 2015 varies among the Groups: between 60% in Group 1 and only 15% in Group 3. It depends - amongst other factors - on the share of solid waste disposal sites where recovery installations exist (see Figure J 5).

Figure J 5: Share of CH_4 emissions and CH_4 recovery and flaring in managed landfills in 2015 and 2050



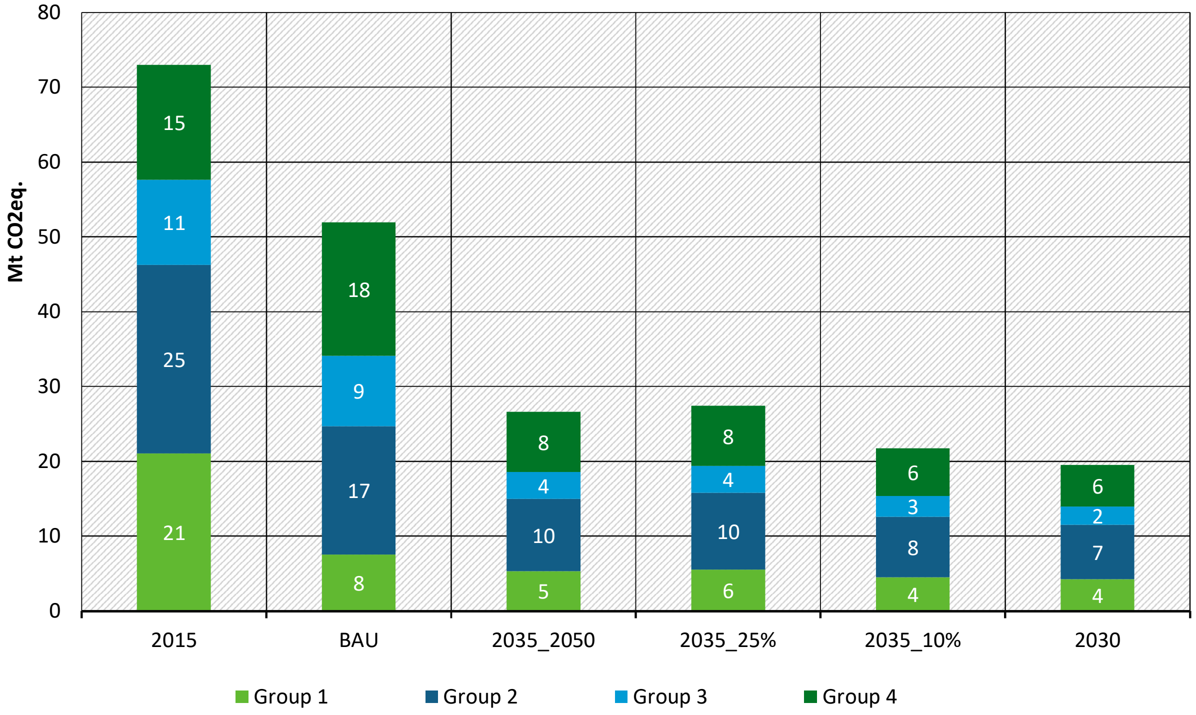
Source: UNFCCC 2017, scenario assumptions

The installation of CH_4 flaring and recovery technologies can strongly reduce CH_4 emissions from landfills. Thus, as shown in Figure J 4, there is still large potential to reduce CH_4 emissions from landfills by installing technologies to flare and recover CH_4 especially in Group 3 and 4. German literature studies show that the collection rate is between 50 – 60% after completion of the landfills and application of a surface coverage (Krümpelbeck 1999). A wider range of practical tests on existing gas collection systems have shown that the realistic coverage should be between 40 - 50% (Forsting 2017). Based on this fact it is assumed that CH_4 recovery can be increased to 40% in Group 3 and 4, to 50% in Group 2 and remains constant at 60% in group 1 given the reduced disposal of organic waste (see Figure J 4).

J.3.3 CH_4 emissions

Figure J 6 shows the net CH_4 emissions 2050 from managed landfills for different scenarios and for 2015. In the BAU scenario, assuming no increase of CH_4 recovery technologies, total CH_4 emissions will only be reduced by 21 Mt CO_2-eq. in 2050 in comparison to 2015. In comparison, the reduction at CH_4 generated is much higher in this period. Differences are mainly due to the fact that CH_4 emissions have already been avoided through the use of flaring and recovery technologies, especially in Group 1 and Group 2. Higher reductions can be realized if recovery of CH_4 is increased to 40% in Group 3 and 4 and to 50% in Group 2 and by drastically reducing the amount of waste disposed on landfills in the next years. In comparison to 2015, CH_4 emissions from landfills will be reduced by 45.5 up to 53.5 Mt CO_2-eq. in 2050 if landfilling of waste is reduced to 10% of total municipal waste generated until 2030 or later. In comparison to the BAU scenario, assuming no reduction in the current waste disposal rate until 2035, CH_4 emissions can be reduced by 25 – 32 Mt CO_2-eq. Reducing municipal waste disposal already in 2030 to almost 10% of total municipal waste generated, saves an additional of 8 Mt CO_2-eq. in comparison to the scenario of -25% reduction in 2035.

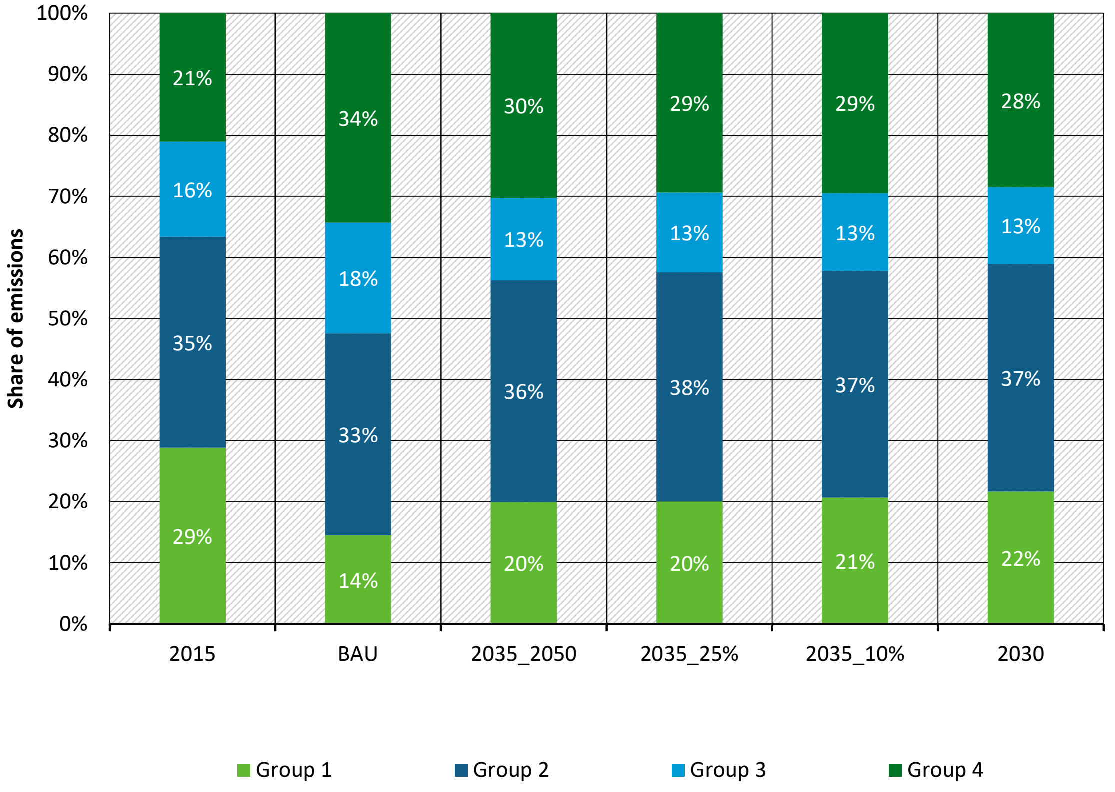
Figure J 6: CH_4 emissions from managed landfills in 2050 in comparison to 2015



Source: Own calculation (Oeko-Institut)

Figure J 6 shows the share of CH_4 emissions from managed landfills of the selected MS by groups in different scenarios. This reflects the current waste management practices in the MS. For Group 1, the current waste management practices with low organic waste disposal rates and high CH_4 recovery rates most likely ensure a low emission path until 2050 already in the BAU scenario. The share of CH_4 emissions from Group 2 is decreasing in the BAU scenario, but increasing in all other scenarios in comparison to 2015. Results of the BAU scenario would indicate an increased share of CH_4 emissions from Group 3. Increasing the share of CH_4 recovery represents a high reduction potential in Group 3, which leads to reduced shares of CH_4 emissions in all other scenarios. The current waste management practices of Group 4 would strongly increase the share in total CH_4 emissions in the BAU scenario between 2015 and 2050 due to high disposal rates of organic waste per capita and low CH_4 recovery rates in 2015. Also, absolute CH_4 emissions would increase in the BAU scenario in Group 4, whereas in all other groups emissions would already decrease in the BAU scenario. Therefore, the reduction in 2050 strongly depends on the development of waste management in Group 4.

Figure J 7: Shares of representative groups in total CH_4 emissions from landfills for different scenarios



Source: Own calculation (Oeko-Institut)

Table J 6 shows the total emission reduction in the BAU scenario in comparison to 2015 for the different groups. It shows that high emission reduction take place in MS included in Group 1 and Group 2 already in the BAU scenario.

Table J 6: CH_4 emission reduction in the BAU scenario in comparison 2015 in Mt CO_2-eq.

	Group 1	Group 2	Group 3	Group 4	Total in comparison to 2015
BAU in comparison to 2015	-13.5	-8.0	-2.0	2.5	**-21.0**

Source: Own calculation (Oeko-Institut)

Table J 7 shows the total emission reduction in comparison to the BAU scenario for the different groups. It shows that highest emission reduction can take place in MS included in Group 2 and Group 4 representing almost 70% of total CH_4 emission reduction in all scenarios.

Table J 7: CH_4 emission reduction in comparison to BAU scenario in Mt CO2-eq.

	Group 1	Group 2	Group 3	Group 4	Total in comparison to BAU
2035_2050	-2.2	-7.5	-5.8	-9.8	**-25.3**
2035_25%	-2.0	-6.9	-5.8	-9.8	**-24.5**
2035_10%	-3.0	-9.1	-6.6	-11.4	**-30.2**
2030	-3.3	-9.9	-7.0	-12.3	**-32.4**

Source: Own calculation (Oeko-Institut)

J.3.4 Conclusion

In comparison to the year 2015, CH_4 emissions from solid waste disposal can be reduced by a maximum of 53.5 Mt CO_2-eq. in 2050 (without assuming landfill stabilization through ventilation). Analysis shows that the timing for reducing the amount of landfilling organic waste significantly influences the emissions from landfills in 2050. Continuing the current waste management practices until 2035 would lead to high CH_4 emissions in 2050. There are large differences between the four groups in terms of potential CH_4 emission reductions in the different scenarios. In Group 1, large reductions will take place in the BAU scenario. Thus, the contribution of Group 1 to total CH_4 emission reduction is very small in all other scenarios (see Table J 7). Large reduction potentials in comparison to the BAU scenario are found in Group 2 and Group 4, but also in Group 3. Parts of the total emission reduction outlined in Table J 7 can be reached by installing CH_4 recovery and flaring technologies at the landfills. However, the main part of reduction would result from reducing the amount of solid waste disposed on landfills. Thus, in comparison to Group1 where the BAU scenario would represent a low carbon pathway, the emission reduction for 2050 in Group 2, 3 and 4 is heavily dependent on a change of current waste management practices.

Results show that changing the current waste management practices in the next years highly effects emissions in 2050. The effect of reducing landfilled waste to 10% in 2035 or to 25% in 2035 is not as crucial as expected though. The total difference between a reduction to 10% in 2030 or to 25% in 2035 or to 10% in 2035 and no further reduction until 2050 is only 8 Mt CO_2-eq. For the MS, it makes a difference if municipal waste disposal will have to be reduced to 10% of total municipal waste generated until 2030, 2035 or later. However, what is very important is to change the current waste disposal practices and reduce the actual high rates of organic waste disposal per capita.

With the implementation of the 2018 amendment of the landfill directive, the BAU scenario is not the most realistic scenario as the target to deposit only 10% of municipal waste in 2035 is already in place. However, it should be ensured that this is also implemented in all MS. For the time after 2035, there is no target to further reduce the disposal on landfills. Scenario settings assume that solid waste disposal of organic waste will be reduced to zero in 2050. A comparison of the results from the scenario 2035_10% and 2035_2050 show that by reducing the amount of organic waste disposed to zero can reduce emissions in 2050 by another 5 Mt CO_2-eq.

Differences of 5 or 8 Mt CO_2-eq. are very small in comparison to the current high total emissions in the EU. However, for reaching the final target of -95% in 2050 also these small amounts of emission reductions are relevant.

J.4 Relation to results of the scenario GHG-neutral EU2050

Based on the results of the scenario GHG-neutral EU2050, CH_4 emissions from landfills are reported at 15.5 Mt. CO2-eq. in 2050, if landfilling of waste will be stopped already in 2030. Besides the reduction of landfilling waste to 10% of total municipal waste generation and installations of recovery and flaring technologies, the model assumes a further reduction of about 30% by using landfill stabilization technologies. The implementation of this technology is not considered in the detailed analysis, but it can be assumed that it is possible to further reduce CH_4 emissions from landfills by a minimum of 30% due to the use of landfill stabilization technologies.

The detailed analysis shows that CH_4 emissions from landfills are higher in 2050 the later landfilling of organic waste is reduced to a minimum. However, if existing waste policies are implemented in all MS, it is possible to reduce CH_4 emissions from landfills by 70% in comparison to 2015. Assuming a further reduction of 30% due to stabilization technologies, the detailed analysis of the selected MS shows that it is possible to decrease CH_4 emissions from landfills in the selected scenarios between 74% and 81% in comparison to 2015. Of the total necessary reduction of 85 Mt CO_2-eq calculated in the scenario GHG-neutral EU2050 about 60 Mt CO2-eq. (including 30% reduction due to landfill stabilization) will be reduced in the twelve selected MS. 25 Mt CO_2-eq. would need to be reduced in unmanaged landfills and in the other EU MS that were not part of the detailed analysis.

Further emission reductions in the waste sector will depend on the development of waste management practices. If waste is no longer disposed in landfills other waste treatment routes become relevant. Following the principles of a sustainable waste management, the highest reduction potential is related to waste avoidance. This is especially relevant for food waste, but of course also for all other waste types. For waste that is not avoided recycling capacities need to be increased. This is especially true for paper, which is still landfilled to a large amount, but also for textiles, plastics, glass, metal etc. Thus, for many MS, significant efforts and high investments to increase recycling rates and improve the treatment of residual waste are necessary in the next years.

J.5 List of references

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K Consumption of animal products

K.1 Introduction

Achieving long-term climate goals requires a reduction in livestock numbers, given that technical options for reducing greenhouse gases from agriculture are limited. The necessary reduction in livestock numbers is part of the GHG-neutral EU2050 scenario and leads to an estimated 44% reduction in agricultural emissions compared to 2015[24]. Since increases in the performance of the remaining livestock cannot compensate for maintaining current production levels, the reduction in livestock numbers is also associated with a decline in the supply of animal products. If demand exceeded supply, the result would be the import of animal products. This would export environmental risks of animal production to other countries and threatens their climate targets (leakage effect). A climate-friendly diet, which goes hand in hand with a reduction in the consumption of animal products, is therefore decisive for achieving the goal of a GHG-neutral Europe. The impact assessment of the EU Commission's 2050 Long Term Strategy includes also various scenarios of changes in diets that take into account a decline in meat and milk consumption (EU 2018). Most recently, also the IPCC special report "Climate Change and Land" (IPCC 2019) stressed the need for changes in animal husbandry and nutrition.

Within this analysis the following questions will be answered:

- Given the limited emissions budget of the agricultural sector in 2050, how many animal products from indigenous production can still be consumed in EU-28 MS?
- What changes in current dietary habits would be necessary in the single MS?
- Are national and European nutritional recommendations consistent with the climate targets of the agricultural sector in 2050?

A short analysis of the nutritional habits of the individual EU MS with regard to meat and milk consumption shows that nutritional habits differ quite considerably. In some MS the current consumption corresponds to a climate-friendly diet, the main question being how to maintain this level of consumption, while in others the high consumption of animal products needs to be drastically reduced. To better reflect the heterogeneous conditions in the MS a more detailed analysis of MS was carried out. The results should indicate in which regions a change in diets is essential to achieve the 2050 targets. To carry out the detailed analysis, we developed a set of scenarios to show the necessity of dietary changes for emission reduction in the agricultural sector in 2050.

K.2 Methodology and assumptions

The analysis is based on five steps, which are described in the following subsection:

1. Selection of data on current consumption of animal products (milk and meat) and nutritional recommendations for EU MS based on national data, FAO data and related data.
2. Creation of a simple coupled model approach to the production and consumption of milk and meat for all EU-28 MS.

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[24] In comparison to 1990 emissions from the agricultural sector decrease by 55%.

3. Set up of different scenario assumptions considering production and consumption issues including current diets, performance increase in animal production and climate targets in 2050.
4. Grouping of all EU-28 MS into representative groups depending on current consumption patterns.
5. Comparison with the dietary recommendations

1. Selection of data on current consumption

The Food and Agricultural Organization (FAO) provides a consistent data set on historic and current consumption of dairy and meat products for all EU MS. For the following commodities production and consumption data were extracted from the database[25]:

- Bovine Meat
- Butter, Ghee
- Cheese
- Cream
- Meat, Other
- Milk – Excluding Butter
- Milk, Whole
- Pigmeat
- Poultry Meat

The latest published data are available for the year 2013. FAO data is presented in Primary Equivalent (consumer weight equivalent) for consumption and production.

2. Creation of a coupled model approach to the production and consumption

To calculate different scenarios for the changes of production and consumption for all EU-28 MS an Excel-based model was set up. This model is used to project the future development of dairy and meat production and consumption by product and per Member State in the different scenarios. The following input data for the analysis covers:

Production

- Animal numbers (dairy cows, other cattle, big and poultry)
- Dairy milk yield (kg/cow)
- Carcass weight (bovine, pig, poultry in kg/head)
- Production of dairy products (total milk production)
- Milk equivalents to translate milk in dairy products

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[25] http://www.fao.org/faostat/en/#data/CL

Production of meat (beef, pig and poultry) and dairy products is the product of animal numbers and productivity (milk yield, carcass weight).

Consumption

- Population numbers per MS
- Consumption of dairy products and meat (beef, big, poultry) in kilogram per capita and year
- Supply balance

Based on the input data, the consumption level of animal products that is in line with climate targets for the agricultural products can be identified for 2050. Therefore, consumption for the GHG-neutral EU2050 scenario is estimated by combining information on the development of livestock for dairy cattle, other cattle, pig and poultry from the GHG-neutral EU2050 scenario with assumptions for the development of dairy cow yield and carcass weight. Data from EU Commission (2019) and FAO-stat (2019) are used for the current state. For 2050, data from *EU agricultural outlook 2018-2030* and from the scenario *GHG-neutral EU2050* were used. Data sources for the population are taken from the EU's reference scenario (EU COM 2016).

3. Scenario settings

For the detailed analysis we developed a set of scenarios for all EU-28 MS to show the effects of the 2050 climate targets for the agricultural sector on consumption Based on data for the year 2016 and on the model results for the agricultural GHG emissions in 2050 in the scenario GHG-neutral EU2050, information on necessary changes in the consumption of meat and dairy products to cope with climate targets is identified. This in-depth analysis aims to present the necessary changes in consumption of milk and meat resulting from the GHG-neutral EU2050 scenario. Thus, the GHG emission level of GHG-neutral EU2050 for the agricultural sector is taken as the starting point and the remaining production of animal products is determined. For coupling production and consumption three scenarios were considered. Additionally, a baseline scenario has been set up, as this is not part of the GHG-neutral EU2050 scenario development. The BAU scenario shows the expected development in milk and meat consumption based on data from the European agricultural outlook for the year 2030 (EU 2019). Besides a business as usual scenario (BAU) two scenarios were analysed. The first scenario assumes a higher productivity (scenario HP_2050) due to an increase in milk yields beyond the current level. The second scenario assumes that productivity is fixed at the current level and no further increase in milk yields is assumed.

The aim of the analysis is to identify necessary changes in nutrition for individual country groups and MS. This is of great interest in view of the very different dietary habits within the EU. The model created for this is very static. It does not include upstream factors. For example, changes in the forage base are not considered (grassland versus forage maize). Technical changes in manure management are also not taken into account (e.g. percentage of pasture, percentage of manure fermentation). Therefore, no additional calculation of emissions related to the scenarios will take place.

Table K 1 includes a description of the scenario settings for dairy products.

Table K 1: Overview of specific scenario settings for dairy products

Scenario	Description of scenario - Production	Description of scenario - Consumption
Business as usual (BAU)	• Increase of milk yield per cow based on own assumption (climatic conditions, yield increase in the past), average for EU 13 = 6,900 kg/cow, average EU-15 = 8,300 kg/cow • Reduction of dairy cows in 2050 based on assumptions from EU agricultural outlook (EU 2019) for the year 2030, reduction in EU-15 by -3%, reduction in EU-13 by -17%	• Increase EU dairy product consumption to 287 kg milk equ./cap/yr. in EU-15[26] and 238 kg milk eq./cap/yr in EU 13[27] based on assumption from EU agricultural outlook (reduction for MS that have a higher consumption, increase for MS with lower consumption today)
Higher Productivity HP_2050	• Animal numbers for dairy cows from GHG-neutral EU2050 scenario • Milk yield increase similar to BAU scenario	• Consumption based on total milk produced in the scenario, divided by number of inhabitants in EU-28 in 2050
Fixed Productivity FP_2050	• Animal numbers for dairy cows from GHG-neutral EU2050 scenario • No milk yield increase in comparison to 2016 data, milk production takes place in the same system with lower animals	• Consumption based on total milk produced in the scenario, divided by number of inhabitants in EU-28 in 2050, MS with lower dairy consumption than EU-28 average remain at level of dairy consumption 2013.

Source: own assumptions (Oeko-Institut)

Table K 2 includes information on scenario settings for meat production and consumption.

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[26] All EU MS before 2004

[27] New MS since 2004

Table K 2: Overview of specific scenario settings for meat

Scenario	Description of scenario - Production	Description of scenario - Consumption
Business as usual (BAU)	• Increase of carcass weight – linear trend of past data until 2030 (and 2050=2030): ○ cattle 1,6% ○ pigs 5% ○ poultry EU15 2%, EU-13 17% • Reduction of animals based on assumptions from EU agricultural outlook 2018-2030: ○ Cattle: EU-15: -3%, EU-13: -17% ○ Pigs: EU-15: -9%, EU-13: -14% ○ Poultry: EU-15: 0%, EU-13: +1%	• Change of consumption until 2030 (and 2050=2030) - based on assumptions from EU agricultural outlook 2018-2030: ○ cattle EU-15: -6%, EU-13: +8% ○ pigs EU-15:- 3%, EU-13: +13% ○ poultry EU-15 +3%, EU-13 +8%
Higher Productivity HP_2050	• carcass weight - like BAU • Reduction of animals based on assumptions UBA- GHG-neutral EU2050: ○ Cattle: EU-15: -45%, EU-13: -30% ○ igs & poultry: EU-15: -50%, EU-13: -30%	• Change of consumption based on GHG-neutral EU2050 animal numbers. Consumption based on total beef, pork and chicken produced in the scenario, divided by number of inhabitants in EU-28 in 2050.
Fixed Productivity FP_2050	• carcass weight - like 2016 • Reduction of animals based on assumptions like HP_2050	• Change of consumption based on GHG-neutral EU2050 animal numbers. Consumption based on total beef, pork and chicken produced in the scenario, divided by number of inhabitants in EU-28 in 2050. MS with lower meat consumption than EU-28 average remain at level of meat consumption 2013.

Source: own assumptions (Oeko-Institut)

4. Identification of representative groups

Dairy products

For a better presentation of results and a more focused discussion of the observed differences against current consumption of dairy products, all 28 EU MS are grouped into representative groups, based on FAO data for the year 2013. All MS with a very high consumption are in Group 1, while Group 4 includes MS with the lowest dairy consumption in EU 28.

Table K 3 gives an overview on groups and belonging MS.

Table K 3: Cluster definitions for dairy

	Consumption	Country 1	Country 2	Country 3	Country 4	Country 5	Country 6	Country 7	Country 8	Country 9
1.Group	Very high > 300 kg/cap/yr	Belgium	Finland	France	Germany	Sweden	Austria			
2.Group	Medium high > 225 kg/cap/yr	Latvia	Netherlands	Denmark	Greece	Czechia	Poland	Lithuania	Ireland	Italy
3.Group	Medium low 180-225 kg/cap/yr	United Kingdom	Estonia	Luxembourg	Slovenia	Romania				
4.Group	Very low 100 – 180 kg/cap/yr	Croatia	Malta	Hungary	Slovakia	Portugal	Spain	Bulgaria	Cyprus	

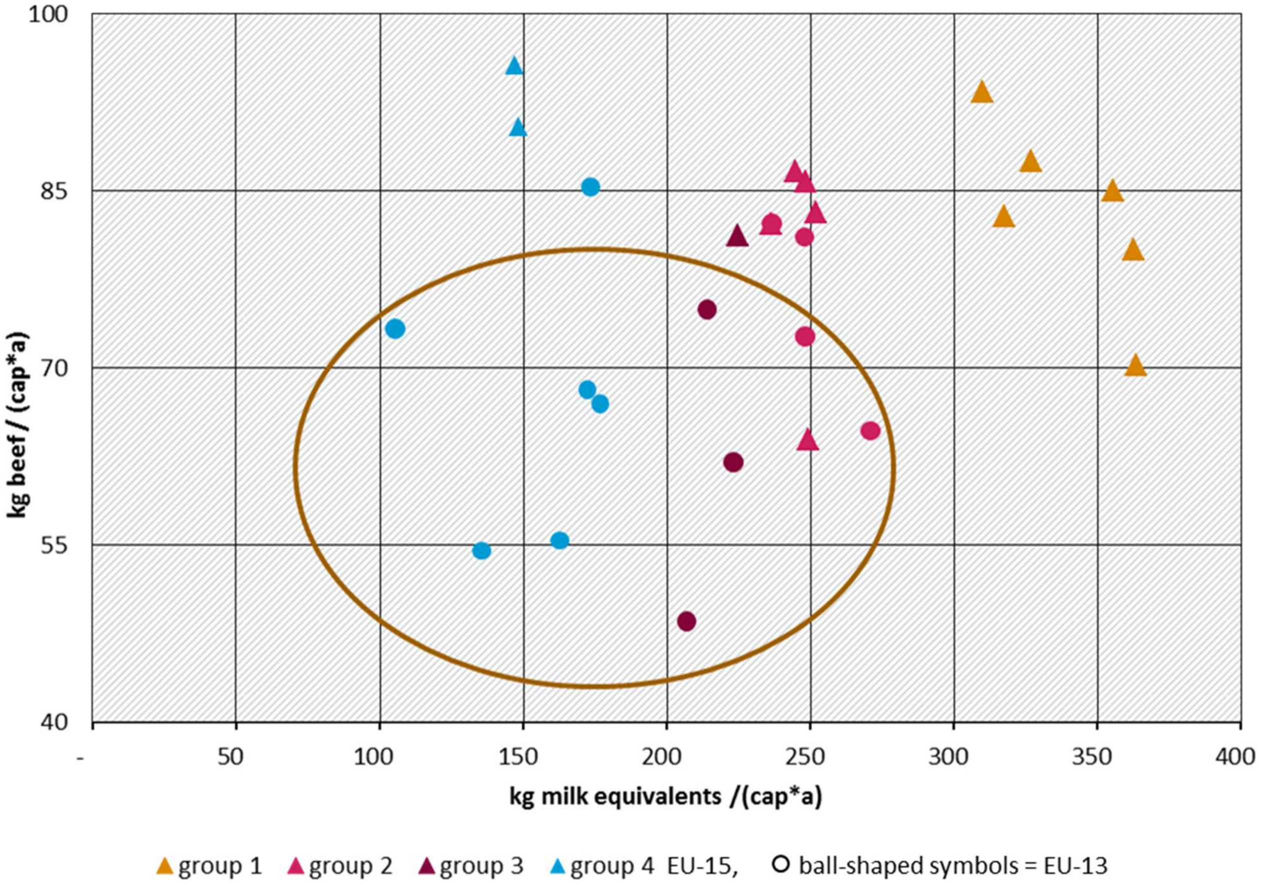
Source: own allocation (Oeko-Institut)

Figure K 2 shows the consumption of dairy products in the representative groups. There are large differences in the consumption patterns with regard to the consumption of cheese, cream, butter and fresh dairy products. Especially in Group 1 and Group 2, the consumption of fresh dairy products represents only a small part of all dairy products consumed and a higher consumption of cheese, cream and butter. This leads to a higher dairy consumption in absolute milk equivalents as for the production of cheese, cream and butter more milk is needed.

Meat products

Representative groups for the consumption of meat are not in line with the consumption of dairy products. Grouping single MS to representative groups is difficult as consumption patterns are different with regard to beef, pork and poultry meat consumption, which cannot be standardized. By analyzing current consumption patterns in all MS a separate presentation of EU-15 and EU-13 seems useful. Figure K 1 shows that total meat consumption in the EU-13 is lower than in the EU-15.

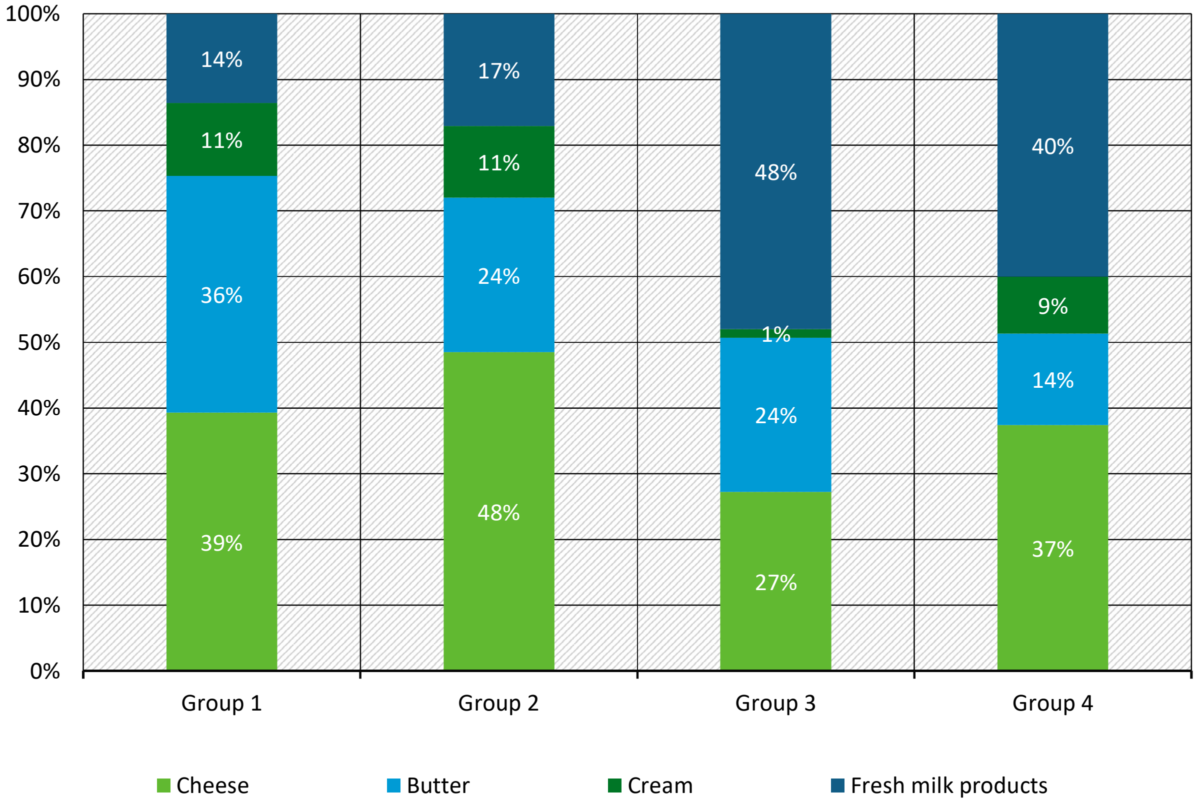
Figure K 1: Share of dairy products in total milk consumption 2013 (in milk equivalent)



Source: own calculation (Oeko-Institut) based on FAO 2019

Meat consumption in most EU-15 MS is characterized by high total meat consumption with a significantly higher proportion of beef than in the EU-13 MS, see Figure K 2. Average meat consumption in EU-15 MS is 60 kg/cap/yr, ranging from 69 kg/cap/yr in Luxembourg to about 49 kg/cap/yr in Belgium. In EU-13 MS average meat consumption is 48 kg/cap/yr, with an exception of high meat consumption of 61 kg/cap/yr in Malta to 35 kg/cap/yr in Romania. Thus, results will be presented for EU-15 and EU-13 MS.

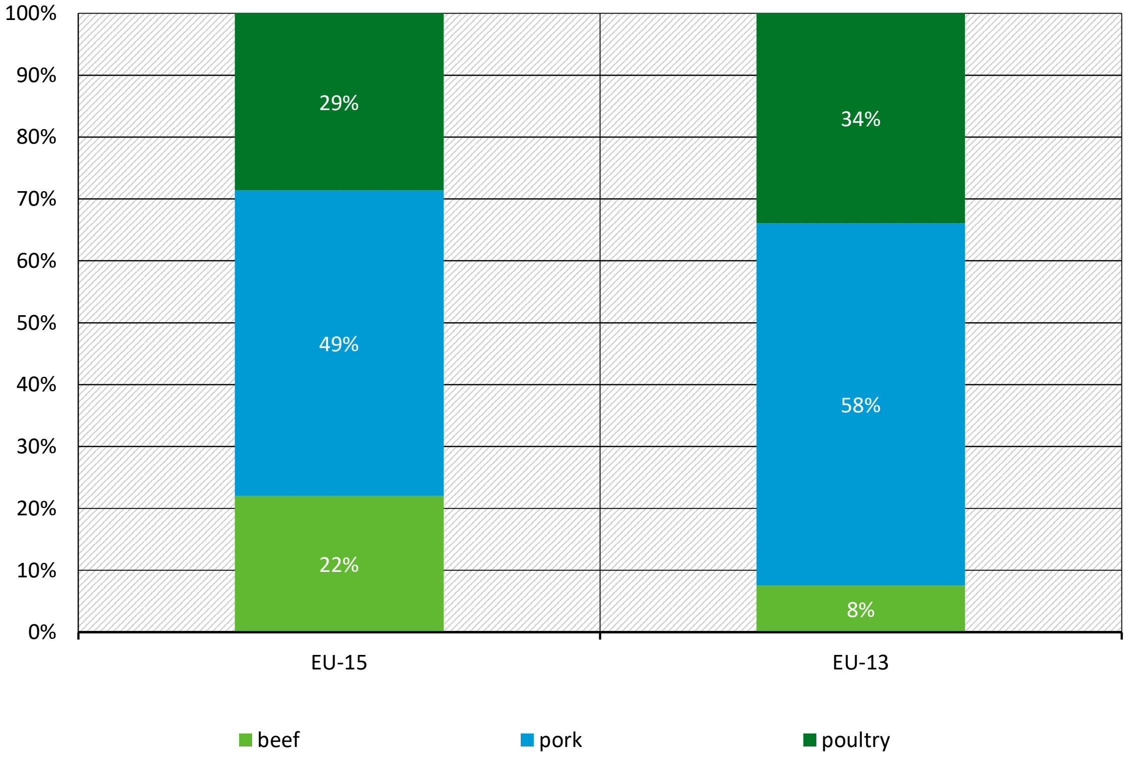
Figure K 2: Share of dairy products in total milk consumption 2013 (in milk equivalent)



Source: own calculation (Oeko-Institut) based on FAO 2019

Figure K 3 shows the consumption of beef, pig and poultry meat for EU-15 and EU-13.

Figure K 3: Share of beef, pig and poultry meat in total meat consumption 2013



Source: own calculation (Oeko-Institut) based on FAO 2019

K.3 Nutritional recommendations and current consumption

The World Health Organisation advises a daily protein intake of 0.83 g per Kilogram body weight (WHO et al. 2007). Based on this number, Westhoek et al. (2011) calculated a recommended protein intake per capita of 50 g per day for the Dutch population. This figure was taken for EU-28. It includes the consumption of animal and vegetable proteins.

Table K 4 displays dairy and meat production and resulting protein intake for all MS. A comparison with the WHO recommendation shows that in many EU MS the consumption of animal products alone exceeds WHO recommendations (Protein consumption from consumed fish and eggs not included). Thus, reduced consumption of animal products is also necessary due to health reasons.

Table K 4: Consumption of dairy and meat products

Country	Consumption of meat in kg/cap/yr 2013	Consumption of dairy products in milk eq. in kg/cap/yr 2013	Total protein intake (dairy and meat products) in g/cap/day 2013
Belgium	49	364	52
Bulgaria	38	135	35
Czechia	51	248	46
Denmark	57	249	52
Germany	60	327	61
Estonia	41	223	45
Ireland	61	245	54
Greece	54	249	58
Spain	66	147	54
France	61	355	57
Croatia	46	177	49
Italy	59	236	56
Cyprus	53	105	41
Latvia	43	271	41
Lithuania	54	236	50
Luxembourg	69	217	62
Hungary	46	172	40
Malta	61	173	53
Netherlands	63	252	64
Austria	64	310	59
Poland	53	248	46
Portugal	62	148	47
Romania	35	207	43
Slovenia	50	214	43
Slovakia	38	163	35
Finland	54	363	60
Sweden	57	318	56
United Kingdom	57	225	50

Source: FAO 2019 (data for meat consumption is transferred from raw meat to meat intake by assuming a difference of 30% due to consideration of the bone portion etc.)

Other studies with a focus on world food availability and sustainable food production, such as the one from the EAT Lancet Commission (2019) recommend a lower protein intake from animal products in the range of 27 g/cap/day. The upper limit lies within the range of the WHO recommendation at approximately 50 g/cap/day, while the lower value represents a vegan diet with no animal proteins (see Table K 5).

Table K 5: Recommendations for meat and dairy intake from the healthy reference diet

	MIN g/day	MEAN g/day	MAX g/day
Whole milk or derivative equivalents	0	250	500
Beef and lamb	0	7	14
Pork	0	7	14
Poultry	0	29	58
Fish	0	28	100
Eggs	0	13	25
Total protein intake	**0**	**27**	**54**

Source: Willet, W. et al. 2019

National nutritional recommendations differ sometimes from WHO recommendations or Lancet Commission recommendation. Table K 6 shows nutritional recommendations from national authorities for selected MS. The recommendations for meat consumption show a similar range of about 500 g/week in all MS with the lowest level of 300 g/week/cap in Germany. Also for dairy products, recommendations from national authorities are in a common range. Most MS recommend the consumption of 50 – 60 g cheese and 200 – 250 g of milk or yoghurt. Only nutritional recommendations from Finland show a higher consumption of up to 600 g/cap/day fresh milk consumption.

Table K 6: National nutritional recommendations for animal products from selected MS

	Meat Products		**Dairy products**		
Country	**Quantitative**	**Qualitative**	**Quantitative**	**Qualitative**	**Source**
France	For those who like red meat, limit consumption to max. 500 g per week. For those who like charcuterie, do not exceed 150 g per week	Limit red meat consumption (beef, pork, veal, lamb, goat, horse, wild boar, venison) and favour the consumption of poultry. Limit the consumption of charcuterie, and favour boiled ham.	2 dairy products per day (can be increased to 3 in case of small portions). Portion: 1 portion = 150 ml milk, 125 g yoghurt, 30 g cheese.	Favour cheeses with the highest calcium content and less fat. Given the risks associated with contaminants, be sure to vary the dairy products.	Haut Conseil de la santé publique, 2017[28]
Germany	No more than 300-600 g of prepared meat and (low-fat) cold cuts per week. Portion: 100-150 g meat, 15-25 g cold cuts	Meat and sausages in moderation. Choose low-fat products. White meat (poultry) more favourable than red meat (beef, pork).	Every day, eat: 200-250 g low-fat milk and milk products and 2 slices (50-60 g) of low-fat cheese. Portion: 150 g fermented milk products, 1 glass of	Milk and dairy products every day. Prefer low-fat products.	Deutsche Gesellschaft für Ernährung, 2017[29]

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[28] https://www.hcsp.fr/Explore.cgi/Telecharger?NomFichier=hcspa20170216_reperesalimentairesactua2017.pdf
[29] https://www.dge.de/ernaehrungspraxis/vollwertige-ernaehrung/10-regeln-der-dge/

	Meat Products		**Dairy products**		
			milk, 1 slice of cheese = 30 g		
Spain	NA	It is not necessary to take meat every day. Several times a week is recommended.	NA	Dairy products are the basis of the diet and should be consumed daily.	Agencia Española de Consumo, Seguidad Alimentaria y Nutrición, 2008[30]
Roma-nia	2-3 servings of lean meat (preferably poultry) or fish, egg per day. Portion: 100 g cooked meat	Limit your intake of meat. Remove visible fat from meat and remove the skin from chicken. Include a variety of lean meat, poultry, pulses, eggs, fish. Limit your intake of liver or other organ meats. Choose fish or white meat over red meat.	2-3 servings of fresh dairy products Portion: A cup of milk or yoghurt, ½ cup cottage cheese, 50 g feta	Prefer low-fat products like skimmed milk.	Consiliul Directoral Societății de Nutrițiedin România, 2006[31]
Slovakia	0-2 portions of meat, fish and eggs per day. Limited portion for children 60-90 g. Red meat once per week.	Eat in moderation. Buy fresh, not frozen meat - limit fat content. Non-smoked meat products with reduced salt. Give preference to white, lean meat, fish.	2 portions of milk or dairy products daily. Portion: 1 glass milk (250 ml) or yogurt (150 ml) or 2 slices of cheese (50g)	Increase intake of skimmed milk, low fat yogurt and reduced fat cheese	Public health authority of the public, 2016[32]
Bulgaria	Consume poultry without the skin and lean red meats up to 3 times/week Portion 100g/serving	Replace meat and meat products with fish, poultry or pulses. Choose lean meat.	Consume daily a glass of yoghurt or milk (200 ml) and 50 g cheese. Portion: 200 ml milk/yoghurt and 50 g cheese	Choose milk and yoghurt with low fat content (1.5%) or skimmed milk (0.1-0.5%). Prefer fresh cheese, low fat cheese and curds to cheeses with high fat content. Prefer cheese and curds with reduced or low salt content.	Ministry of Health National Center of Public Health Protection, 2006[33]
Sweden	Not more than 500 g red and processed meat a week. Equivalent to 600-750 g raw meat	Eat less red and processed meat.	2-5 dl of milk or fermented milk a day is all you need to make sure you get enough calcium	Switch to low-fat dairy products! Choose low-fat, unsweetened products enriched with vitamin D.	Swedish National Food Agency, 2015[34]
Finland	Max. 500 g a week of red meat (cooked weight; raw weight = 700-750 g) Portion: 100-150 g meat (cooked weight)	Red meat (beef, lamb, pork): choose low-fat and low-sodium. Limit intake of red and processed meat products. Reduce the use of meat products and red meat.	5-6 dl of liquid milk products and 2-3 slices of cheese daily.	Prefer low-fat, select max. 1% fat content for milk, buttermilk, yoghurt, curdled milk. Use skimmed milk, skimmed buttermilk, non-flavoured or low sugar yoghurt. Max. 17% fat and preference to reduced salt content in cheese. If necessary can be replaced with V-derived drinks fortified with Ca and vitamin D, e.g. soy/oat drinks.	Finnish State Nutrition Advisory Board, 2014[35]

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[30] http://www.aecosan.msssi.gob.es/AECOSAN/docs/documentos/nutricion/Come_sano_y_muevete_12_decisiones.pdf

[31] https://www.spitalsmeeni.ro/docs/ghiduri/ghid_alimentatie_populatie.pdf

[32] http://www.uvzsr.sk/en/docs/info/Letak_Zdravy_tanier_EN.pdf

[33] http://ncpha.government.bg/files/hranene-en.pdf

[34] https://www.livsmedelsverket.se/globalassets/publikationsdatabas/andra-sprak/kostraden/kostraden-eng-a4-utskriftversion.pdf?AspxAutoDetectCookieSupport=1

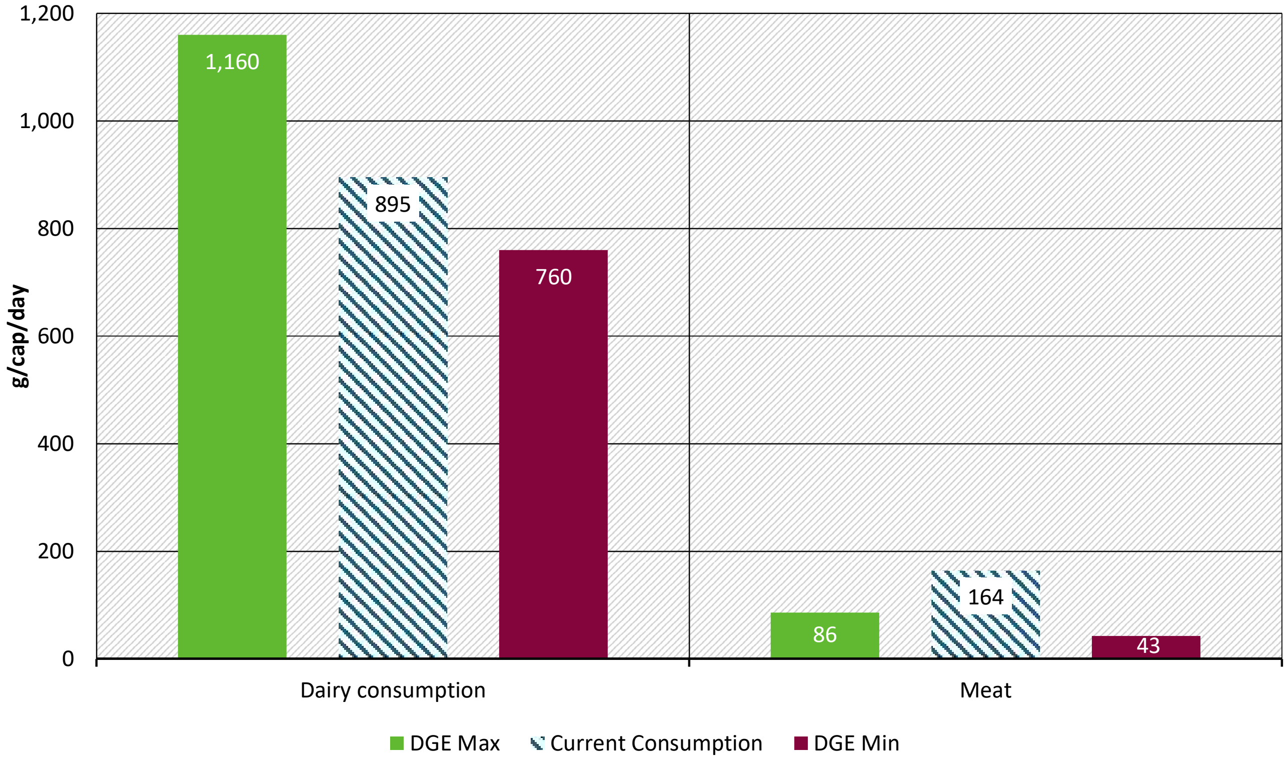
[35] http://aineisto.ruokavirasto.fi/evira20181231/www/globalassets/vrn/pdf/ravitsemussuositukset_terveytta-ruoasta_2014_fi_web_v4.pdf

Source: EU 2019c

None of the nutritional recommendations include a direct recommendation for the consumption of butter or cream. However, some MS might include recommendations for the consumption of butter and cream under the nutrition circle for oils and fats. Both the amount of fat consumed and its quality play a decisive role in the prevention of nutritional diseases. However, no quantitative limits are set for the consumption of butter and cream in this context. But from an environmental point of view quantitative targets would be particularly effective, since large milk volumes are required for the butter production. Butter therefore has a high CO2 footprint.

Figure K 4 shows the differences between the current consumption level and consumption level required according to nutritional recommendations for the example of Germany. It shows that especially for meat a reduction of the current consumption level is necessary to be in line with nutritional recommendations. The current dairy consumption is within the range of the nutritional recommendation. Thus a clear indication to trigger a further reduction of dairy consumption is not given.

Figure K 4: Differences between nutritional recommendations and current consumption for the example of Germany



Source: Recommendation of the German society for nutrition (DGE)

K.4 Scenarios and results

K.4.1 Dairy products

Production and consumption of dairy products are calculated based on the development of dairy cow numbers in the BAU scenario and in the GHG-neutral EU2050 scenario. For the High productivity (HP_2050) and for the fixed productivity scenario (FP_2050) the same number of dairy cows is assumed. Differences in the scenario are based on assumed milk yields per cow in 2050 (see Table K 1)

Table K 7 shows the development of dairy cows in comparison to 2016 for the different scenarios and in the representative groups in 2050. Development of dairy cow numbers in the BAU scenario is quite opposite to the development in the target scenarios (HP_2050, FP_2050) for 2050. In Group 1 the lowest reduction of dairy cows takes place in the BAU scenario, while in the target scenario the highest reduction of dairy cows takes place in Group 1. For Group 4 it is the opposite, a high reduction is already introduced in the BAU scenario, whereas in the target scenario the reduction that has to take place is the lowest among all groups. This is mainly due to the grouping of MS according to current dairy consumption patterns. Many MS with high dairy consumption belong to EU-15 MS with high production levels in the BAU scenario. In these MS reduction in animal stocks take places as a reaction of the lower consumption. Whereas most MS with low dairy consumption belonging to EU-13. In these MS milk consumption patterns do not change as drastically in the target scenarios as in the EU-15 MS.

Table K 7: Reduction in dairy cows in the GHG-neutral EU2050 scenario in comparison to 2016

	Group 1	Group 2	Group 3	Group 4	Total in comparison to 2016
Reduction in BAU in comparison to 2016	-3%	-8%	-9%	-9%	**-6%**
Reduction in HP_2050 and FP_2050 in comparison to 2016	-44%	-41%	-39%	-37%	**-42%**

Source: own calculation (Oeko-Institut)

K.4.2 Production of dairy products

Figure K 5 shows the dairy production in different scenarios in comparison to 2016. Most dairy milk is produced in MS in Group 1, followed by Group 2. In the BAU scenario all MS show an increase in dairy production even if dairy stocks are already decreasing[36]. This exemplifies the assumption that performance increases for milk production will take place in all groups for all MS. To achieve the EU's climate targets in 2050, dairy stocks have to be decreased by an average of 42% for EU 28 (see Table K 7). Thus, a drastic reduction in dairy production would take place in Group 1 and Group 2 in the scenarios HP_2050 and FP_2050, but also in Group 3 and Group 4 production would decrease. Due to higher milk yields the reduction in dairy production is not as strong in the HP_2050 scenario as in the FP_2050 scenario, where no yield improvements are assumed. Figure K 5 shows that the BAU scenario results in the highest production levels, which are inconsistent with EU targets, thus requiring the strongest reduction.

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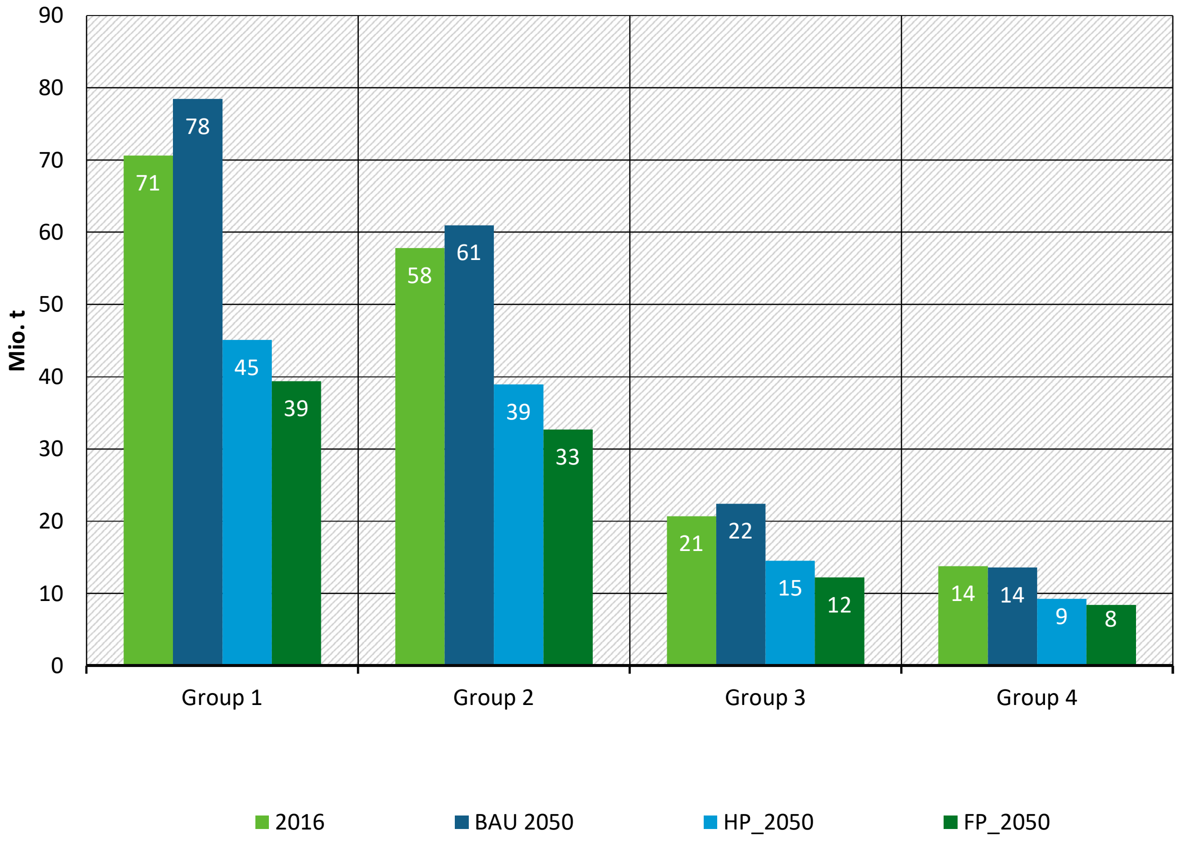
[36] According to the EU agricultural outlook dairy stocks in EU 15 will decrease by 3% and in EU-13 by 17%

Figure K 5: Production of dairy milk 2016 and in different scenarios in 2050

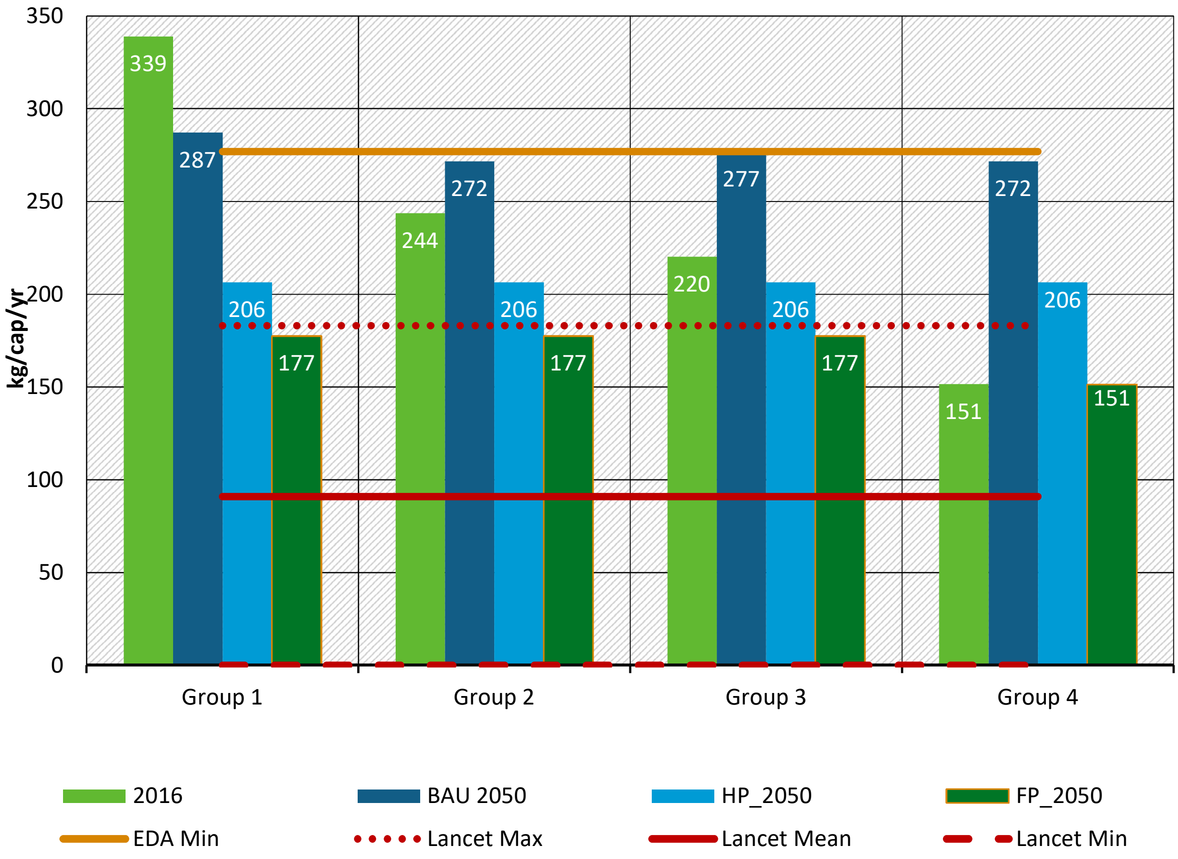


Source: own calculation (Oeko-Institut)

K.4.3 Consumption of dairy products

Figure K 6 shows that consumption of dairy products per capita are highest in Group 1 and Group 2. This shows the relation between high production levels and high consumption levels, as dairy production is also the highest in Group 1 and Group 2 (see Figure K 5). Dairy consumption per capita is lowest in Group 4, with very low production capacities due to a small dairy stock. This also reflects natural and climatic conditions in the MS. In Group 1 MS, dairy consumption is higher than EU average. Thus, based on scenario assumptions (see Table K 1), a reduction in dairy consumption takes place in Group 1 already in the BAU scenario. It is assumed that MS in all other Groups will increase their consumption to EU 15 or EU 13 average in the BAU scenario and consume more dairy products than in 2016. In comparison to 2016 and to the BAU scenario, MS of Group 1, 2 and 3 will have to reduce their consumption in scenario HP_2050 and FP_2050 to be in line with climate targets for the agricultural sector in 2050. With no increase in consumption above 2016 level, dairy consumption in MS of Group 4 represents a climate friendly diet, with lower consumption levels than in all other MS in FP_2050. Also in comparison to all other groups, MS of Group 4 could increase their dairy consumption in the target scenario HP_2050.

Figure K 6: Consumption of dairy products in 2050 in comparison to 2016



Source: own calculation (Oeko-Institut)

Note: EDA = European Dairy association

In addition to consumption per capita Figure K 6 includes information on the total amount of dairy consumption from different nutritional recommendations. The orange line includes the lower limit of the recommendation from the European Dairy association. It shows that dairy consumption in Group 1 in 2016 and in the BAU scenario is above the lower limit of the EDA recommendations. Consumption in all other groups is below the EDA recommendation in all scenarios.

The red lines in Figure K 6 represent the recommendation from the Eat Lancet Commission on dairy foods (whole milk or derivative equivalents – eg. cheese). According to the recommendation the maximum amount of dairy consumption should not exceed 500 g/cap/day. The lower limit is specified as zero and the mean with 250g/cap/day. In the higher productivity scenario (HP_2050) potential dairy consumption per capita is higher than the maximum value of the recommendation. For the fixed productivity scenario (FP_2050) the potential consumption is slightly lower than the maximum recommendation from the Eat Lancet Commission.

K.4.4 Supply balance for dairy products

Within the calculation of the GHG-neutral EU2050 scenario, MS specific dairy cow numbers are determined for the year 2050. In order to avoid strong economic distortions, reduction in livestock numbers took place in all MS. Table K 8 shows an overview on reduction in livestock numbers and reduction in consumption.

Table K 8: Reduction in livestock number and reduction in dairy consumption

	Group 1	Group 2	Group 3	Group 4	Total in comparison to 2016
Reduction in dairy consumption in FP_2050 in comparison to 2016	-48%	-27%	-19%	0%	**-33%**
Reduction in dairy consumption in HP_2050 in comparison to 2016	-39%	-15%	-6%	+36%	**-20%**
Reduction in animal numbers in HP_2050 and FP_2050 in comparison to 2016	-44%	-41%	-39%	-37%	**-42%**

Source: own calculation (Oeko-Institut)

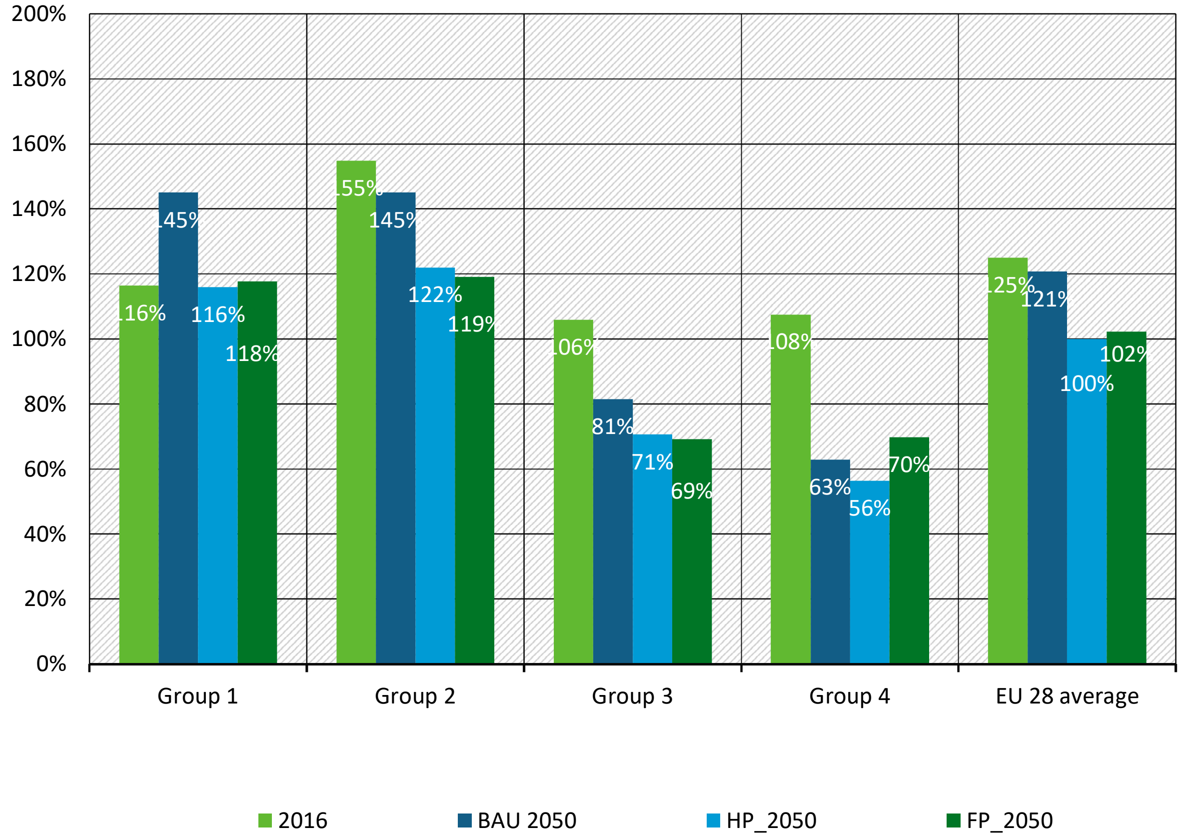
Overall, expected EU level reduction in dairy consumption is lower than reduction in livestock numbers. This is in line with the assumption that produced dairy products are primarily used to meet the inner European demand. This is also reflected in the supply balance of dairy products for EU-28 in Figure K 7, where self-sufficiency of dairy products decreases from almost 125% in 2016 to 100% in 2050 and production only covers domestic demand.

However, according to Table K 8 in Group 3 and 4 reductions in livestock numbers is higher than required reduction of consumption. This leads to a lack in self supply of dairy products in those MS as consumption exceeds the production (see Figure K 6). For MS in Group 1 and 2 it is vice versa. Production of dairy is higher than consumption. This is mainly caused by a sharp decline in consumption in order to achieve climate targets, but also due to higher exports in 2016.

Results show, that in order to achieve a well-adjusted supply balance in all MS, dairy stock in Group 3 and 4 should not be reduced by -39% and -37% (see Table K 7) in comparison to 2016, but by less. In return, MS of Group 1 and 2 would have to reduce their dairy production beyond -44% and -41% (for example by shifting to grassland based dairy farming).

Figure K 7 shows that with the dairy stock which was approved in the GHG-neutral EU2050 scenario, the MS of Group 3 and 4 are no longer able to meet their own dairy demand. Supply balance in Group 1 remains stable in comparison to 2016, while self-sufficiency in Group 2 decreases by almost 40% in the fixed productivity scenario (FP_2050) due to a stronger reduction in livestock numbers. However production level in Group 1 and 2 will remain higher than consumption.

Figure K 7: Supply balance of dairy 2016 and for different scenarios



Source: own calculation (Oeko-Institut)

K.4.5 Conclusion for dairy products

Overall, in order to reach 2050 climate targets a reduction of the dairy cow stock by -42% on EU average must be accompanied by a 33% reduction in dairy consumption. Export of dairy products outside the EU would no longer be feasible without further domestic reduction in consumption. All MS, except those of Group 4 have to decrease their consumption of dairy products until 2050 to be in line with climate targets for the agricultural sector. A helpful driver is the development and market launch of replacement products. Especially for the replacement of animal fats such as butter there are already corresponding replacement products available. A wide range of substitutes is now also available for the range of fresh milk products.

Based on the detailed analysis of coupling production and consumption of dairy products a recommendation that is in line with the climate targets of the GHG-neutral EU2050 scenario was set up. In comparison to current consumption, consumption of dairy products needs to be reduced by about 30% to comply with climate targets (see Table K 9). According to the estimated production level, consumption of dairy products in 2050 are almost in line with the maximum consumption value of the recommendations from the EAT Lancet commission. Recommendation from the Eat Lancet Commission for dairy products are thus in line with EU climate targets for the agricultural sector. Considering the mean value of the Lancet recommendation, both production and consumption could be further reduced. However, given the current high level of consumption and the development in the BAU scenario, this seems unfeasible. Table K 9 represents an overview on current consumption and future consumption of different dairy products. For future recommendations total quantity of produced milk was converted into different dairy products. The recommendations a) and b), which are in line with the scenario GHG-neutral EU2050, represent different variants of milk products that can be produced from the total quantity of milk produced. The recommendations of the Eat Lancet Commission were also converted into different products by way of example. The current consumption and the national nutritional recommendations were taken into account. Table K 9 shows that especially the current consumption of butter and cream needs to be reduced in order to comply with climate targets. Under the scenario assumptions, the future consumption of butter is only possible if the consumption of other milk products is further reduced. This is reflected in recommendation a) A consumption of 10 g butter per day is related to a reduction of 130 g fresh milk products and 15 g cheese per day in comparison to recommendation b), as this amount of milk equivalent is required in order to produce 10 g butter.

Table K 9: Comparison of current and future nutritional recommendations and consumption for dairy products

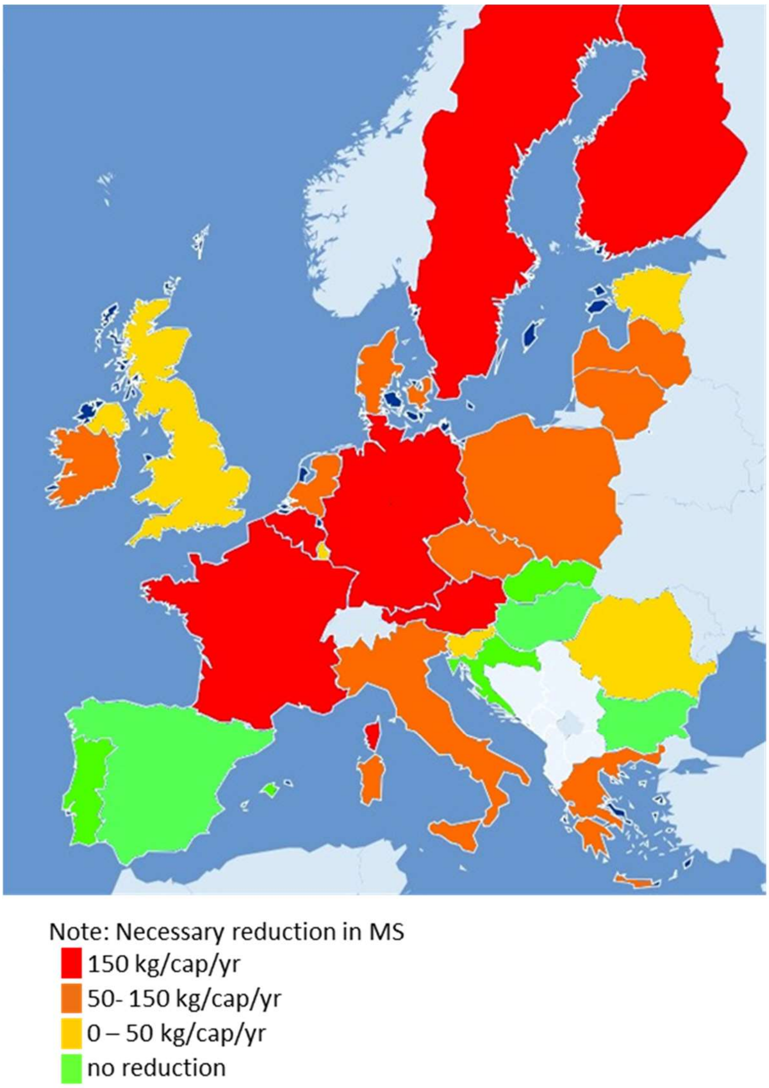
	Fresh milk products (including yoghurt) g/cap/day	Cheese g/cap/day	Butter and cream g/cap/day	Total milk consumption in milk equivalent g/cap/day
Current consumption EU average 2016	243	51	23	707
BAU scenario EU average 2050	236	55	24	762
European Dairy associations	650 - 975	40 - 90	n/a	760 - 1320
National recommendations	200 - 675	50 - 90	15 -30	760 - 1680
Recommendation in line with GHG-neutral EU2050 scenario (a)	160	25	10	487
Recommendation in line with GHG-neutral EU2050 scenario (b)	290	40	-	487
Recommendation EAT Lancet Commission* max	300	40	-	500
Recommendation EAT Lancet Commission* mean	150	20	-	250

Note. Production of 1 kg butter = 20 litre milk = 3.3 kg cheese = 24 litre yogurt

Source: European Commission 2018, own calculation (Oeko-Institut), *Buckwell & Nadeu 2018

Figure K 8 shows the necessary reduction for the groups of MS in dairy consumption. Especially in Northern MS consumption of dairy products is high, while in southern MS and MS in the south east consumption of dairy products is lower.

Figure K 8: Necessary reduction in milk consumption in the MS until 2050



Source: own representation (Oeko-Institut)

K.4.6 Meat products

Production and consumption of meat is calculated based on the development of cattle, pig and poultry numbers in the BAU scenario and in the GHG-neutral EU2050 scenario. For the high productivity (HP_2050) and for the fixed productivity scenario (FP_2050), the same number of animals is assumed, but carcass weight is higher in the high productivity scenario (HP_2050).

Table K 10 shows the development of animals in comparison to 2016 for the different scenarios for EU-15 and EU-13 in 2050. In the BAU scenario, reduction in animal numbers is lower for EU-15 than for EU-13, while in the target scenario livestock in the EU-15 needs to be stronger reduced than in EU-13.

Table K 10: Reduction in animals (cattle, pigs, poultry) in the GHG-neutral EU2050 scenario in comparison to 2016

	EU-15	EU-13
Reduction in BAU in comparison to 2016	Cattle: -3% Pig: - 9% Poultry: 0%	Cattle: -17% Pig: - 14% Poultry: + 1%
Reduction in HP_2050 and FP_2050 in comparison to 2016	Cattle: -45% Pig: -50% Poultry: -50%	Cattle: -30% Pig: -30% Poultry: -30%

Source: own calculation (Oeko-Institut)

K.4.7 Production of meat

Figure K 9 shows the meat production in different scenarios in comparison to 2016. Most meat is produced in EU-15 MS in all scenarios. In the BAU scenario all MS show an increase in meat production even if animal numbers are already decreasing[37]. This is due to increasing carcass weights per animal, both in EU-15 and EU-13 MS.

To achieve the EU's climate targets in 2050, ruminent stocks have to be decreased by an average of 42% for EU 28 (Table K 10) Thus, a drastic reduction in meat production would take place in most of the MS in the scenarios HP_2050 and FP_2050 Table K 8 shows that the BAU scenario results in the highest production levels for total meat, which are inconsistent with EU targets, thus requiring the strongest reduction.

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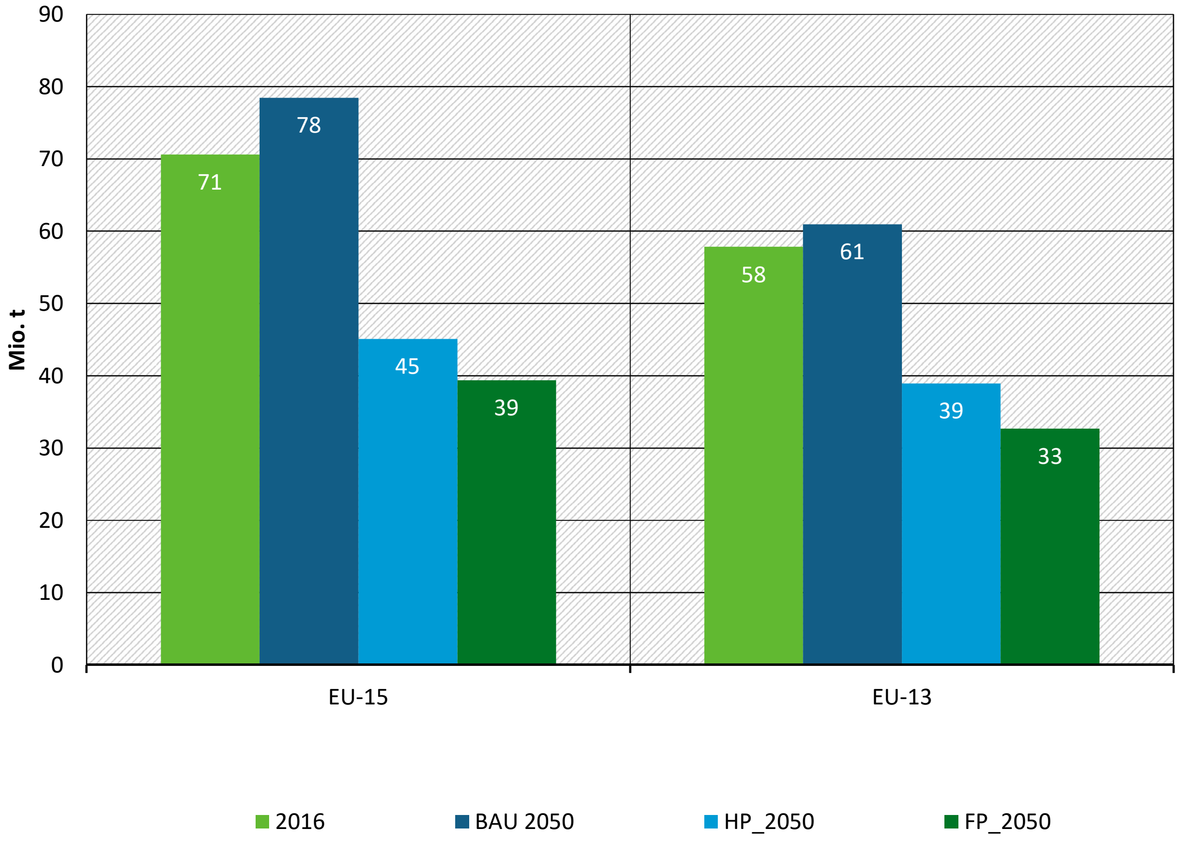
[37] According to the EU agricultural outlook dairy stocks in EU 15 will decrease by 3% and in EU-13 by 17%

Figure K 9: **Production of meat (sum of beef, pork and poultry) 2016 and in different scenarios in 2050**



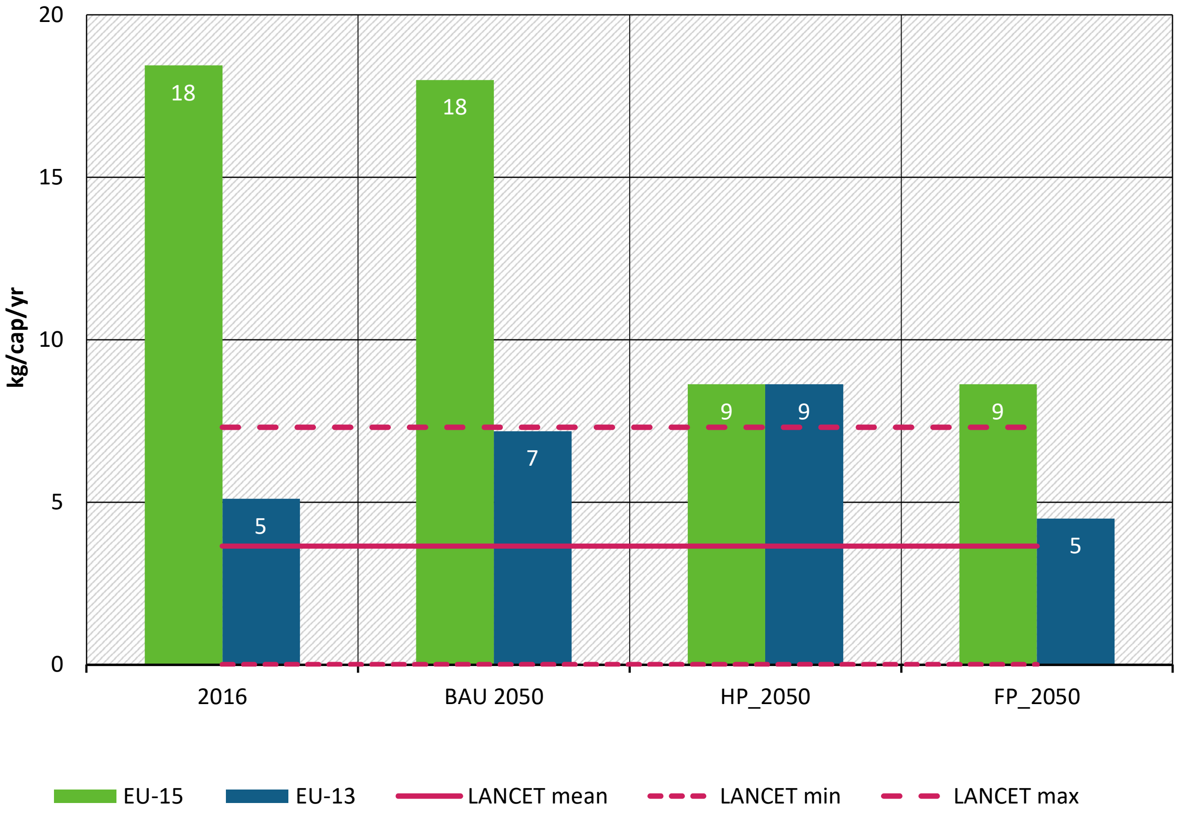
Source: own calculation (Oeko-Institut)

K.4.8 Consumption of meat

For coupling consumption and production data, data on meat consumption in this chapter is based on raw meat. This includes all the meat produced from the animal (including bones etc.) before it is cooked and prepared. About 70% of the raw meats are available for direct consumption.

Figure K 10 shows that consumption of beef per capita is three times higher in EU-15 than in EU-13. In the BAU scenario the latter shows a significant increase in consumption until 2050. In both target scenarios, the maximum consumption of beef is 9 kg per capita and year. This is the maximum amount of consumption which is derived from the production (production divided by consumption). The group of the EU-15 MS has to reduce its total beef consumption significantly, whereas EU-13 MS still have the possibility to increase their consumption. Only the lowest values of beef consumption (single MS in EU-13), are more or less in line with the medium recommendations of the EAT Lancet commission. All other scenarios have significant higher consumption than the Lancet commission recommended.

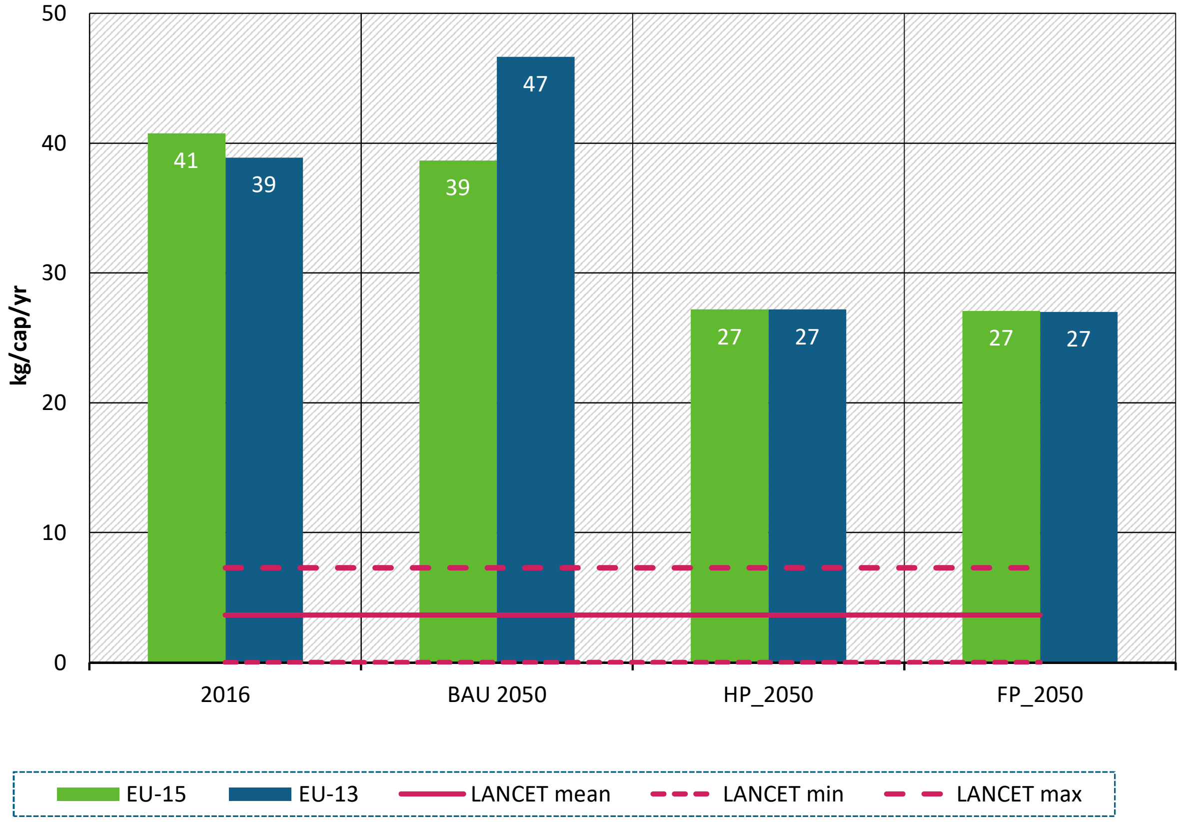
Figure K 10: Consumption of beef in different scenarios 2050 in comparison to 2016 in raw meat



Source: own calculation (Oeko-Institut)

Figure K 10 shows high pork consumption in all MS, which drastically increases in the BAU scenario. The maximum amount of consumption in the target scenario, which is derived from the production (production divided by consumption) requires a reduction of 10 to 20 kg/cap/yr. However, the consumption value in the target scenarios is far above the maximum values from the recommendations of the EAT Lancet commission for pork consumption. The dietary recommendation of the Eat Lancet commission is based on a high poultry consumption, which is accompanied by a low pork consumption. There are various arguments for this, one of which is that poultry meat is more efficient in terms of feed use.

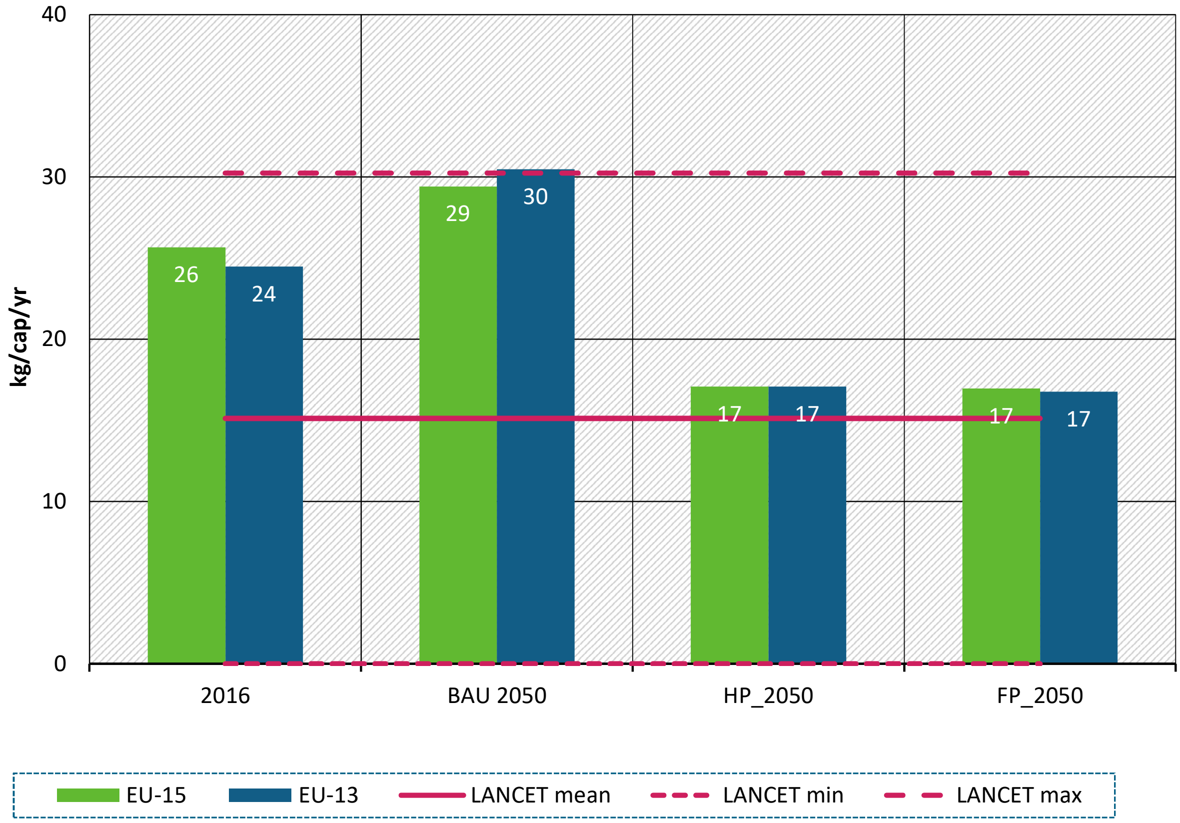
Figure K 11: Consumption of pork in different scenarios 2050 in comparison to 2016 in raw meat



Source: own calculation (Oeko-Institut)

Figure K 12 shows similar poultry consumption in all MS, which further increases in the BAU scenario. In comparison to all other meat types the increased consumption in the BAU scenario is in line with the maximum values from the recommendations of the EAT Lancet commission for poultry consumption. The maximum amount of consumption which is derived from the production (production divided by consumption) is more or less in line with the medium recommendations of the EAT Lancet commission.

Figure K 12: Consumption of poultry in different scenarios 2050 in comparison to 2016 in raw meat



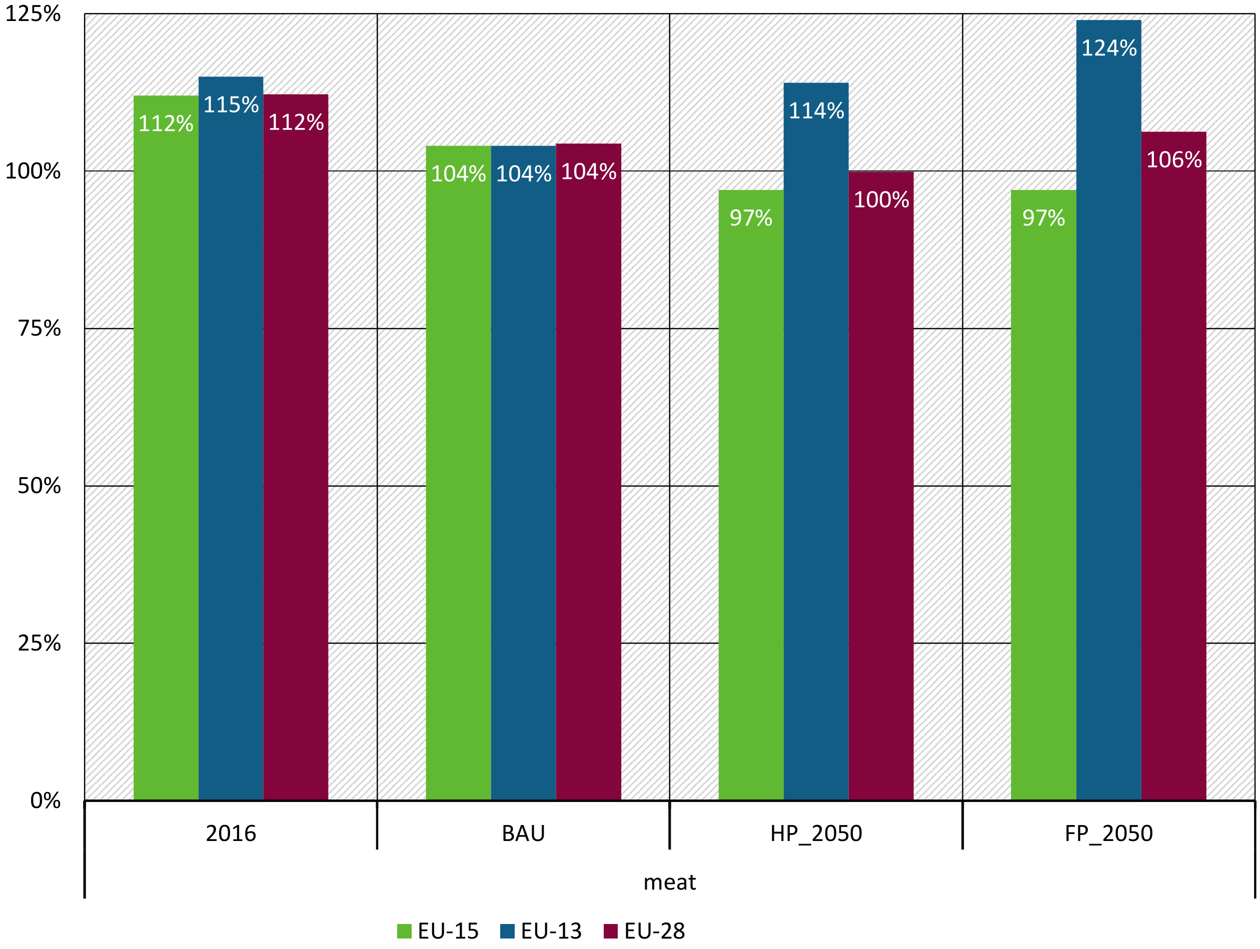
Source: own calculation (Oeko-Institut)

K.4.9 Supply balance for meat

Figure K 13 shows the development of the supply balance for total meat in the different scenarios. On average EU-28 is an exporter of meat in 2016 and in the BAU scenario. In the target scenarios self-sufficiency decreases from 112% in 2016 to almost 100% in 2050 and production only covers domestic demand. This is in line with the assumption that produced meat products are primarily used to meet the domestic European demand. Only in the FP_2050 scenario meat can be exported if consumption in MS with low meat intake remains at this low level until 2050.

While production of meat in the EU-13 MS is almost in the same range as for EU-15 MS (see Figure K 9), consumption is considerably lower. This is reflected in higher self-sufficiency in EU-13 MS in comparison to EU-15 MS in all scenarios. In the target scenarios self-sufficiency in EU-13 MS further increases, through a lower reduction in livestock in the GHG-neutral EU2050 scenario.

Figure K 13: **Supply balance for meat 2016 and in different scenarios**



Source: own calculation (Oeko-Institut)

K.4.10 Conclusion meat consumption

Table K 11 shows that current total meat consumption is well above climate-friendly consumption and is expected to increase further in the BAU scenario. It can be also seen that for a GHG-neutral Europe, the population must reduce its meat consumption. The present national recommendations (upper values) correspond to the recommendations which are in line with climate targets. The lower values correspond to the recommendations of the EAT Lancet Commission, which, in addition to climate targets, also considered other environmental aspects and the food security of the world population in 2050.

From a climate point of view, the recommendations for beef are the lowest for all types of meat. This is because cattle as ruminants have high emissions from enteric fermentation. Hence, current consumption of beef is too high, especially in the EU-15 countries. In the long term, more than a halving should be achieved here. In contrast to this, in the EU-13 countries there is still the opportunity to increase consumption. However, this should not be explicitly forced. Beef production should be better geared to milk consumption.

For pork and poultry, consumption is of the same order of magnitude for both, EU-15 and EU-13. For a climate-friendly diet, the consumption of pork meat in the EU-28 would have to be reduced by about 30% compared to BAU. For poultry meat, a reduction of around 25% would be necessary in the EU-28 to achieve climate targets. The recommendations of the EAT Lancet

Commission are significantly lower. This is mainly due to the fact that poultry meat is given preference over pork in their diets. There are various arguments for this, one of which is that poultry meat is more efficient in terms of feed use. In the present study it was assumed that people change their habits only slowly - this applies to both nutrition and agricultural production. This is the reason for the relatively high rates of pork in the diets within both scenarios, HP_2050 and FP_2050.

Table K 11: Comparison of current and future nutritional recommendations and consumption (in g of retail weight equivalent per capita and week)

	Beef g/cap/week	Pork g/cap/week	Poultry g/cap/week	Total meat g/cap/week
Current consumption EU-15 average 2016	237	530	308	1,075
Current consumption EU-13 average 2016	65	503	292	859
BAU scenario EU-28 average 2050	205	521	354	1,081
National recommendations*	?	?	?	300-600
Recommendation in line with climate targets	106	362	226	693
Recommendation EAT Lancet Commission* max	98	98	406	602
Recommendation EAT Lancet Commission* mean	49	49	203	301

Source: EU 2018, own calculation (Oeko-Institut), * Buckwell & Nadeu 2018

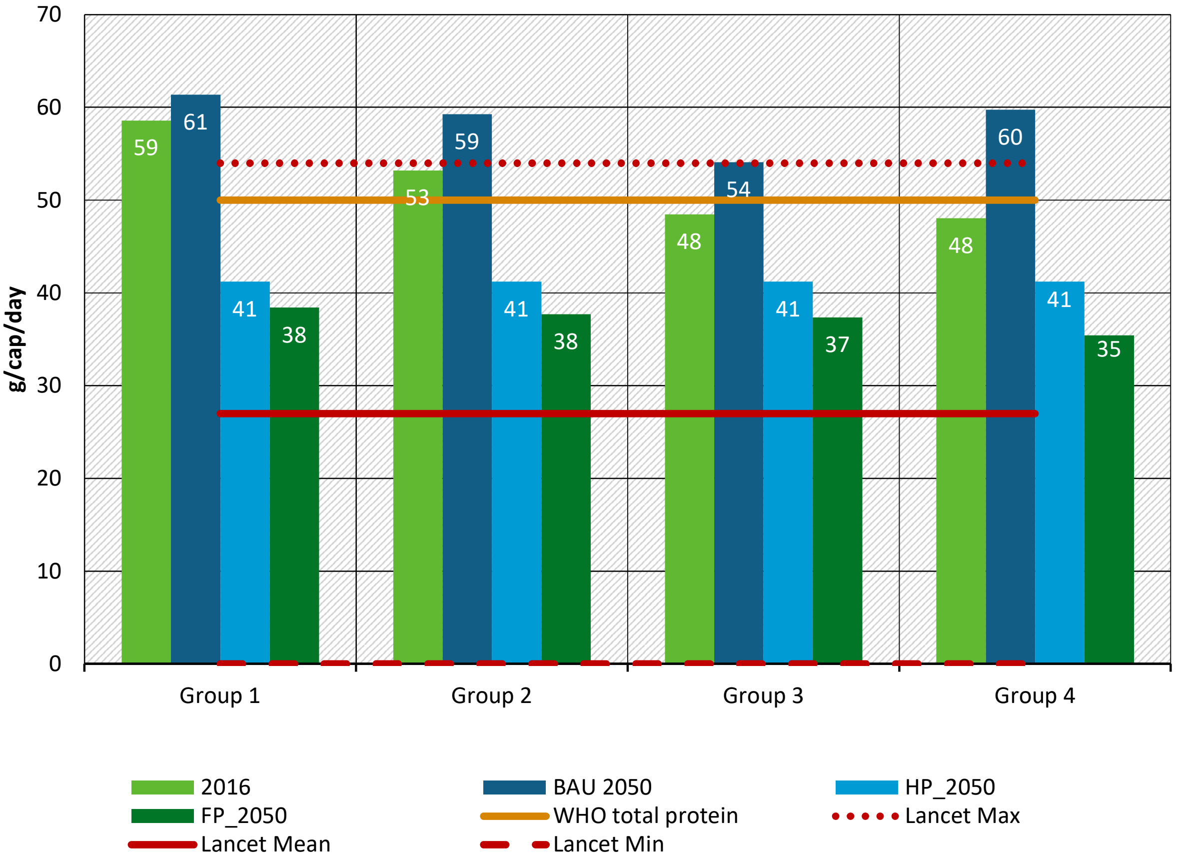
Again, it should be stressed that most MS already have national recommendations for meat consumption which comply with the principles of a climate-friendly diet (see Table K 6). However, people do not follow the dietary recommendations for meat and consumption levels are far above nutritional recommendations.

K.4.11 Protein intake by animal products

Figure K 14 shows the development of protein intake from dairy and meat consumption in the different scenarios. Similar to a further increase in consumption of dairy and meat products, protein intake increases in the BAU scenario. The further increase in the BAU scenario is inconsistent with nutritional recommendations and also with EU targets, thus requiring the strongest reduction in the target scenarios.

Protein intake in the scenario HP_2050 and FP_2050 is lower than recommendations from the WHO for total protein intake – minimum animal protein intake still meets 71% of total recommended intake which is not differentiated in vegetable and animal origin. And it is also lower than the maximum value from the EAT Lancet Commission recommendation – maximum undercoverage still meets 70% of recommended intake. However, the WHO value is only for total protein intake without any information on the distribution between vegetable and animal proteins. The value of the EAT Lancet commission includes also proteins from the consumption of fish and eggs, which are not considered in this analysis. In addition, the Lancet Commission gives a range of recommendations. Their lower value does not contain any animal proteins and corresponds to a vegan diet.

Figure K 14: **Protein intake from dairy and meat consumption 2016 and in different scenarios in 2050**



Source: own calculation (Oeko-Institut)

K.4.12 Conclusion

This analysis sheds new light on nutrition and shows the guard rail necessary for achieving climate targets. The scenario results show which effects the reduction of the animal population has on nutritional habits. In order to get in line climate targets with livestock and nutrition, a significant change in dietary habits is needed.

The results of the analysis are based on the assumptions of the GHG-neutral EU2050 scenario. In the agricultural sector one base assumption of this scenario is the reduction in livestock numbers. In consequence this must lead to changes in diet if the EU will not induce relevant imports of animal products which would lead to leakage effects. There are many possibilities with regard to the design of future food and agriculture. However, the scenarios considered here do not take into account a complete change in agricultural production and also in consumption habits. This is true for farmers with regard to the economic system and for consumers with regard to the change in consumption. Therefore, in in this scenario in the year 2050, farmers still produce pig, poultry and cattle similar to the current system only with fewer animals. And people still eat the same products from these animals but less. The reduced intake of these products must be compensated for. It is only assumed that alternative products are based on more efficiently produced food than classical animal products. This means that fewer plant products are needed for their production (e.g. vegetarian substitutes, vegetables, cereals, pulses, fish, in vitro products). Thus uncertainties remain. In the literature, only one similar study was found which links climate targets to livestock number and consumption (Buckewell et al. 2018), whereas the EAT Lancet study included several environmental aspects and also the important aspect of food supply of the world population in 2050. The results of this study with regard to dietary changes are similar to the one of our analysis. This shows that climate targets and nutrition goals could be compatible to each other. A change in diet that goes hand in hand with reduced consumption of animal products is necessary to achieve climate targets and, on the other hand, to ensure food supply for a growing world population.

Above all, the analysis clearly shows that compared to traditional dietary habits, the necessary changes are drastic in many EU MS. Furthermore, the climate-friendly diets are also not in line with today's nutritional recommendations, especially concerning milk consumption. Therefore, the official recommendations urgently need to be revised. Since behavioral changes are protracted, a change in dietary recommendations should be prompt and timely. Behavioral changes cannot be scouted and promoted as long as people think they are unhealthy. In the future, protein uptake via plant proteins will play a greater role in order to avoid critical shortage. However, it must also be emphasized that most MS already have national recommendations for meat consumption that are in line with the principles of a climate-friendly diet (see overview in Table K 6). As consumption – especially in the EU-15 – is significantly higher, there does not seem to be a clear link between dietary recommendations and consumption levels in reality. For the introduction of political instruments on the demand side, this means that besides an expansion of information and education, instruments of price control should also be introduced.

A helpful driver is the development and market launch of vegetarian replacement products, such as vegetable or in vitro meat and also vegetable milk or other milk substitutes. This should be further observed and promoted from two different points of view: First, the products are a real alternative from the perspective of the animal welfare discussion alone. Second, these products are particularly interesting as substitutes for milk and beef, as no technical solution for significantly reducing methane emissions from enteric digestion is yet in sight.

Whether a GHG-neutral Europe will be possible in 2050 depends to a large extent on whether we achieve the transformation in nutrition. If we succeed, the agricultural sector will adjust its production pattern accordingly, provided that decreasing demand is translated into decreasing production and not offered to the world market. For today's climate policy in the agricultural sector, this means that, in addition to production, it must primarily address demand side. This requires strong instruments to support a change in diet.

K.5 Relation to results of the role model for a GHG-neutral EU2050

The level of emissions from the agricultural sector is strongly linked to the agricultural production level by the underlying biological processes. According to the EU Roadmap (EU 2011), emissions from the agricultural sector are to be reduced by 42 – 49% compared with 1990 levels in order to achieve an overall reduction of 80% compared with 1990 levels. Further reduction will be necessary within a GHG-neutral world (Paris Agreement). Based on the settings of the GHG-neutral EU2050 scenario, emissions from the agricultural sector need to be reduced by 55% compared with 1990 levels. This will only be achieved through two mechanisms. On the one hand, a drastic change in consumption habits and, on the other hand, fewer exports of animal products due to reduced agricultural production in Europe. The detailed analysis shows the effects of the two mechanisms on production and consumption level of animal products and identifies consumption levels which are in line with climate targets and animal stocks. In relation with activity data from the agricultural sector from the GHG-neutral

EU2050 scenario, a nutritional recommendation for 2050 which is in line with climate targets for the EU Agricultural sector could be set up.

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L Detailed analysis of solution spaces for a GHG-neutral EU

L.1 Introduction

In this chapter, we analyse the solution space of the scenario GHG-neutral EU2050. This shows how the scenario compares to other studies, highlights possible alternatives in the different sectors, but also shows limitations to these alternatives. In order to take account of the different aspects, we follow two approaches.

The first section compares the scenario GHG-neutral EU2050 with other scenarios of similar ambition. Energy-related sectors are compared via a decomposition analysis. This allows to disaggregate the influence of different energy sources, fossil CO2 intensity, efficiency measures and other levers on the emission reduction. For the sectors related to land use and agriculture, such a disaggregation is not possible and we compare the descriptors directly.

Due to interdependencies between sectors, not all solutions are possible. The focus of the second section is therefore to highlight limitations due to the interaction between sectors. These interactions have been discussed in a workshop with experts in two groups, one with a focus on renewable fuels vs. material supply and one with a focus on novel fuels vs. energy efficiency and sufficiency. These expert discussions also serve to highlight points that require further research.

L.2 Solution spaces in comparison

One way to determine the range of possible solutions to the problem of GHG reduction is by comparison. Other studies have been carried out on the matter and these may serve as reference points to open up the solution space of the scenario presented in this report. Of course the differences between the scenarios come about not randomly or solely because of different methods but rather because of different underlying assumptions on future technologies, agriculture, consumption patterns and the overall organization of the economy. Nevertheless, a quantitative comparison of results between scenarios is a good starting point to span the solution space to the problem and relate it to the results previously presented here.

This section is split in two parts. The first covers those sectors whose GHG emissions are essentially caused by their use of energy and applies a decomposition analysis. The decomposed results of other studies have been presented in a companion study (Matthes et al. 2019). Here, they are compared with the current scenario.

The non-energy related sectors cannot be analysed by means of a decomposition analysis. Here, we compare our results directly with other values taken from literature.

L.2.1 Energy-related sectors

For several sectors, the GHG emissions are determined by their mix of energy sources. These are the power supply, industry, the tertiary and residential as well as the transport sector. These are analysed by means of a decomposition analysis and the results compared to decomposed results of other studies. In addition to the separate sectors, total primary energy supply is analysed. This section first gives a short introduction to this method before turning to the actual comparison.

The decomposition analysis applied here has also been used in a companion study to compare different scenarios for reducing GHG emissions (Matthes et al. 2019). This report presents the methodology in detail and only a summary is given here.

Building on basic concepts (presented in Kaya/Yokobori 1997), the emissions of one sector can be given by the following equation (also see Wachsmuth/Duscha, 2018).

$$E = A^{ref}\frac{A}{A^{ref}}\frac{G}{A}\frac{F}{G}\frac{E^{f}}{F} - C = A^{ref}agfe - C = \prod_{k} x_k - C$$

with

E	emissions of the sector
A	driving force of the sector in GHG-neutral EU2050
A^{ref}	reference driving force of the sector (from a reference scenario for most sectors)
G	energy supply to the sector
F	fossil fuel use of the sector
E^{f}	fossil fuel emissions from the sector
C	emissions captured and not emitted, referred to as *CCS* in the following
a	driving force relative to A^{ref}
g	energy efficiency
f	fossil fuel share in total energy supply
e	emissions intensity of fossil fuel use, referred to as *CO_2 intensity*
x_k	one of $A^{ref}, a, g, f,\ e$

The basic assumption is that these levers evolve independently of one another. Following (Xu/Ang 2013), the Logarithmic Mean Divisia Index (LMDI) method is applied to determine the additive contribution of each lever (except C) to total GHG emission reduction between two points in time, a final and the base year (2050 and 2015 in our case):

$$\Delta E_k = \frac{E^T - E^0}{\ln E^T - \ln E^0} \cdot \ln\left(\frac{x_k^T}{x_k^0}\right)$$

with

ΔE_k	(additive) contribution of lever x_k to the change in emissions
$0,\ T$	indices for values for the final and the base year

The influence of ΔC is not determined by means of LMDI, but directly from the difference of captured emissions between the final and the base year. The fossil fuel share to total energy supply (f) can be further broken down by giving it as difference of the total and all non-fossil energy sources:

$$f = 1 - r - h - n - l - s$$

with

r	share of direct use of renewables
h	share of use of district heating
n	share of direct use of nuclear energy
l	share of use of electricity
s	share of use of synthetic fuels

Each of these energy sources is considered to be free of emissions and its use is considered as an additional lever. The contribution of f to emission reduction then becomes:

$$\Delta f = \Delta r + \Delta h + \Delta n + \Delta l + \Delta s$$

Two steps are necessary to calculate the emission reduction of these levers. First, the difference in the share of each energy source relative to the difference in the share of all non-fossil energy sources is calculated:

$$\Delta\tilde{y}_j = \frac{\frac{y_j^0}{G^0} - \frac{y_j^T}{G^T}}{\frac{1}{G^0}\sum_j y_j^0 - \frac{1}{G^T}\sum_j y_j^T}$$

with

y_j one of r, h, n, l, s

$\Delta\tilde{y}_j$ change in share of energy source j relative to change in share of all non-fossil energies

This indicates the share this energy source has in the difference between the two years. These values are then multiplied onto Δf in order to arrive at the change in emissions due to changes in the use of the renewable energy source:

$$\Delta y_j = \Delta f \cdot \Delta\tilde{y}_j$$

In summary, the difference in emissions between a future year (2050 in the following) and a base year (2015 for GHG-neutral EU2050), can then be put down for each sector as follows:

$$\Delta E = \Delta A + \Delta a + \Delta g + (\Delta r + \Delta h + \Delta n + \Delta l + \Delta s) + \Delta e + \Delta C$$

The levers of the energy mix (Δr, Δh, Δn, Δl, Δs) are the same for all sectors. As stated above, ΔC will be referred to as *CCS*, Δe as *CO₂ intensity* and Δg as *energy efficiency*. The activity A differs for each sector and will be explained and named correspondingly. For most sectors, A^{ref} is the same as A, but taken from a reference scenario. In this case Δa is just a relative change in driving force. In case $A = A^{ref}$ for all years, $a = 1$ and $\Delta a = 0$, so the relative change in driving force (Δa) has no influence on an emission reduction. In case of total primary energy supply, population is used in place of A^{ref} and GDP for A, so a becomes GDP per capita.

In order to make different scenarios comparable, an inter-scenario adjustment is applied to rescale the different levers according to the change in activity relative to a common baseline. This is explained in the annex of the companion study (Greiner at al. 2019).

For all sectors, the results are discussed using a spider diagram. The emission reductions of each lever are presented as percentages of the emissions in the base year. This does not show the total reduction in GHG emissions but allows a comparison of different scenarios. The range of results of these other scenarios is given as a comparison. The reference scenario used in the analysis is the same as that used by Matthes et al. 2019, the EU Reference Scenario from 2016 (EU COM 2016) The range of ambitious scenarios that arrive at least at a reduction of 95% of GHG emissions (called *95% scenarios* in the following) is colored in green. The range of less ambitious scenarios with a reduction of 80-90% (called *80% scenario*) is given by two red lines indicating their extreme values. Values for the decomposition of the scenario presented in this study are indicated by a blue line and labelled *GHG-neutral EU2050*.

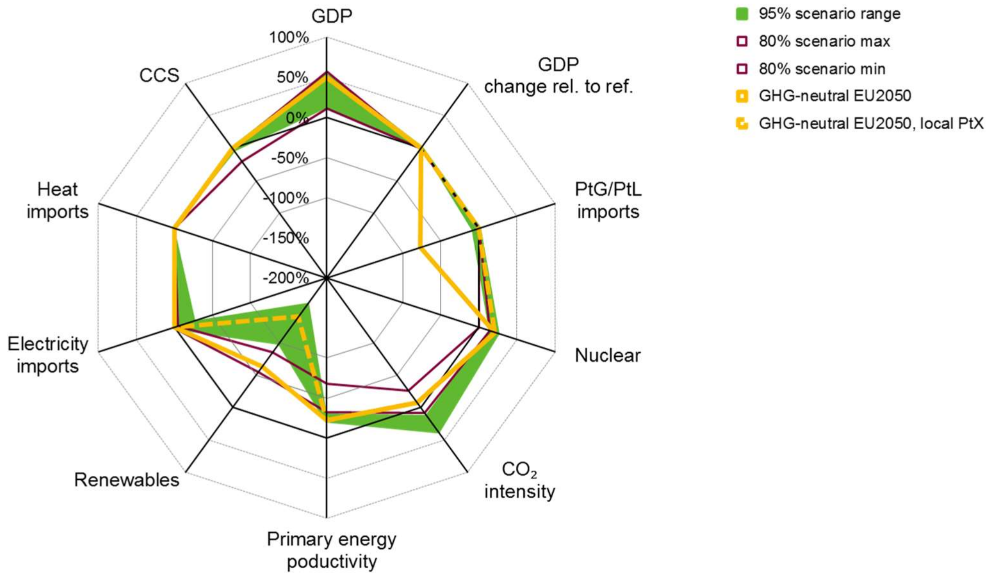
Some caveats of the method should not go unmentioned. A methodological point is that the levers are undefined if emissions go to zero. In order to circumvent this problem, a minimal amount of remaining fossil fuels with corresponding emissions must be assumed. For those sectors where emissions go to zero, the corresponding emissions are chosen in such a way that the effect of the lever fossil CO_2 intensity on emission reduction is marginal, as it has actually no meaning when fossil fuels are not used anymore. Also, as discussed by Wachsmuth and Duscha (2018), energy efficiency and CO_2 intensity are not independent. If no intermediate time steps are considered and the final emissions approach zero, as in our case, the method underestimates the contribution of energy efficiency. This is the reason why the contribution of energy efficiency to emission reduction appears smaller in the scenario GHG-neutral EU2050 than in the 95% scenarios and these in turn are associated with a smaller contribution than the 80% scenarios.

The following 95% scenarios have been analyzed: Advanced energy [r]evolution for Europe (Greenpeace 2015), the Vision Scenario for the EU (Matthes et al. 2018) and the KS95 scenario from the Climate Protection Scenario 2050 project for Germany (Öko-Institut/Fraunhofer ISI 2015). For the 80% scenarios, the following were analyzed: the High Efficiency, High Renewables, Delayed CCS, Low Nuclear and Diversified from the Energy Roadmap 2050 for the EU (EU COM 2011), the energy [r]evolution scenario for Europe (Greenpeace 2015), the 450ppm Scenario from the World Energy Outlook 2016 for the EU (IEA 2016), the KS80 scenario from the Policy Scenarios 2050 project for Germany (Öko-Institut/Fraunhofer ISI 2015), the Demand Reduction Scenario from the Deep Decarbonization Project for Italy (Virdis et al. 2015), and the Energy Scenario 2050 for Sweden (Gustavsson et al. 2011). All scenarios are described in the companion study (Matthes at al. 2019).

Total Primary Energy Supply (TPES)

The driving force of TPES is GDP and the population is used as reference value. Therefore, GDP per capita appears as additional lever. Figure L 1 shows results of the decomposition analysis for TPES, giving the contributions of each lever to total emission reduction. The results are shown for two alternatives. The solid line stands for results under the assumption that all novel fuels are imported, while the dashed line indicates results under the assumption of a production of novel fuels within the EU. All other levers are identical for these two variants.

Figure L 1: Contributions of different emission levers to the total emission reduction by 2050 for total primary energy supply



Source: Own representation (Fraunhofer ISI) based on data from Matthes et al. (2019)

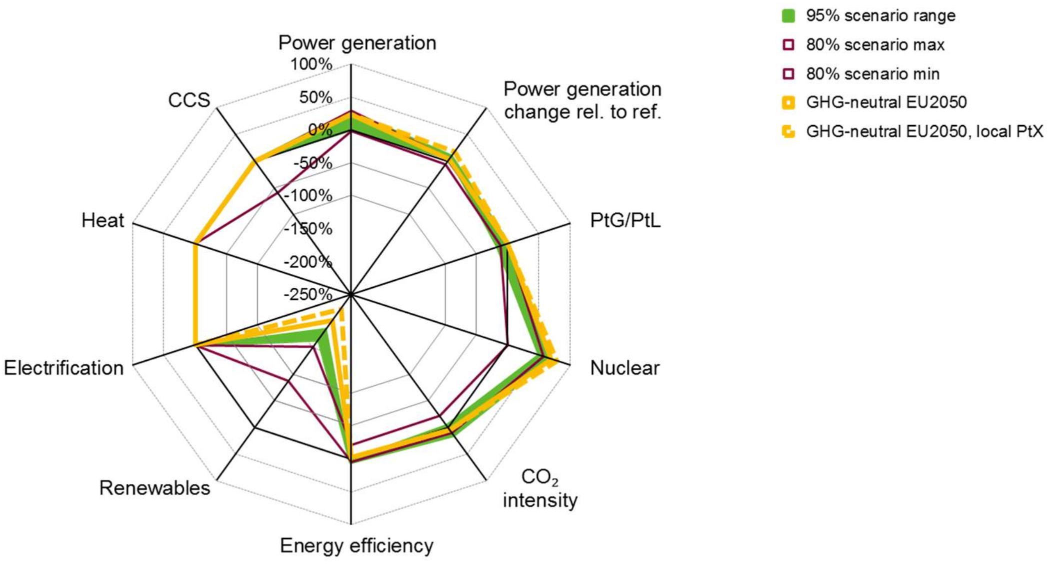
- The increase in GDP would by itself lead to an increase of emissions of slightly more than 50%-points of 2010 in the scenario GHG-neutral EU2050. There is no additional effect of GDP change relative to reference scenario. TPES is decarbonised by a rise in primary energy productivity, but mainly by the combination of renewable energy sources (electricity, biogenic and novel fuels) and eventually the import of novel fuels.

- In case novel fuels are produced domestically (dashed line), the emission reduction comes almost completely from increased use of renewables. If they are imported (solid line), this additional increase is not necessary. Interestingly, all other full decarbonisation scenarios (i.e. with a GHG reduction of about 95%) assume mainly a local production of renewable fuels (biogenic and/or novel fuels) and then need a higher share of renewables. If the novel fuels are imported, it is this import that leads to the largest difference between this scenario and the 80% reduction scenarios. The only other full decarbonisation scenario which assumes an import of novel fuels is the German KS95 (Oeko-Institut/Fraunhofer ISI 2015).
- The change in fossil CO_2 intensity is irrelevant for the scenario GHG-neutral EU2050 due to the full decarbonisation. Changes in nuclear energy have a slightly increasing impact on emissions due to the strong reduction of its use in 2050 in GHG-neutral EU2050, similar to all other scenarios analysed for the study. CCS technologies are hardly applied in the full decarbonisation scenarios. There is no import of heat and no import of electricity.
- In summary, the full decarbonisation scenarios show few alternatives on how to decarbonise total primary energy supply: as they all assume strongly limited use of nuclear power and CCS, renewable energies contribute the vast share of the emission reduction. However, there is large leeway with regard to a possible import of novel fuels.

Power supply

Figure L 2 shows results for the power supply. Here again, we consider two variants of the scenario, depending on whether novel fuels are imported or produced domestically. The latter requires substantially more electricity, see Section A.3.

Figure L 2: **Contributions of different emission levers to the total emission reduction by 2050 for power supply**



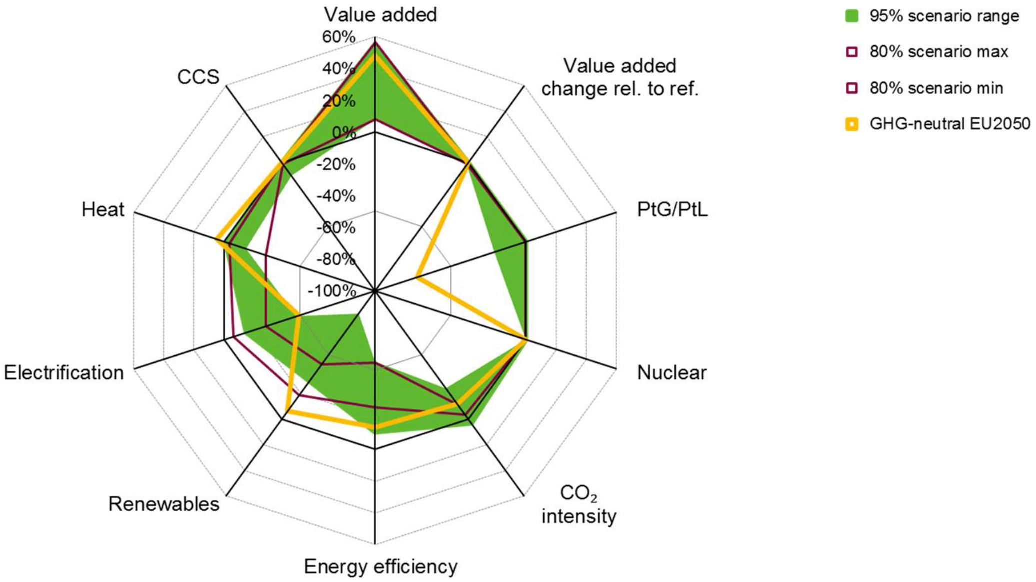
Source: Own representation (Fraunhofer ISI) based on data from Matthes et al. (2019)

- The increase in power generation (driving force) by itself would lead to an increase in emissions by 23%-points of 2010. Depending on whether novel fuels are produced domestically or imported, the additional increase in emissions in the scenario GHG-neutral EU2050 is 3%-points or 17%-points, respectively.
- The sector is decarbonised and the increase in emissions is compensated by a change in the energy supply. In total, the shift away from fossil fuels leads to a decrease in emissions by 108%-points compared to 2010. The two parts that make up this number are the strong increase in use of renewables and the fade out of nuclear energy. Emissions reduction by renewables is stronger if novel fuels are produced domestically. The phaseout of nuclear energy corresponds by itself to an increase of emissions of 69%-points of 2010 (78%-points if novel fuels are produced domestically). This additional increase must also be compensated for by an increase in renewables, which is why the scenario GHG-neutral EU2050 sees a slightly stronger reduction by renewables than any of the other 95% scenarios.
- The other levers do not apply to power supply: CCS is not used in any of the scenarios of higher ambition, and novel fuels play only a small role for power supply.
- In summary, there is little leeway for the decarbonisation of the power sector since all energy is provided from renewable sources. The necessary amount is determined by the phase out of nuclear energy and depends on the share of novel fuels produced within the EU.

Industry sector

Results for the industrial sector are shown in Figure L 3Figure L 3. Driving force is the value added in constant monetary values (EUR2013).

Figure L 3: Contributions of different emission levers to the total emission reduction by 2050 for the industry sector



Source: Own representation (Fraunhofer ISI) based on data from Matthes et al. (2019)

- The increase in the driving force (added value) alone would lead to an increase of GHG emissions, as for all other scenarios. The increase of added value in GHG-neutral EU2050 is assumed to be equal to that of the reference scenario, so there is no additional change of emissions from the driving force. There is a small increase from the use of heat, which is caused by the relative decrease of its use.
- The industrial emission level based on the driving force are mitigated by several measures to decarbonise the industrial sector. The strongest signal of emission reduction comes from the use of novel fuels, the use of which leads to a stronger reduction than in any other of the scenarios. Also strong is the reduction from the electrification of processes, which is just at the maximum of what the full decarbonisation scenarios assume. The direct use of renewables leads to a reduction of emissions, although by far not as much as in other scenarios due to the limited use of biogenic fuels. Improvements in energy efficiency are at the lower end of the full decarbonisation scenarios.
- There is no use of CCS in the scenario GHG-neutral EU2050. This is different to the other full decarbonisation scenarios, which assume a small emission reduction by CCS in this sector. The fossil CO_2 intensity is determined by the small process emissions that remain in this sector and need to be taken up by carbon sinks provided by other sectors.
- In summary, there is some leeway in industrial sector with regard to the combination of the levers electrification, energy efficiency, novel fuels, biogenic fuels and CCS. The scenario GHG-neutral EU2050 is at the upper end with regard to electrification and use of novel fuels, given that CCS is excluded and the use of biogenic fuels is strongly limited.

Transport

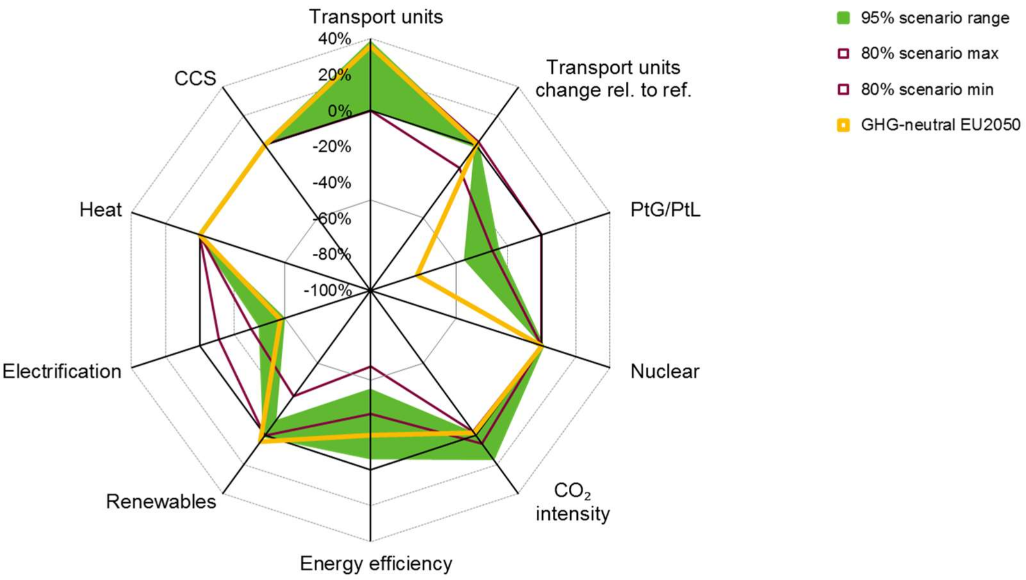
Figure L 4 presents results for transport. This includes passenger and freight transport. Driving force are transport units, which is the sum of person kilometers and one tenth of ton kilometers.

- The increase in transport alone, i.e. the driving force, would lead to an emission increase of just below 40%-points of 2010. This corresponds to the maximum of the other full decarbonisation scenarios. Scenarios with lower increases implicitly assume that the increase of transport demand is limited in one way or another. Again, there is no sectoral demand reduction in GHG-neutral EU2050, so there is no additional change in emissions. Only one 80% scenario sees a reduction in emissions through a change in demand.
- The sector is decarbonised and the increase in emissions due to an increase in transport activity is compensated mainly by use of novel fuels (notably for aviation and navigation) and electrification (mainly for road transport). While the influence of electrification is just within the range of the full decarbonisation scenarios, the use of novel fuels is stronger in GHG-neutral EU2050 than in any of the others. The emission reduction by energy efficiency is also within the range of the full decarbonisation scenarios.
- Heat, CCS and nuclear do not apply for transport and their influence on emissions is therefore zero. There is no direct use of renewables (biogenic fuels) in the transport sector in GHG-neutral EU2050, so this lever also has no influence. Since there are no remaining

emissions, the impact of the fossil CO_2 intensity is marginal, which is not the case in all other scenarios.

- In summary, there is substantial leeway in the transport sector with regard to the combination of the levers electrification, energy efficiency, novel fuels and biogenic fuels, but also with regard to a reduction of transport demand. The scenario GHG-neutral EU2050 does not make use of such a demand reduction. It is at the upper end with regard to electrification and use of novel fuels, given that the use of biogenic fuels in transport is excluded and electrification of heavy-duty vehicles via catenary lines is strongly employed.

Figure L 4: Contributions of different emission levers to the total emission reduction by 2050 for transport



Source: Own representation (Fraunhofer ISI) based on data from Matthes et al. (2019)

Residential sector

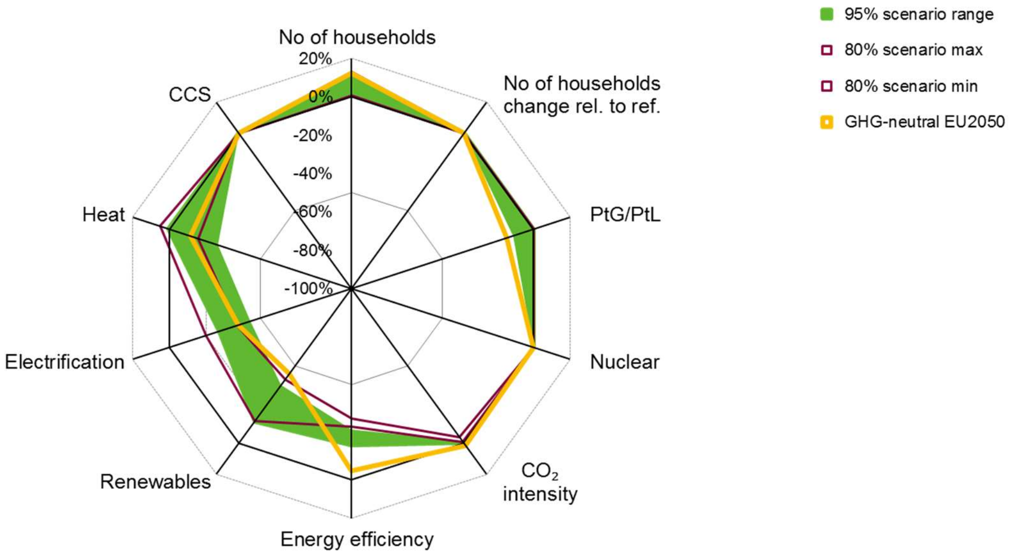
Figure L 5 shows the contribution of different levers on the emission reduction for the residential sector. This covers heating and cooling of buildings as well as the use of appliances and lighting. The sectoral driving force is assumed to be the number of households.

- There is an increase of 12% in the number of households by 2050 and this increase in activity by itself would lead to a corresponding GHG emission increase. There is no additional change of households in GHG-neutral EU2050, so no additional change in emissions from this lever. Nuclear does not apply, and there is no use of CCS in this sector, like in all other scenarios.
- The decarbonisation of the residential sectors relies in equal parts on electrification and an increased use of renewable energies (namely solar and ambient heat). In both cases, the scenario slightly exceeds the reductions of the other scenarios. The same is true for novel fuels, which are also used for heating. District heating sees a relative increase of its use,

which also aids in reducing emissions; the achieved reduction is similar to other studies. The improvements due to energy efficiency measures on the other hand are not as pronounced as in other scenarios.

- In summary, there is certain leeway in the residential sector with regard to the combination of the levers electrification, energy efficiency, district heating and direct use of renewables (solar and ambient heat). The scenario GHG-neutral EU2050 is at the upper end with regard to electrification and the direct use of renewables. Some scenarios assume a much higher annual rate of renovations which leads to a stronger reduction of emissions through energy efficiency.

Figure L 5: **Contributions of different emission levers to the total emission reduction by 2050 for the residential sector**



Source: Own representation (Fraunhofer ISI) based on data from Matthes et al. (2019)

Tertiary sector

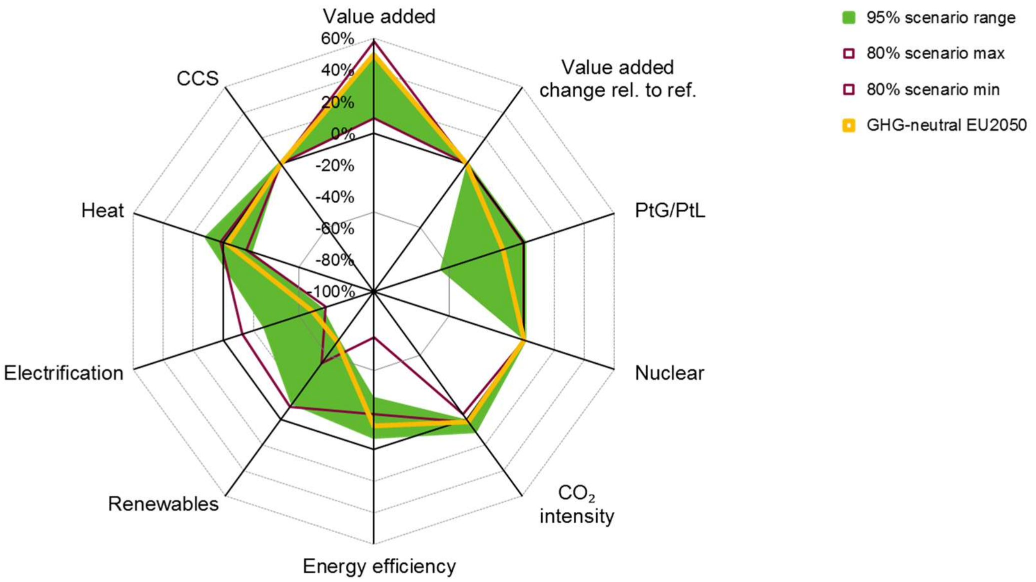
Figure L 6 presents results of the tertiary sector and gives the contribution of each lever to overall emission reduction. As for the residential sector, the results cover heating and cooling of buildings as well as the use of appliances and lighting. On the contrary, the driving force is assumed to be the value added in constant monetary value (EUR2013).

- The driving force of the tertiary sector (value added) leads by itself to an increase of emissions by 50%-points of 2010. This needs to be compensated in order to decarbonise the sector. There is no additional change of the driving force in GHG-neutral EU2050. Nuclear and CCS do not apply here, so they remain zero.
- In the scenario GHG-neutral EU2050, the emissions are partly mitigated by a relative increase in the use of district heating, but mostly by a strong electrification and direct use of

renewables (solar and ambient heat). Similar to the residential sector, their use leads to a relatively pronounced emission reduction when compared to the other scenarios.

- The remaining emissions are mitigated by the use of novel fuels. But the emissions decrease brought about by their use is on the low side of the full decarbonisation scenarios. .
- In summary, there is some leeway in the tertiary sector similar to the leeway in the residential sector. In particular, the scenario GHG-neutral EU2050 is at the upper end with regard to electrification and the direct use of renewables, while some scenarios assume a much higher annual rate of renovations with regard to the energy efficiency lever.

Figure L 6: Contributions of different emission levers to the total emission reduction by 2050 for the tertiary sector



Source: Own representation (Fraunhofer ISI) based on data from Matthes et al. (2019)

Summarizing Remarks

This section compared the emission reduction of those sectors whose emissions depend on the energy use from GHG-neutral EU2050 to other scenarios by means of a decomposition analysis. The following overarching points serve as a summary to the results.

- The effect of the driving forces is quite high for all sectors. For all but one sector, there is no change relative to the reference scenario. This shows that the scenario does not build on a reduction of activity. The only exception is power supply, for which an increase in the power generation compared to the reference scenario leads to an additional increase in emissions.
- There is a relatively strong use of novel fuels in all sectors (except for power supply). It is most pronounced in transport and the industry sector.
- Wherever possible, GHG-neutral EU2050 goes for a strong electrification. The power supply sector itself is decarbonised by use of renewable energy sources. Since the scenario also

assumes a complete phase out of nuclear energy, the increase in renewable energies needs to compensate for more emissions than in any other ambitious scenario.

- The residential and tertiary sector additionally see a relatively strong direct use of renewable energies, in parts more so than any of the other full decarbonisation scenarios.
- The emission decrease from energy efficiency partly differs from the other full decarbonisation scenarios. In the transport sector, it is well in the range, while in the residential and the tertiary sector, it is somewhat lower due to conservative assumptions about the rate of renovations. These findings have to be interpreted in the light of the methodological limitations of a decomposition analysis with vanishing emissions and without time-steps (see above). In particular, energy efficiency is rated lower in the scenario GHG-neutral EU2050, because it achieves a GHG reduction by 100%, while the other scenarios partly achieve only 95% reduction.

L.2.2 Agriculture and LULUCF

Emissions from the agricultural sector do not depend on the use of energy, but on other factors like animal numbers or the use of fertilizers. These factors in turn depend to a large part on the food consumption patterns and the amount of biomass used for energy or other purposes. In addition, the forest management and general distribution of land for different uses are important factors for the emissions of the LULUCF sector. It should also be noted that these sectors deal not only with CO_2, but also with large amounts of other GHG emissions, notably CH_4 and N_2O.

These factors are not linked to the use of energy and therefore, we do not apply a decomposition analysis. The comparison with other scenarios is still possible, but instead of comparing emission reduction of different factors, we compare the total sectoral emission reductions and the factors directly. Table L 1 summarizes the most relevant factors from the agricultural and LULUCF sectors for GHG-neutral EU2050 and three other scenarios of similar ambition. These are Scenario 4 of the study *Net-zero agriculture in 2050: how to get there?* (Lóránt/Allen 2019) and the scenarios *1.5TECH* and *1.5LIFE* of the EU Commission's long-term climate strategy (EU LTCS, see EU COM 2018b). While the former covers agriculture and partly LULUCF, the EU LTCS scenario describes a pathway to net-zero GHG emissions for all sectors of the economy.

Table L 1: Summary of important levers to GHG emission reduction from the agricultural and LULUCF sectors for GHG-neutral EU2050 and other, similarly ambitious scenarios

	GHG-neutral EU2050	Net Zero 2050, scenario 4	EU LTCS 1.5TECH	EU LTCS 1.5LIFE
Agricultural emissions	-44% (comp. to 2015)	-46% (comp. 2010)	-37% (comp. to 2005)	-48% (comp. to 2005)
LULUCF sequestration increase	+58% (comp. to 2015)	+35% only considering freed up agricultural land	+1% (comp. to 2016)	+48% (comp. to 2016)
Agriculture: driving assumptions	Reduce N-input to 30kg/ha. Increase organic farming to 20%. Reduce animal stock by 42%, with a focus on ruminants. No use of nitrification inhibitors of feed additives for CH_4 reduction. Reduce protein consumption to 50g/cap/day	Increase in efficiency by food waste reduction, improved waste management and increase of pasture fed animals (10% emission decrease). 75% reduction of meat consumption, ruminants make up 10% of meat. 10% overall reduction of calorie intake.	Increase productivity (amount per unit of land or animal) to reduce the necessary space. Adopt technology options (selective breeding, precision farming, adjusting water levels, nitrification inhibitors).	Same as 1.5TECH. In addition: Reduction of food waste and dairy and meat consumption by changing preferences.
Forestry: driving assumptions	Increase sink from afforestation by 10%. Cut deforestation emissions by 50%. Leave harvest rate at 70% of increment. Increase life time of wood products by 25%.	Increase forest share from surplus agricultural land.	Maintain forests as carbon sink mainly by forest management.	Increase carbon sink from forests by limiting deforestation and increasing afforestation.

Sources: own compilation (Fraunhofer ISI) based on Lóránt/Allen (2019) and EU COM (2018b)

The following points present a summary and comparison of the three scenarios, referring to the separate descriptions given in Table L 1:

- All scenarios other than 1.5TECH reach a similar reduction of GHG emissions in the agricultural sector. Central to all scenarios is the reduced consumption of dairy and meat products. This implies a reduction in animal numbers, which are stated in two of the scenarios. As 1.5TECH does not consider consumption changes, the reduction of GHG emissions in the agricultural sector are lower here.

- While GHG-neutral EU2050 argues for an increase in the share of organic farming, all other scenarios work with an increase in efficiency. While GHG-neutral EU2050 explicitly excludes the use of nitrification inhibitors and feed additives, the EU LTCS scenarios rely on these technologies, which are not fully market ready at least.

- The measures for LULUCF presented in GHG-neutral EU2050 are relatively detailed compared to the other scenarios. The combination of both other scenarios comes to a similar list as GHG-neutral EU2050. Central is the transformation of agricultural land that has been freed up to permanent other classes, mainly forests, with a focus on reducing the use of organic soils.

- The share of forests increases in all scenarios other than 1.5TECH, which strengthens the role of forests as a carbon sink. The increased lifetime of wood products, another measure to increase the amount of fixed carbon, is also discussed by the 1.5LIFE scenario.

L.3 Solution spaces from expert knowledge

The emission reduction reached in the scenario GHG-neutral EU2050 comes from a combination of different measures. These can be broken down into distinct parameter values chosen or calculated in the different sectors. Each of these values is associated with an uncertainty and within a certain range, there is some leeway to choose each value. But the different values are not independent, they rather influence one another. These inter-sectoral interactions are interesting to investigate in order to complement the detailed structure of each sector in GHG-neutral EU2050.

This section explores these inter-sectoral dependencies. The different parameters will be referred to as descriptors in the following. In a workshop held at Oeko-Institut in Berlin, Germany, on March 14, 2019, two group of experts discussed different descriptors and their interactions. The results of this discussion and conclusions are presented here.

The scenario GHG-neutral EU2050 can be described by close to 100 different parameters in eight sectors. In order to reduce the problem of discussing the interactions between all, two groups were formed, which focussed on different subjects. The focus of group 1 was summarized under the term 'resources' and the discussion centred on questions regarding novel fuels, biomass and the land use sink. The subject of group 2 was summarized as 'energy' and it was set to discuss subjects around novel fuels, energy efficiency and sufficiency.

This split allows to highlight different aspects related to novel fuels, which are an essential part of GHG-neutral EU2050. This also becomes clear by comparing this scenario with others by means of a decomposition analysis, see Sec. L.2.1. The split can also be understood between those sectors related to the use of novel fuels for energy purposes (group 2 with industry, transport, buildings) and those related to their production and use for material purposes (group 1 with the chemical industry, LULUCF, supply). The following two sections summarize the discussion and results of the two working groups.

L.3.1 Group 1: Resources – Novel fuels vs. Biomass vs. Land use sink

The first working group focussed on the interaction of the different sectors with regard to biomass and land use. This concerns mainly agriculture, LULUCF, industry and energy supply. In the discussion, the main descriptors of the scenario GHG-neutral EU2050 in these sectors were identified and their interactions were discussed based on a set of guiding questions:

- How large are the ranges with regard to land use changes and the use of biomass for energy purposes in scenarios with net-zero GHG emissions?
- Which interactions need to be reflected in the assumptions for land use change, material use of biomass and recycling of materials?
- Which leeway remain with regard to land use changes and the use of biomass for energy purposes in scenarios with net-zero GHG emissions in view of the sectoral interactions?

Table L 2 gives an overview of these descriptors. Considering the main subjects of the working group, sector-specific descriptors were structured under four categories: framework, resources, usage and products. In the following, these descriptors and their interactions are discussed by summarizing the points brought up during the workshop.

Table L 2: Main descriptors of GHG-neutral EU2050 discussed in the working group around resources: biogenic fuels vs. materials vs. carbon sinks

Descriptor category	Agriculture	LULUCF	Industry	Energy supply
Framework	Agricultural land	Woodland	Demand for wood products	Energy demand
	Animal stock	Wetland	Demand for basic chemicals	
Resources	Energy crops	Harvested wood	Waste wood	
	Manure	Harvest residues	Black liquor	
	Agricultural residues (straw, …)	Wood pellets	Waste plastics	
Usage		CO_2 sink	Materials	Energy carrier
Products			Wood products	Biogenic fuels
			Basic chemicals	

Source: Own compilation (Fraunhofer ISI) from workshop material.

Main framework drivers of both the GHG emissions and the available resources of the agricultural and the LULUCF sector are the shares of certain types of land uses, namely agricultural land, wetland and woodland. Wetlands are storing large amounts of carbon. Therefore, it is important to stop turning wetland into agricultural land and even more, the re-wetting of organic soils enables a large sequestration of carbon, thereby providing an additional carbon sink to compensate for unavoidable emissions. Climate change itself may have an important impact on the carbon sequestration of organic soils. However, this strongly depends on the region and has not been assessed in detail here.

Of course, the rewetting of organic soils also reduces the cropland in the agricultural sector. However, to reduce the unavoidable emissions from agriculture, it is necessary to reduce the animal stocks to a certain extent. This reduction frees up land resources, which can be partially turned into cropland to compensate for rewetting of organic soils. The remaining freed up land can be turned into woodland. This creates an additional carbon sink, which can partially compensate for the remaining emissions from the agricultural sector. This, hence, yields a synergy between agriculture and LULUCF:

There is an important trade-off between using woodland as a carbon sink and increasing the harvest rate in order to produce higher amounts of wood products, which can be used for energy purposes and thereby reduce the need for synthetic novel fuels. To ensure that carbon re-sequestered is sufficiently fast after harvesting of wood, it is necessary to make use of short-rotation coppices. These, however, come with the burden of additional fertilizer use, which may have negative side-effects on the soils.

Harvested wood is a high-quality material, which should therefore be used mainly for other purposes than energy. In particular, an increased use of wood in the construction sector has the benefit that the use of cement can be reduced and with it the process emissions of clinker production. In turn, harvest residues, waste wood from industry and also the residues of the paper industry, in particular black liquor, are valuable resources to produce biogenic fuels, which can be used both as a feedstock in the chemical industry and as an energy carrier. When biogenic fuels are used to produce basic chemicals, in particular plastics, these become carbon-neutral resources. Still, it is important to recycle also these bio-plastics to reduce the amount of feedstock from biogenic fuels needed.

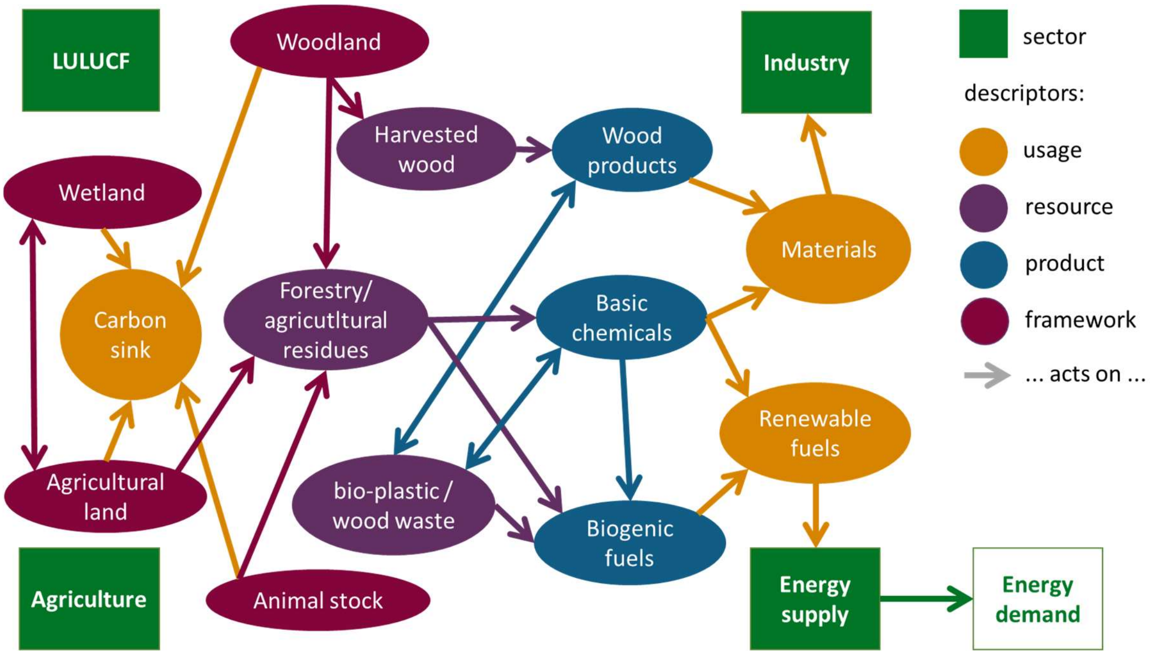
There is another important trade-off between agriculture and energy supply, namely the use of agricultural materials for energy purposes. Due to the interaction with international food markets, there are strong sustainability concerns with regard to growing crops dedicated to energy purposes (so-called energy crops). The scenario GHG-neutral EU2050 thus does not allow for using energy crops. Instead, manure and agricultural residues such as straw can be used to produce biogenic fuels. These can again be used both as a feedstock in the chemical industry and as an energy carrier. The reduction of animal stocks, however, also reduced the potential to make use of manure.

The described cascading use of resources from forestry and agriculture including a circular economy approach with recycling of wood waste and waste plastics fosters an optimized use of the available resources. In total, this helps to reduce the demand for renewable fuels both from the chemical industry and energy supply. In turn, it is necessary to produce lower amounts of novels fuels based on renewable electricity. This provides an important cross link to the interactions of the energy-related sectors described in the following subsection.

Important factors to keep in mind in the context of biomass and land use are the uncertainty about carbon sequestration rates of different types and ages of woods as well as the limited potential of afforestation due to land use limitations and a saturation of carbon sequestration of ageing forests. A possible of use of BECCS, however, is also limited by these aspects.

Figure L 7 presents a graphical overview of the interactions (as arrows) of the different sectors (in boxes) within the scope of different descriptors (in ovals).

Figure L 7: **Graphical representation of the interactions between sectors with a focus on materials vs. renewable fuels**



Source: own representation (Fraunhofer ISI) based on workshop discussion

The following points give a summary of the discussion of sectoral interactions concerning the sectoral interactions related to the use of biomass and land use:

- Framework conditions for the use of biogenic resources are given by the animal stock of the agricultural sector as well as the land use shares of woodland, wetland and agricultural land. These land uses are in direct competition. The land use splitting also has a direct impact on the natural carbon sink. While an increase of woodlands and wetlands serves as an additional carbon sink, the animal stock (in particular bovinal) entails additional non-CO2 emissions, which have to be compensated by carbon sinks.
- As the carbon sink needs to be restored and increased, the use of biogenic products is strongly limited. Therefore, the use of biogenic products should follow a cascading approach. Harvested wood of high quality is meant to be used as a material in the industry sector mainly, neither as a feedstock for basic chemicals nor as an energy carrier.
- Forestry and agricultural residues (including manure) can be a major input to meet the feedstock demand for basic chemicals. If there is a surplus of those residues, they can also be used for energy purposes directly, in particular to produce renewable fuels. Bio-plastics waste and wood waste should be recycled if possible, but at the end of their lifetime can serve to produce renewable fuels as well.
- The cascading use of biogenic resources enables an optimized use, thereby reducing the need for novels fuels as a feedstock for basic chemicals and for energy purposes.

L.3.2 Group 2: Energy: Novel fuels vs. Energy efficiency vs. Sufficiency

The discussion of the second working group considered the interaction of different sectors around novel fuels, energy efficiency and questions of sufficiency. This concerns sectors whose GHG emissions depend on their use of energy. With the experts present at the workshop, the discussion focussed on the industrial, transport and building sectors.

At the beginning of the discussion, the main descriptors of GHG-neutral EU2050 in these sectors were identified. Table L 3 gives an overview of these descriptors. Considering the main subjects of the working group, sector specific descriptors were found and grouped into three categories: energy efficiency, fuel switch and sufficiency. Apart from these points, the discussion group also identified three overarching framework descriptors. In the following, these descriptors and their interaction are discussed by summarizing the points brought up during the workshop. Figure L 8 presents a graphical overview of the interactions (as arrows) of the different sectors (in boxes) within the scope of different descriptors (in ovals).

Table L 3: Main descriptors of GHG-neutral EU2050 discussed in the working group around energy: novel fuels vs. energy efficiency vs. sufficiency

Descriptor category	Industry	Transport	Buildings
Framework	Availability of energy infrastructure		
	Availability of renewable electricity		
	Availability of biomass / electricity based hydrocarbons		
Energy efficiency	Early exchange of installed technology	Increased technical efficiency	Higher renovation rate
	Product and material substitution	Better use of capacity for freight transport	Higher renovation depth
	Higher material efficiency	Choice of transport mode: personal vs. shared vs. public	Ambitious standards for new buildings
Fuel switch	Change of processes, electrification	Electric mobility	Heat networks
	H_2 for processes and energy	H_2 and fuel cell technology	Heat pumps and geothermal heating
	Synthetic fuels for processes and energy	Use of synthetic fuels	Solar heating
Sufficiency	Sustainable consumption	Better use of capacity in and reduction of personal transport	Reduction of the available space/person
	Circular economy		

Source: Own compilation (Fraunhofer ISI) from workshop material

The descriptors of energy efficiency are relatively independent between sectors. Those of the industrial sector center around an exchange of processes in order to use less energy for the same products and an increased material efficiency (less material use with equal results). The descriptors of the transport sector rely on an increased technical and usage efficiency, while those of the buildings sector point out the need for ambitious renovation standards and renovation activity. Despite these very different subjects, the use of materials is an area of interaction. The renovation of buildings can serve as an incentive to substitute material or change processes in the industry. Similarly, the improvements of technical efficiency in transport may act on the material efficiency in industry. By their nature of dependency on the industrial sector, the transport and building sectors therefore provide a lever of influence if the correct incentives are set. This is indicated in Figure L 8 by the one sided arrows of buildings and transport acting on industry.

The descriptors collected under the term fuel switch are much more interlinked, since they partly rely on the availability of the same fuels. In industry, it is again the change of processes, including the use of H_2 or synthetic hydrocarbon fuels, which determines the reduction of GHG emissions. The same fuels could be used in transport, where the direct use of electricity is another important and partly alternative descriptor. The use of the same fuels could lead to synergies in the development of both sectors. A market success of novel fuels in transport may make it an affordable option for industry. In this respect, the extensive use electricity for transport could hinder the use of novel fuels in the industry. These interactions are indicated in Figure L 8 by the double arrows linking the respective sectors. However, it was pointed out by the working group that these aspects require detailed modelling, since these supposed technological synergies may be cut off by an increase in the price if the synthetic fuels are not available.

The buildings sector seems separate from transport and industry, because of its focus on a switch in technologies towards direct use of renewable energy sources, such as solar and geothermal heat. But this technological switch may become slower if novel fuels become available at cheaper prices. This closely links this development to the other sectors. But again, a discussion of these interactions alone does not suffice to consider all economic and policy aspects that determine the actual sign of the interaction. It rather requires a detailed modelling study that includes all three sectors and possibly other sectors.

The need for investment and technological change can be limited by adapting the behaviour towards a more sustainable lifestyle and incorporating sufficiency measures. Each of the related measures would lead to a reduction of GHG emissions in their respective sector. This makes sufficiency a powerful lever on GHG emissions. An overarching concept partly related to sufficiency is the establishment of a circular economy, which has an influence on all sectors. It was also pointed out by the working group that the awareness for sufficiency measures in one sector may also bring about sufficient behaviour in other sectors. Figure L 8 therefore puts sufficiency at the centre of the three sectors, acting on each of them and possibly on itself. This is, however, debatable as sufficiency in one area of life could also be seen to legitimate non-sufficiency in others. These effects therefore also require further studies.

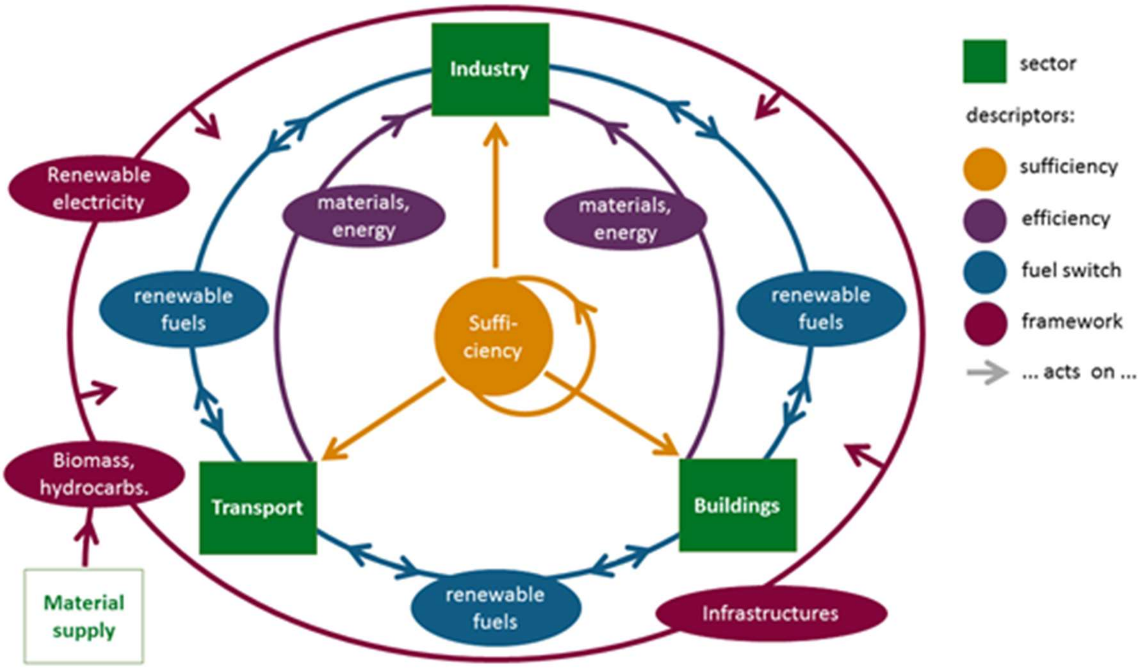
Interactions between categories within one sector were not discussed by the working group, as these are covered by the sectoral modelling and the sectoral ranges, identified in the decomposition analysis (see Section L.2). These were seen as manifold and quite apparent, e.g. ambitious renovation standards may promote the use solar or geothermal heating or innovations in mobility may account for a fuel switch as well as energy efficiency increases. Also not discussed was the rebound effect - i.e. an increased usage due an increased availability, which may compensate the gains brought about by gains in energy efficiency.

Both technical descriptor categories (energy efficiency and fuel switch) are strongly influenced by three overarching descriptors of energy supply: the availability of renewable electricity, of adapted energy infrastructures and of biomass or hydrocarbons for their transformation into heat and synthetic fuels. These overarching descriptors limit or enable change in any of the sectors. The availability of biomass also closely links the discussion around energy to that of resources in the other working group, see Section L.3.1.

The following points give a summary of the discussion of sectoral interactions concerning the use of energy. Figure L 8 presents a graphical interpretation of the interactions between sectors.

- While the energy efficiency improvements in the different sectors require separate technologies and policies, buildings and transport could stimulate industrial material and energy efficiency increases and process changes because of their dependent nature. E.g., an increase in energy-efficient renovation activity would stimulate an increase in demand of material, which could be covered by low-carbon cements if the correct incentives are set.
- The availability of novel fuels to one sector could increase its use in others and influence the transformation to alternative technologies. On the other hand, prices for novel fuels could increase if all sectors increase their demand. This affects all three sectors discussed in this working group. However, the exact implications cannot be discerned by a discussion alone, but rather requires a detailed modelling study.
- Sufficiency measures are a powerful lever on the transformation of all sectors. It influences all sectoral descriptors as well as the characteristics of the larger scale concept of a circular economy. Whether or not sufficient behaviour in one sector implies similar changes in another sector and how to foster these changes requires further investigation.
- The availability of energy infrastructures and renewable energies are overarching levers required for the transition in the different sectors. The investment into infrastructures requires detailed assessment to prevent technological lock-ins.
- Biomass or other sources of carbon are necessary to synthesize hydrocarbons. This closely links the discussion presented here to that of resources and the land use sink presented in Section L.3.1.

Figure L 8: Graphical representation of the interactions between sectors with a focus on novel fuels vs. energy efficiency vs. sufficiency



Source: Own representation (Fraunhofer ISI) based on workshop discussion

L.4 Summary

This chapter discusses the solution space of the scenario GHG-neutral EU2050. Each subsection gives an extensive summary of its own, which is not repeated here.

Overall, the chapter shows that the scenario fits well into the range of others similar studies. Some special characteristics include the fact that no activity reductions are taken into account. In the fully decarbonised scenario, this leads to a relatively high share of novel fuels as energy carrier and this in turn has implications on all other sectors. It increases the necessary renewable energy capacity but in turn also requires the supply of materials. To what degree the use of novel fuels in different sectors increases or decreases the availability requires further research. The materials to synthesize novel or renewable fuels are in part supplied by the agricultural and LULUCF sectors. In this respect, there is competition with other uses of biomass, e.g. the supply for direct use for energy supply but also in the form of wood products, which have the chance of long-term storage of carbon. In the agricultural sector itself, the scenario is in tune with other studies in that a reduced consumption of meat and dairy products is unavoidable. Land freed up from this process needs to be converted to permanent carbon sinks, with a focus on forests and rewetting organic soils.

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