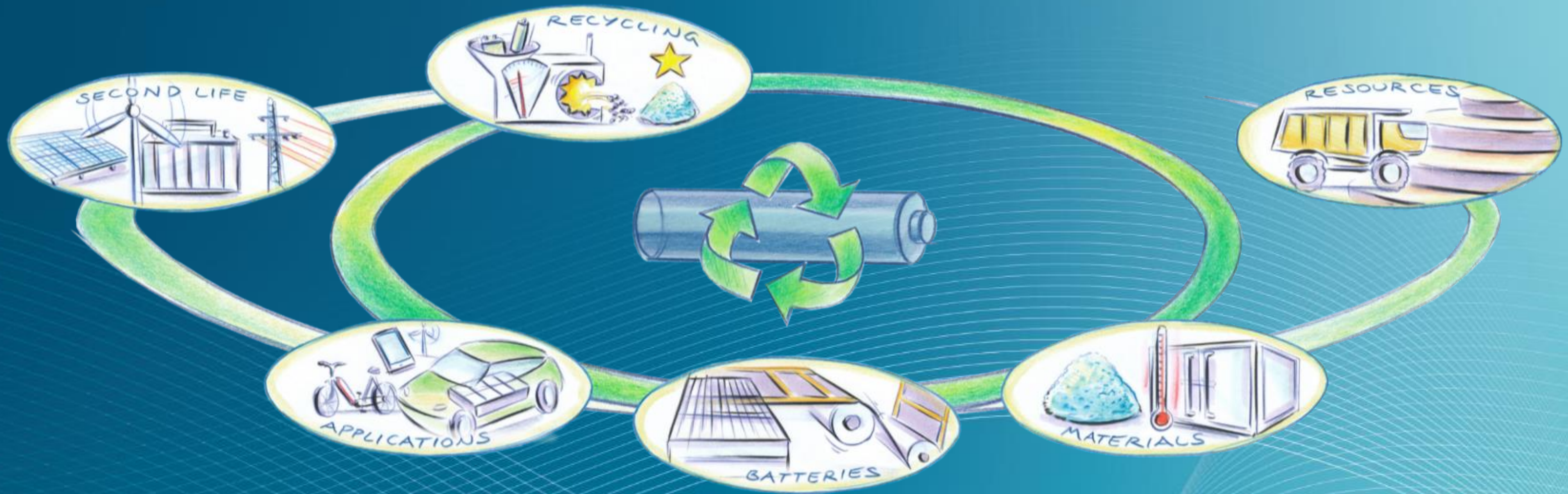

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Fraunhofer Institute for Systems and Innovation Research ISI

Dresden Battery Days 2023 – 26th September

Sustainability pathways in a future European battery ecosystem

Dr. Axel Thielmann

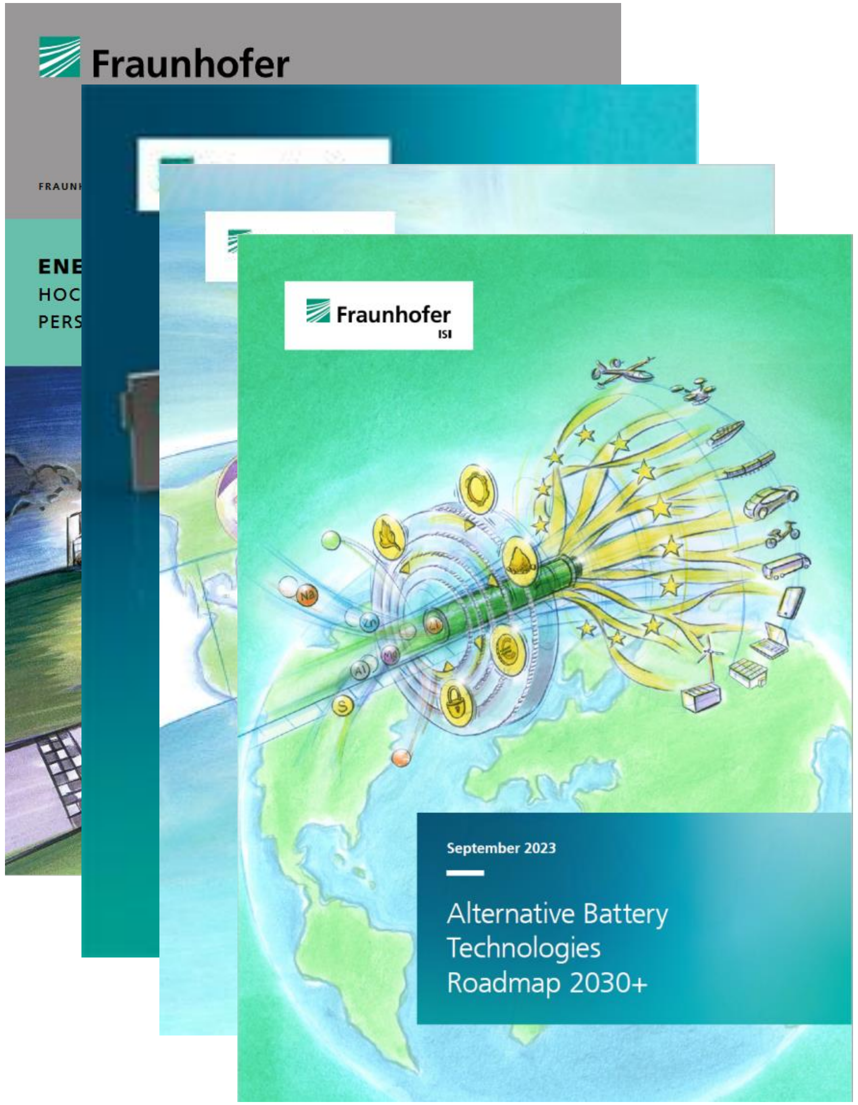
Battery research at Fraunhofer ISI

Technology and market intelligence

- Data based approach for technology and market modelling, e.g. FhISI LIBDB, xEVDB, CELLtool

- Since 2010: Technology and application specific roadmaps, e.g. LIB, eMobility, stationary
- 2017: High-energy battery roadmap
- 2022: Solid-state battery roadmap
- 2023: Alternative batteries roadmap
- 2023/24: High-energy battery roadmap

- 2016-2023: Battery production equipment roadmap jointly with VDMA



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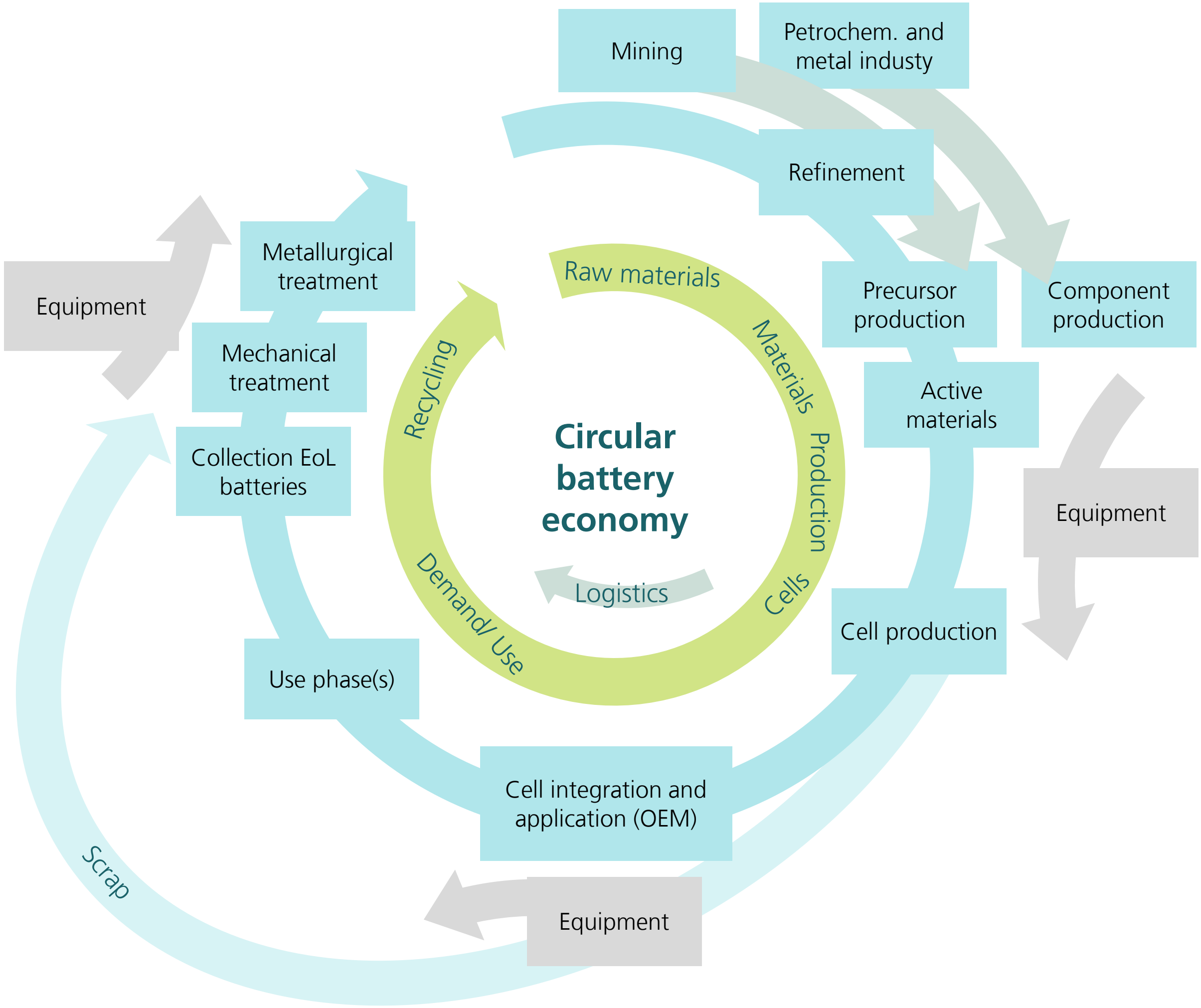
The circular battery economy

Structure of a global value creation chain

1. Raw materials and recycling
2. Battery materials
3. Battery cells and production
4. Demand and use
5. Logistics and localisation
6. Alternative battery technologies



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Sustainability impacts along the battery value chain

Towards a common frame for assessment

Scope:

- Not EV vs. ICE (decided in favour of batteries)
- Optimized batteries: global sustainability vs. EU (local/geo. aspects)
- Assessment frame beyond LCA (e.g. with alternative techn., market to societal, political aspects)

Value Chain vs Impact Dimensions

Europe	Raw material situation	Energy and CO2-footprint	Local (environmental) impact	Independence and sovereignty	Cost and scale
Raw materials Battery materials Battery cells & production Demand and use Logistics and localization Recycling … Alternative batteries	?	?	?	?	?

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Sustainability pathways in a future European battery ecosystem

Dresden Battery Days 2023

1. **Raw materials and recycling**
2. Battery materials
3. Battery cells and production
4. Demand and use
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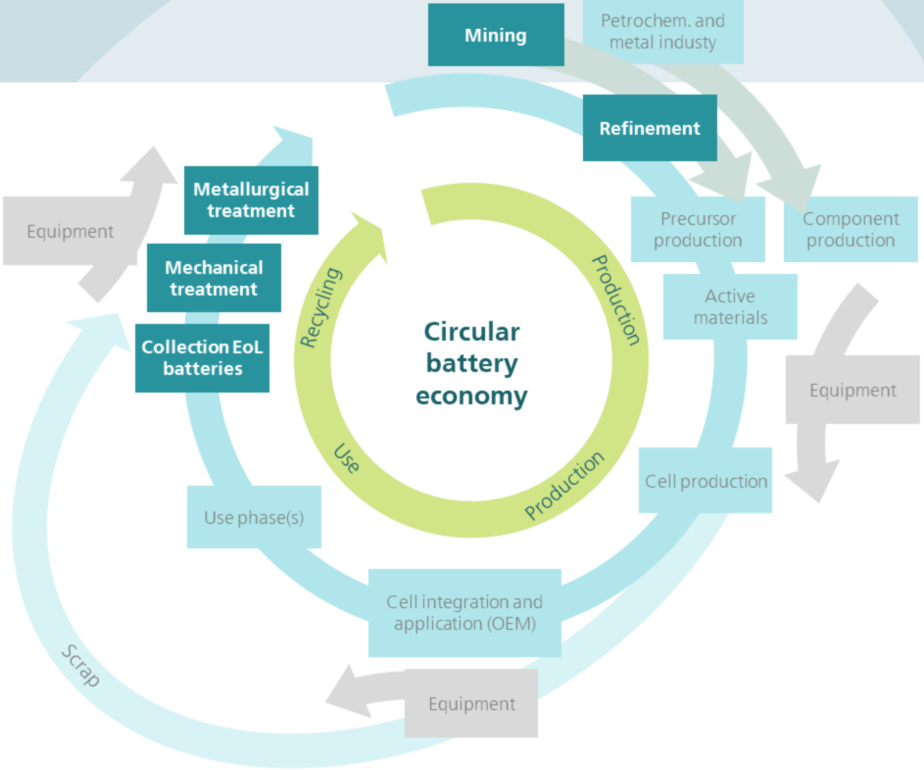
6. Alternative battery technologies

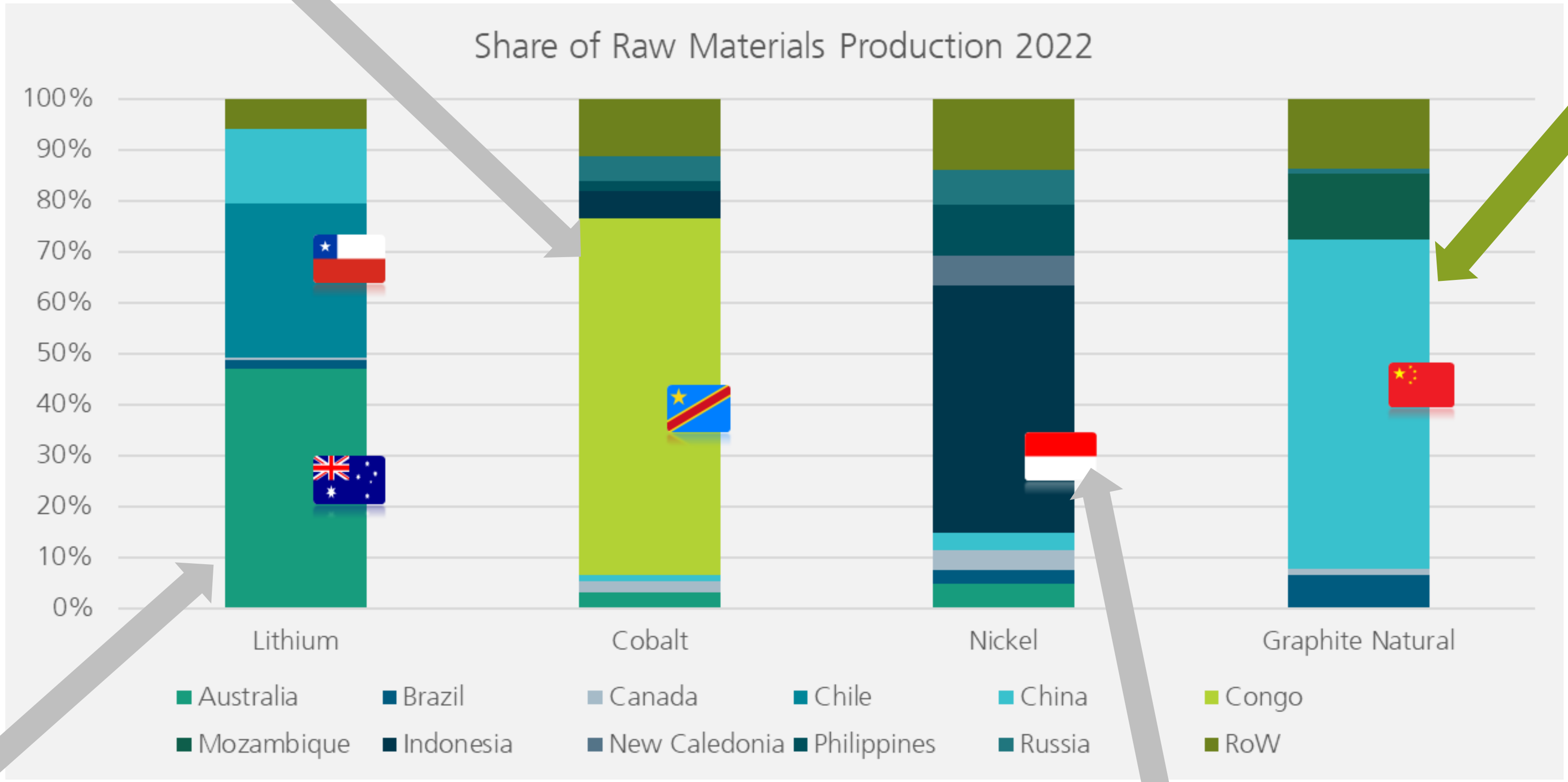


Raw Materials production

no EU production today

For **Cobalt**, all of the 5 largest mines are located in **Congo**. With 34,7 kt per year production, the largest one is owned by Glencore

Biggest producer of **Graphite** for batteries is Posco in Korea (95 kt per year), followed by 7 **Chinese** producer.



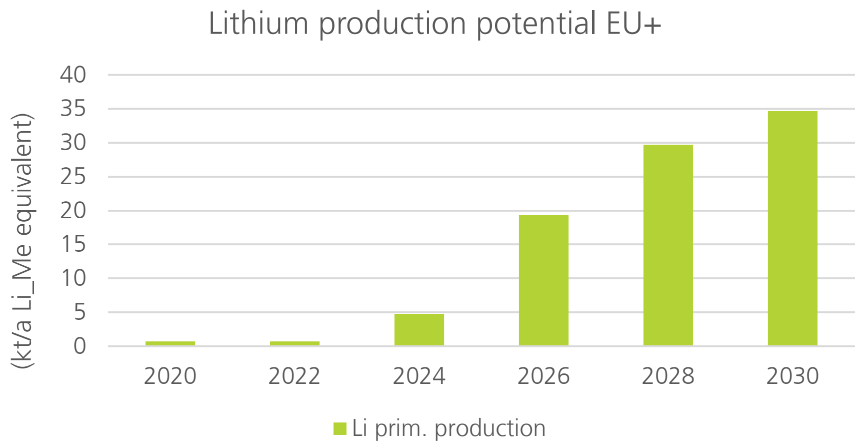
Top 6 of largest mines are placed in **Australia**. Largest one is the Talison **Lithium** Mine in Greenbushes with 147,8 kt LCE per year

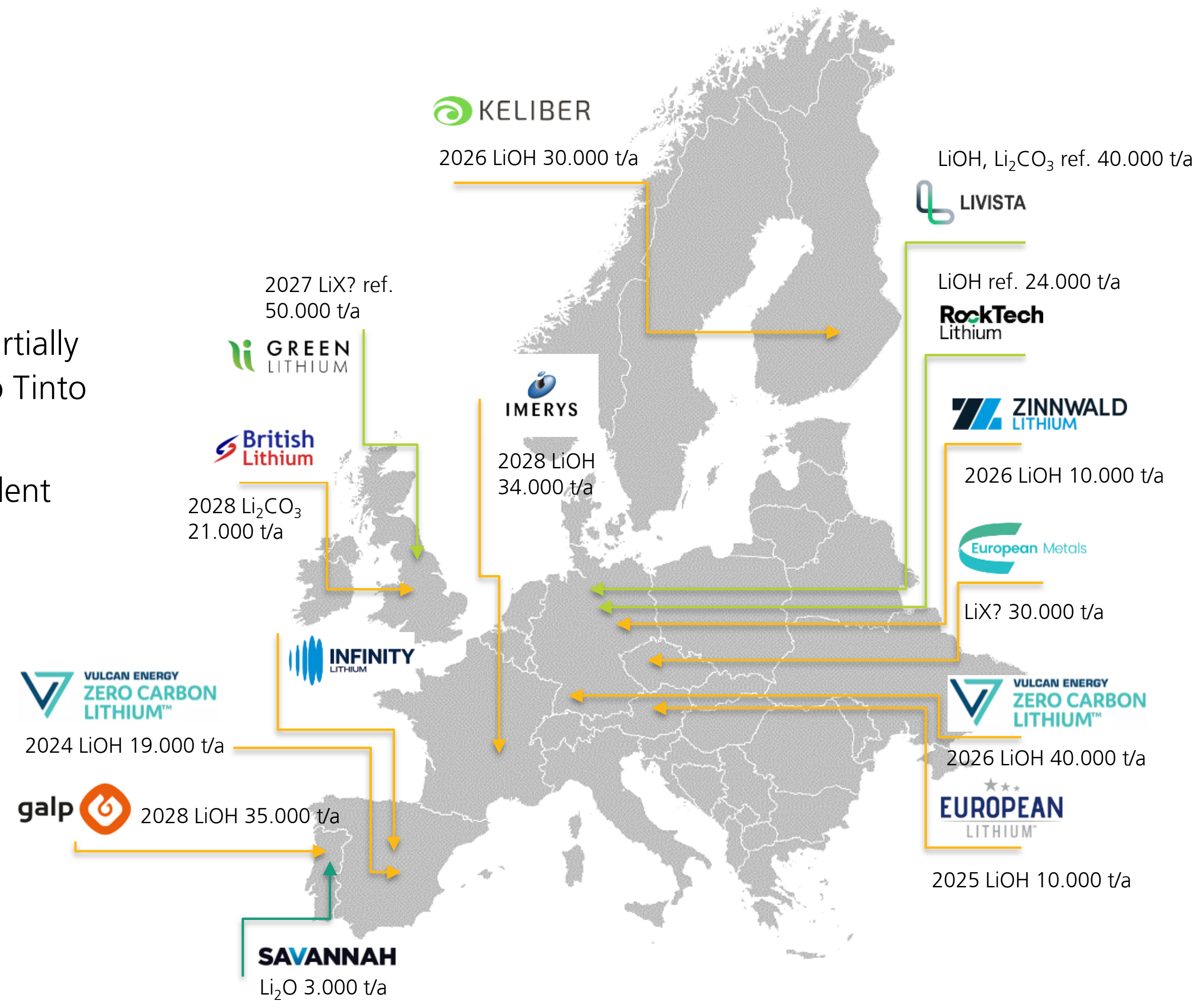
Largest **Nickel** Mine is placed in **Russia** (Kola MMC Mine – 146 kt per Year), followed by another Russian, two Philippines and one in Columbia.

European Lithium projects

Contribution to self sufficiency?

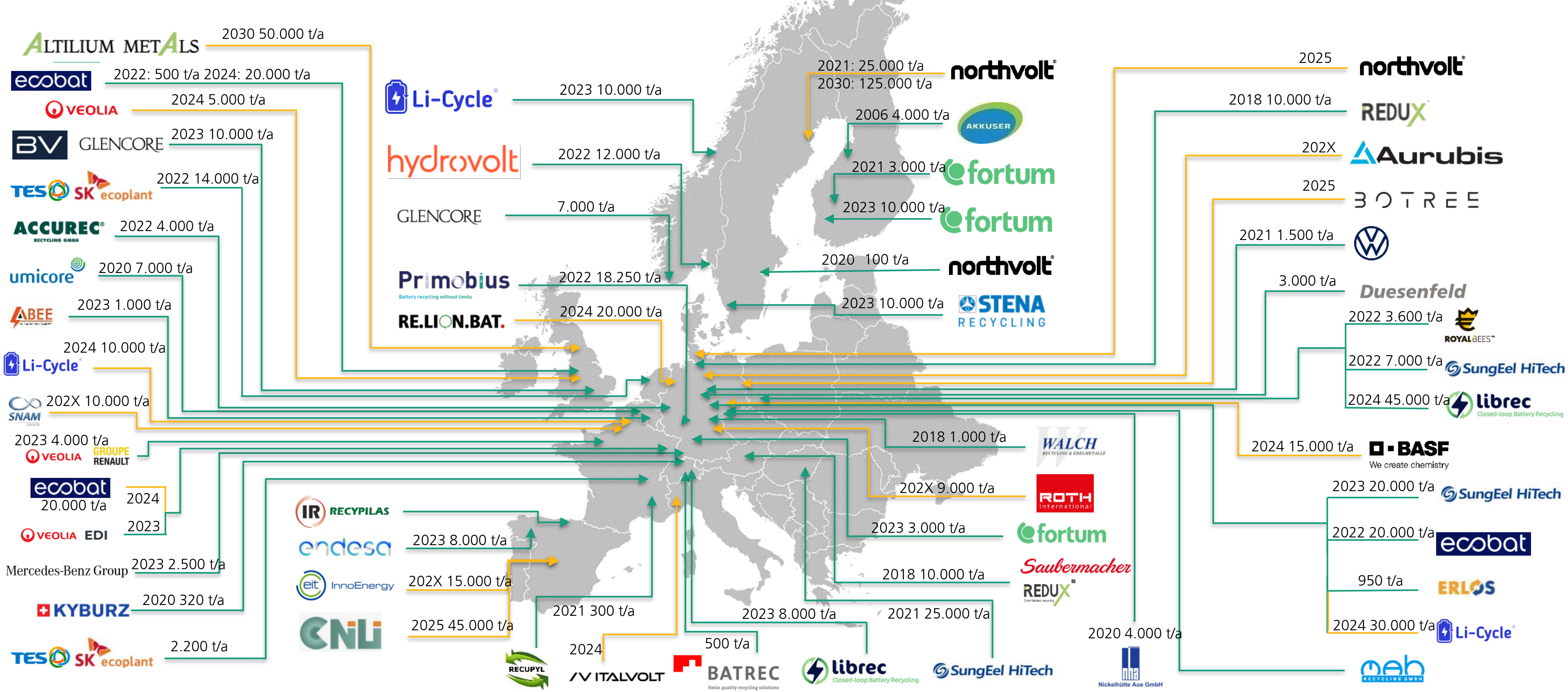
- Growing landscape of Li-mining projects, mostly in development / exploration phase.
- Partially new (green) approaches, e.g. liquid extraction, partially greater resistance due to environmental concerns (e.g. Rio Tinto in Serbia)
- Current announcements add up to >30 kt/a Li_me equivalent





European battery recycling projects

Installed (by end of 2023)
Planned



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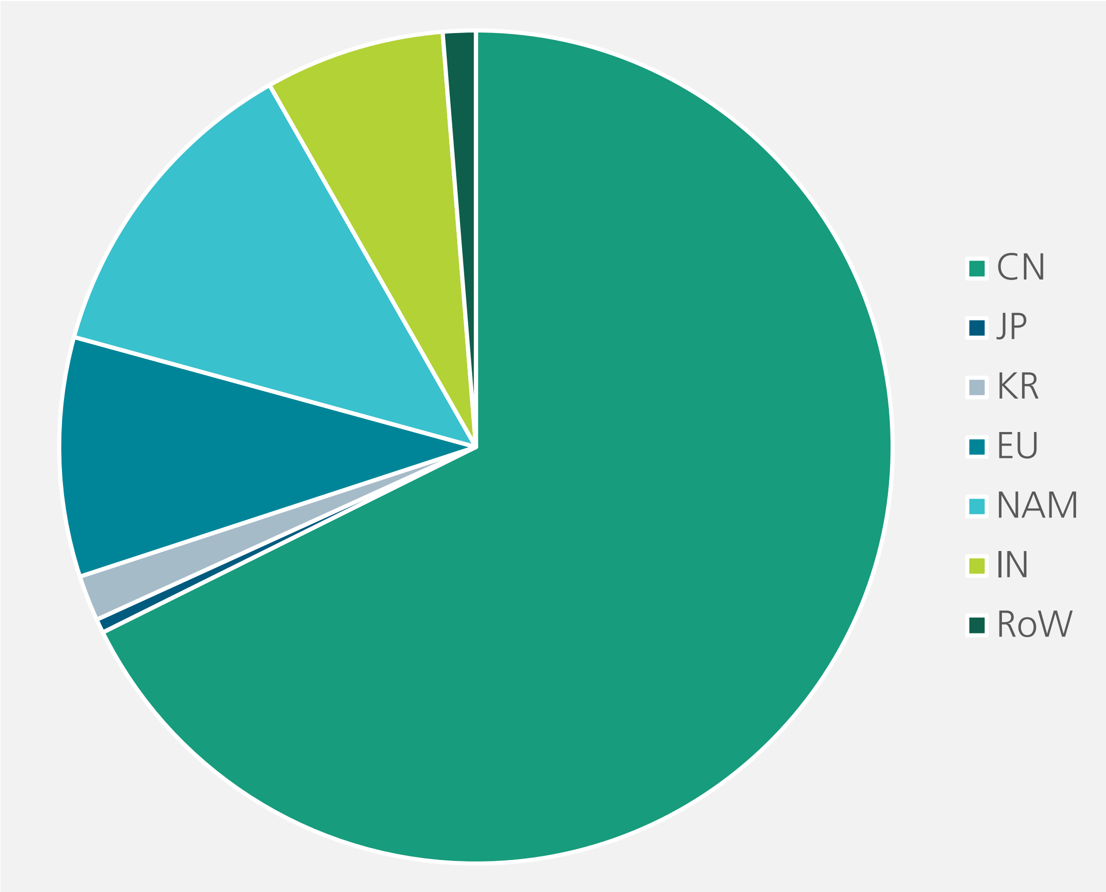
Emerging recycling market with decommissioned batteries take-off 2030-2040

Recycling activities start globally

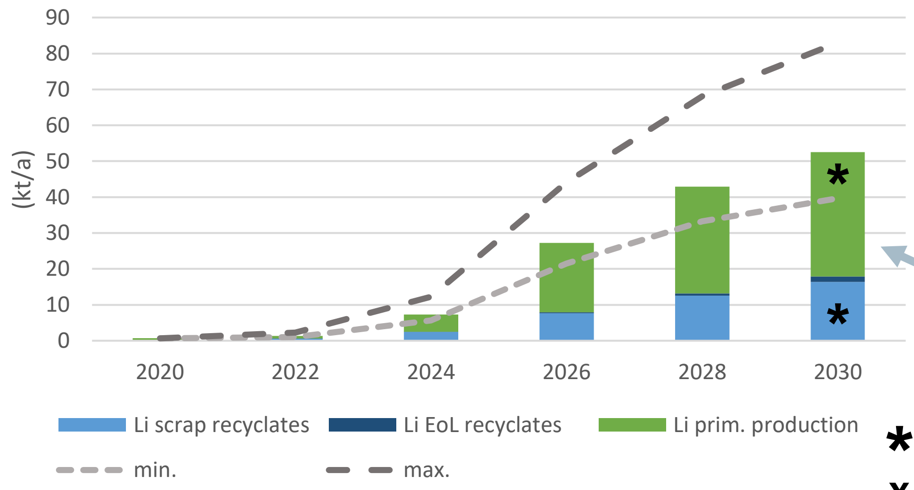


Most of the recycling capacities announced so far in China due to the production crap available there. In addition, some plants in North America and Europe are in the realisation phase or planned.

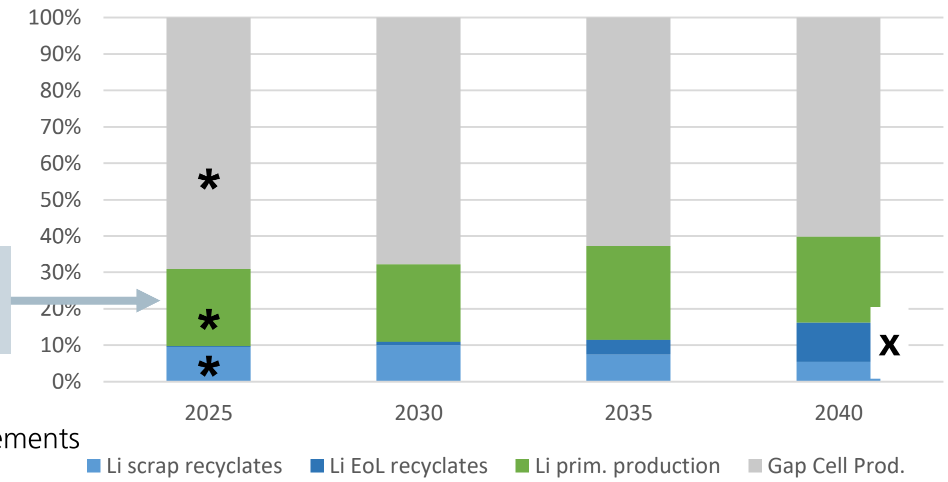
Circular battery value chain

Example Lithium

- EoL battery recycling kicks in after 2035.
- Scrap from cell production can be a major source for recycling Li, but it does not change the balance, as it leads to increased demand at the same time.
- Self-sufficiency can't be achieved in the next 20 years, but battery recycling and primary production can contribute significantly.
- EU Critical Raw Materials Act targets for Lithium seem achievable (10% from primary resources, 15% from recycling)



Scrap does not really help!



* based on company announcements

x based on FhISI market model

Circular battery value chain beyond Lithium

Nickel, Cobalt, Graphite and other components

- A lot of focus on Lithium (primary production). Some refinement capacities.
- Some nickel mining (Finland, Greece) and refinement (Finland, France, Austria). Focus on steel, ongoing shift to batteries (e.g. Terrafame for Stellantis). Most likely ongoing dependence on imports. Same for Cobalt.

  → CRMA targets for primary production will most likely not be met (until 2030)
- Some natural graphite in Europe (Sweden, Finland, Norway), some productions capacities for synthetic graphite (France, Italy, Poland, Norway, Sweden), but very low market share

  → CRMA targets for primary production and processing will most likely not be met (until 2030)

Europe	Raw material situation	Energy and CO2-footprint	Local environmental impact	Independence and sovereignty	Cost and scale
Primary production	++ (0-20% self sufficiency depending on material)	-- (vs. South America, factor 3 to 4 higher CO_2-footprint of hardrock vs. brine) 0 (vs. other hardrock projects) (→ several kg CO2/kWh)	-- (shift of emissions to EU)	++ (0-20% self sufficiency depending on material)	+ scaled production less cost and potentially energy impact
Recycling	++ (10-20% self sufficiency depending on material) (potentially Co 40%, Li, Ni, Cu 15% by 2040)	+ (short transport distances, high share of reneweables)		++ (10-20% self sufficiency depending on material)	+ scaled recycling increases economic adv. to primary production

Source: https://rmis.jrc.ec.europa.eu/analysis-of-supply-chain-challenges-49b749
https://op.europa.eu/en/publication-detail/-/publication/c72e89ce-6698-11eb-aeb5-01aa75ed71a1/language-en
https://www.iea.org/data-and-statistics/charts/ghg-emissions-intensity-for-lithium-by-resource-type-and-processing-route
https://www.isi.fraunhofer.de/de/blog/themen/batterie-update/recycling-lithium-ionen-batterien-europa-starke-zunahme-2030-2040.html

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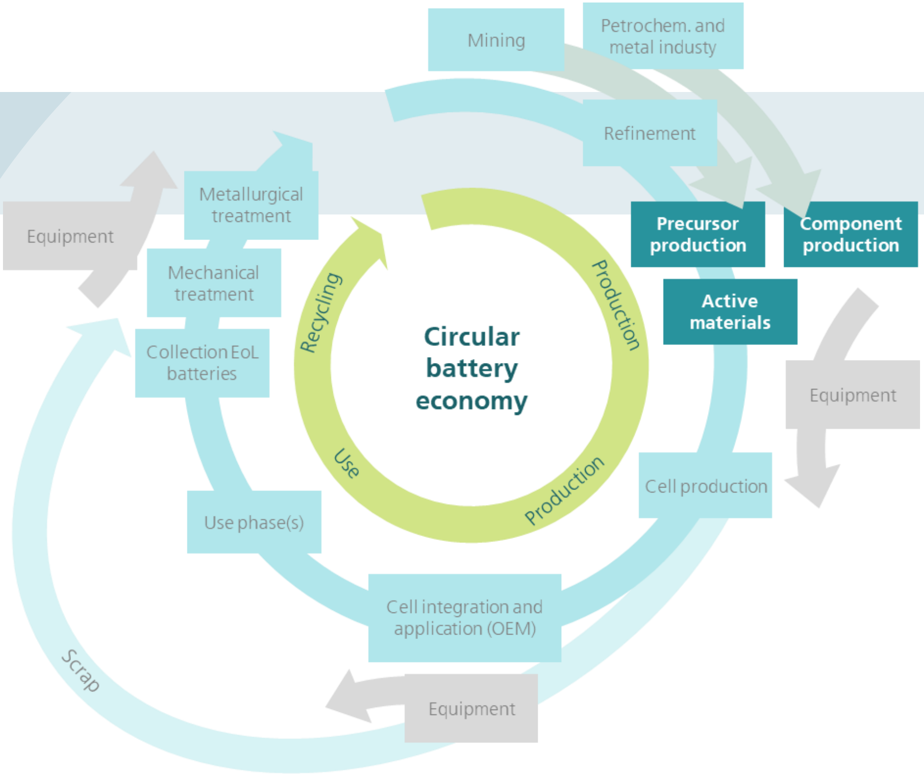
Sustainability pathways in a future European battery ecosystem

Dresden Battery Days 2023

1. Raw materials and recycling
2. **Battery materials**
3. Battery cells and production
4. Demand and use
5. Logistics and localisation
6. Alternative battery technologies



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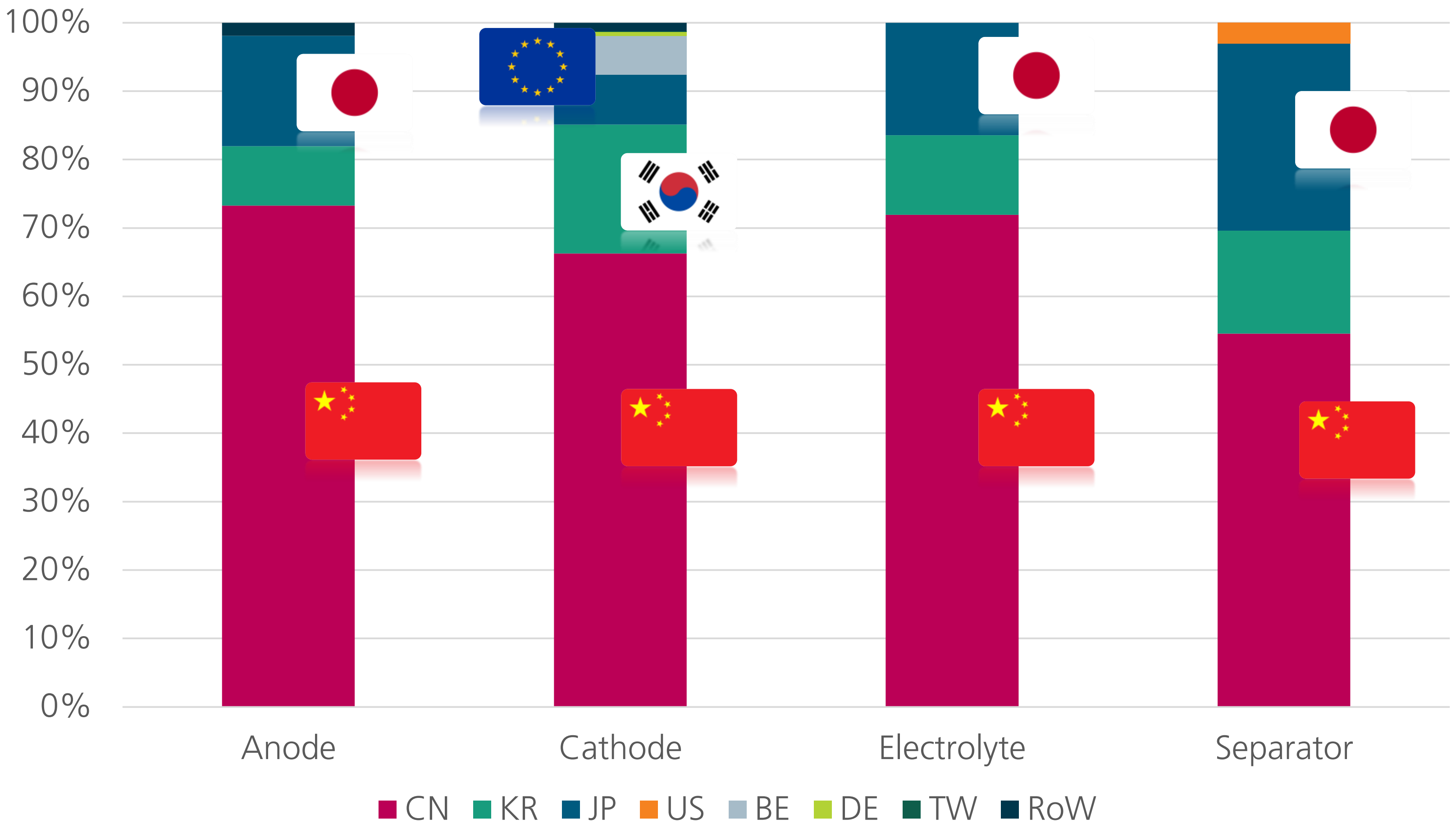
LIB Components

EU share only for CAM



European CAM/AAM projects

Contribution to self sufficiency?

- Predominantly larger players entering the CAM market in Europe.
- Some large scale activity for the production of AAM by newer players. Rather early development stage.
- Focus on Northern Europe due to good access to renewable energy and feedstock (natural graphite) and on Eastern Europe due to proximity to existing giga cell factories.

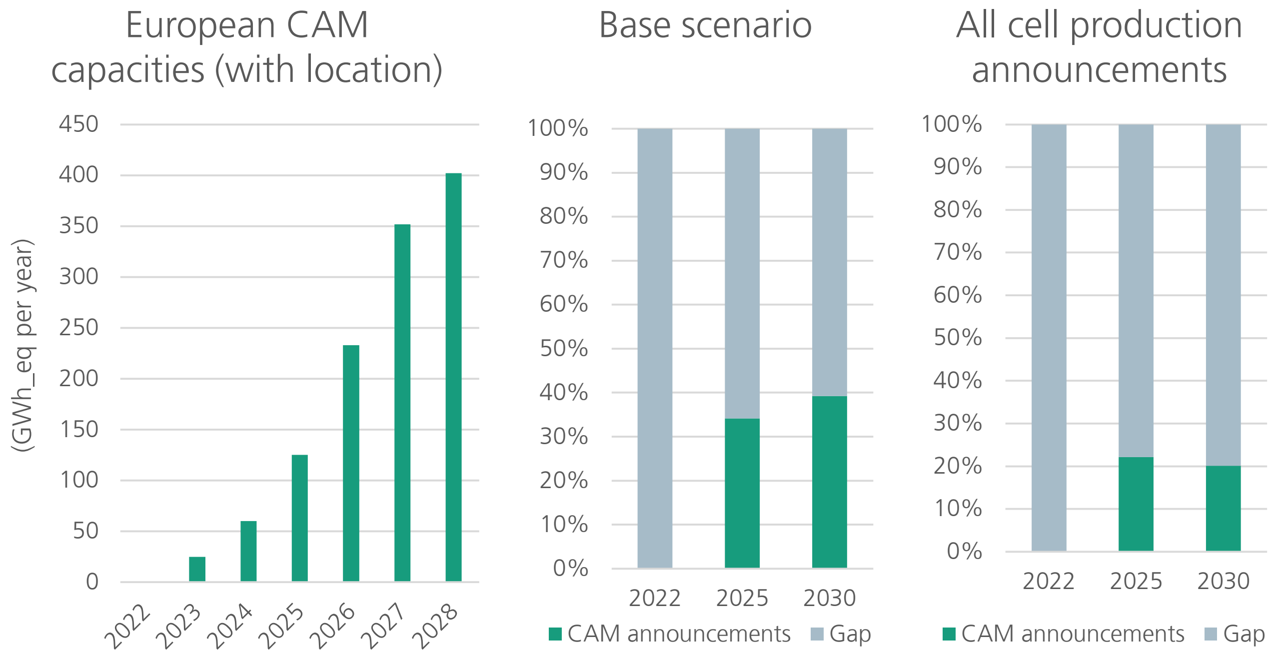
- Drivers are automotive OEMs and their requirements for localization of supply chains, e.g. to comply with EU "rules of origin".*

* Various free trade agreements between the EU and other countries provide for so-called "Rules of Origin".
If these are fulfilled, products are recognized as domestically produced and their trade is subject to the favorable conditions of the free trade agreement.

European CAM/AAM projects

Contribution to self sufficiency?

- Based on announcements, still big gap between CAM production and cell production. In aggressive cell production scenario (all announcements), only 20 % self-sufficiency can be reached.
- Worse situation for AAM



Europe	Raw material situation	Energy and CO_2-footprint	Local environmental impact	Independence and sovereignty	Cost and scale
Components	/	+ (higher average share of renewables compared to CN) (similar or higher CO2-footprint compared to cell production)	- (shift of emissions to Europe)	+ (higher degree of freedom for commercialization of own AM technologies)	? (higher energy cost, other regulative frame conditions)

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Sustainability pathways in a future European battery ecosystem

Dresden Battery Days 2023

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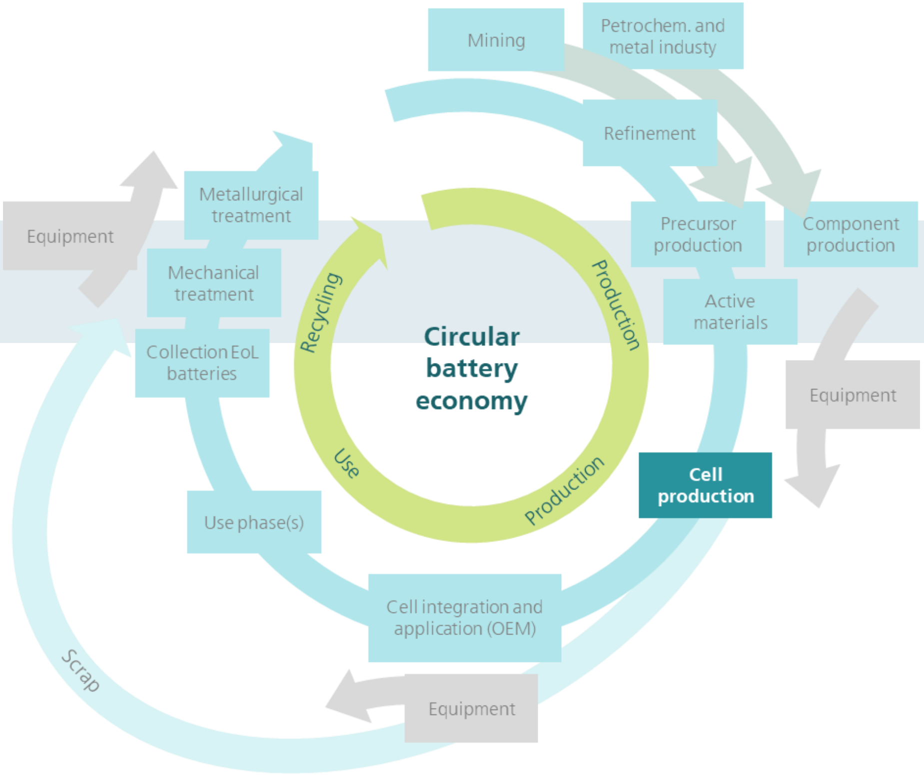
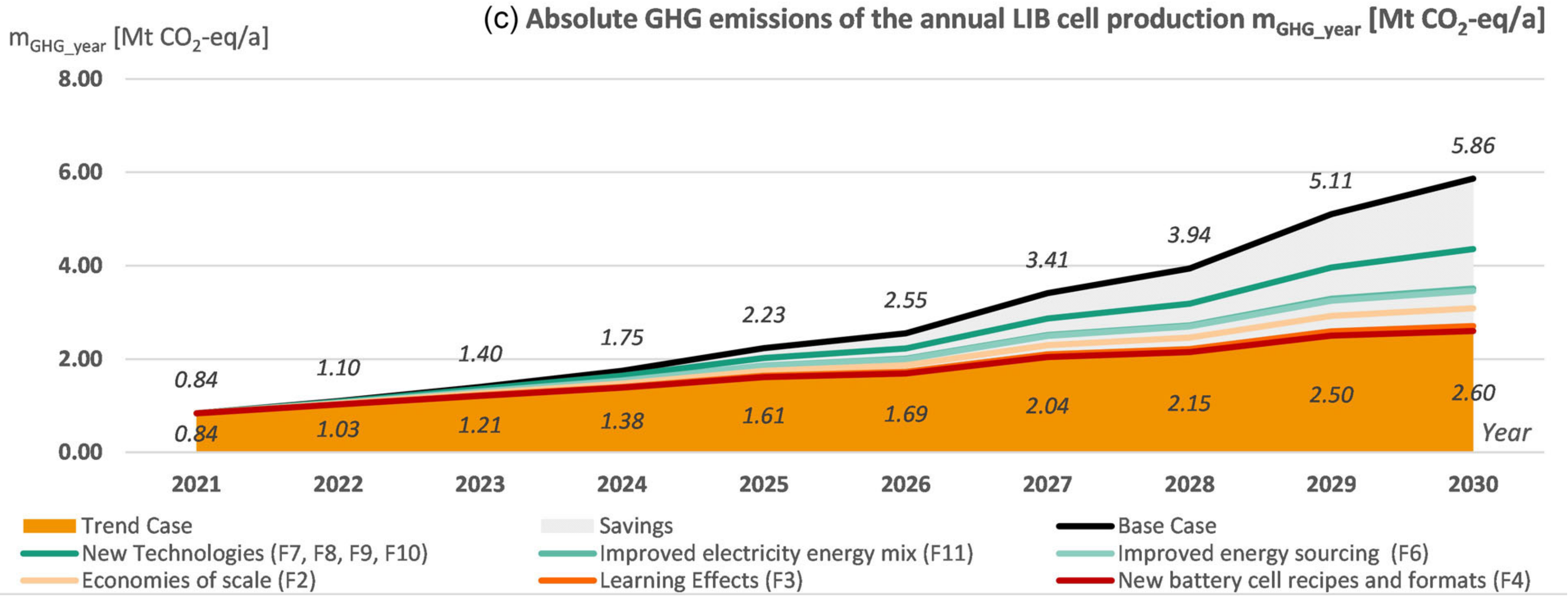


GHG-emissions of the european battery cell production

...and options for reduction



- The energy consumption and GHG-emissions of the European LIB cell production will increase by almost 600% by 2030 if no measures are taken.
- But **energy consumption and GHG emissions could be decreased by 46%and 56% (compared to the Base Case Scenario)** when applying a mix of political, economic, and technological measures
- Thereby the changes in battery cell chemistry and battery cell formats will have no significant effects on energy consumption and GHG emissions.
- The EU-wide increase in the share of RE in the electricity mix is an important measure, but not the most effective when looking towards 2030).

→ The most important measures are economies of **scale** and the application of new **production technologies**.

Source: Degen, F. (2023). Lithium-ion battery cell production in Europe: Scenarios for reducing energy consumption and greenhouse gas emissions until 2030

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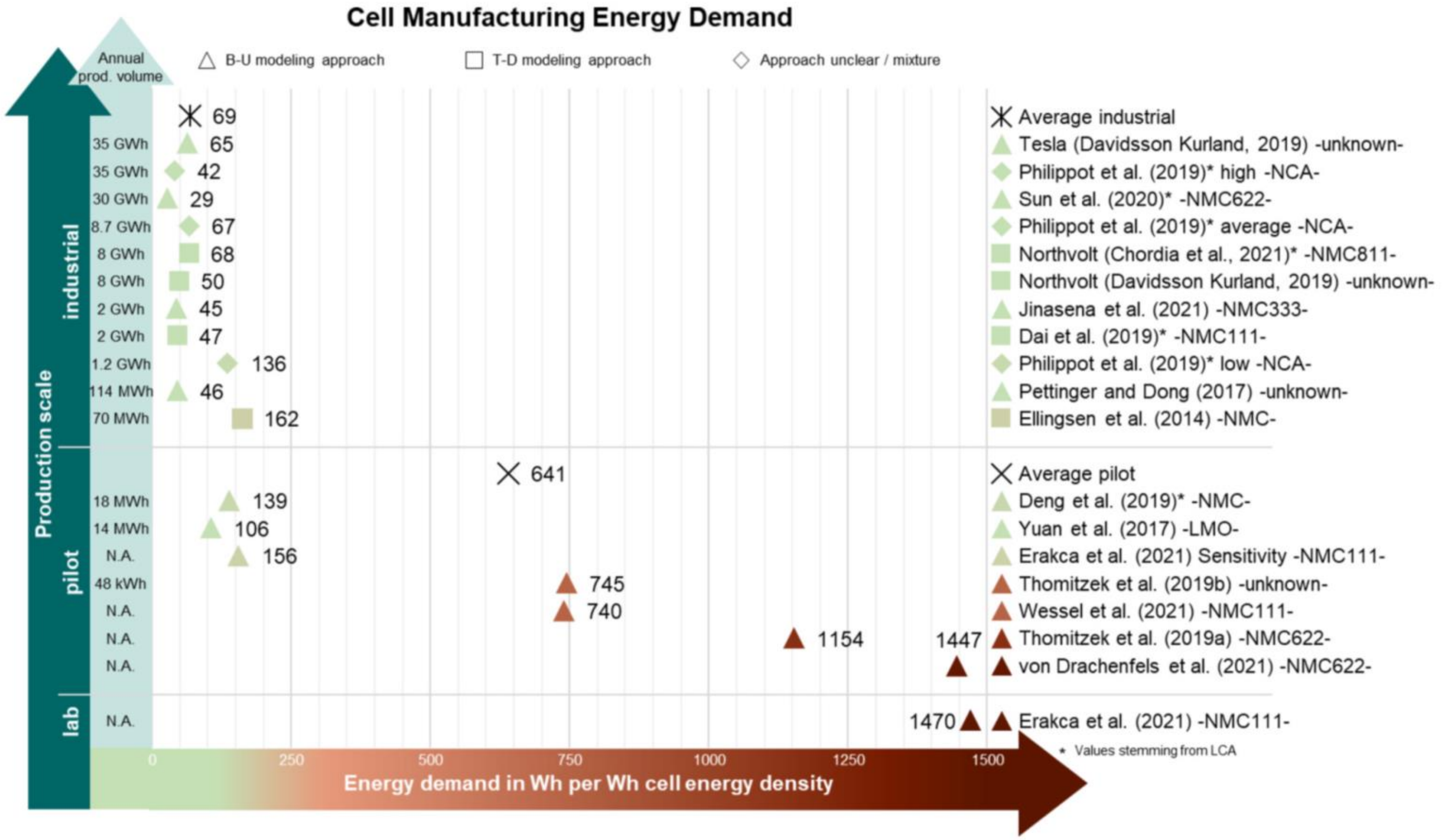
The influence of economies of scale on the GHG-emissions

Results from a comparative literature analyses



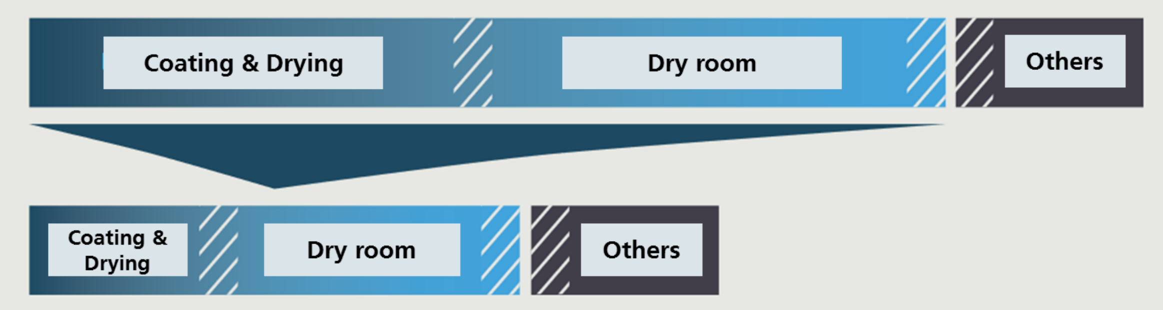
- Different sources in literature indicate the significant effect from high production scales on Energy and CO2eq. during production.
- Comparing the potential of a cell production in lab scale to one of an industrial scale it becomes visible, that the difference is ~ a factor 10

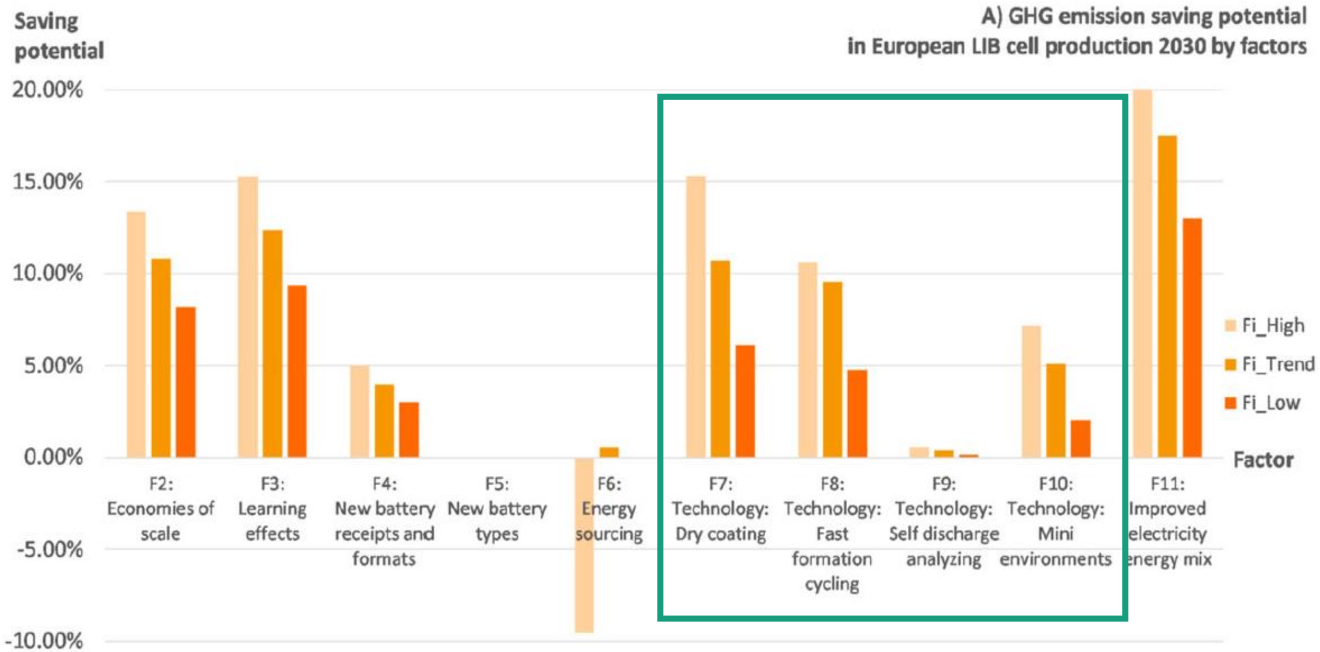
Source: Erakca et al. (2022): Closing gaps in LCA of lithium-ion batteries: LCA of lab-scale cell production with new primary data

Hotspots in cell production and options to reduce emissions

Influence of new technologies

- The most energy intensive processes are coating & drying, the formation and the dry room.
- The overall share of these processes make up for more than 80% of the total GHG emissions during cell production.



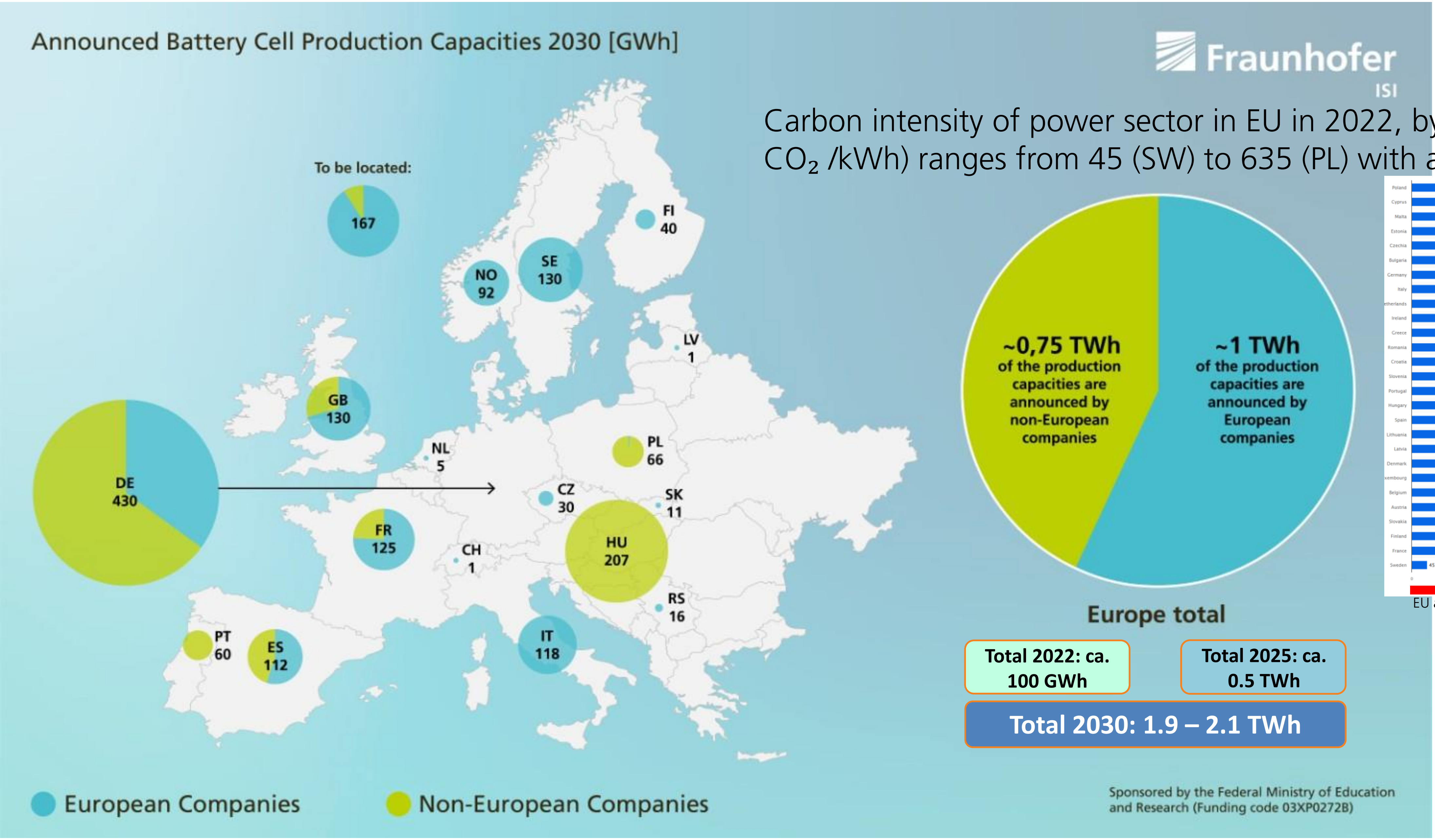


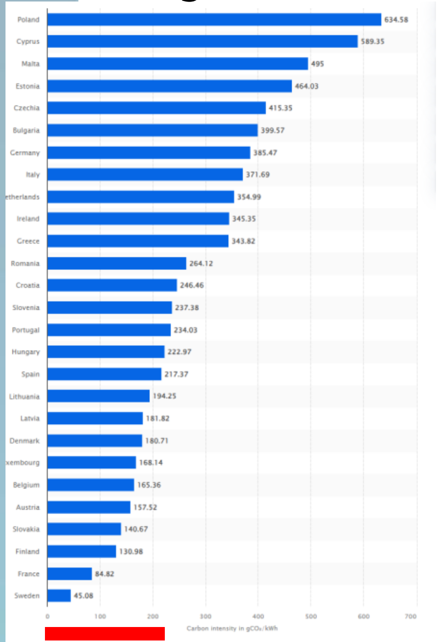
- But by applying new production technology in the three production steps/environments the energy consumption energy consumption and GHG emissions could be decreased.
- This could be achieved by using "Mini environments" in case of the dry rooms, by "dry coating" and "fast formation cycles".
- **By achieving and applying these new technologies the energy consumption and the GHG – emission could be reduced by 24% by until 2030.**

Source: Degen, F. (2023). Lithium-ion battery cell production in Europe: Scenarios for reducing energy consumption and greenhouse gas emissions until 2030

Source: Hettesheimer et al. (2021). Batteriestandort auf Klimakurs: Perspektiven einer klimaneutralen Batterieproduktion für Elektromobilität in Deutschland.

Carbon intensity of power sector in EU in 2022, by country (in g CO_2 /kWh) ranges from 45 (SW) to 635 (PL) with average ~220





EU average

Source: https://www.isi.fraunhofer.de/en/blog/themen/batterie-update/batterie-zell-fertigung-europa-hersteller-europaeisch-international-kapazitaeten-2030.html

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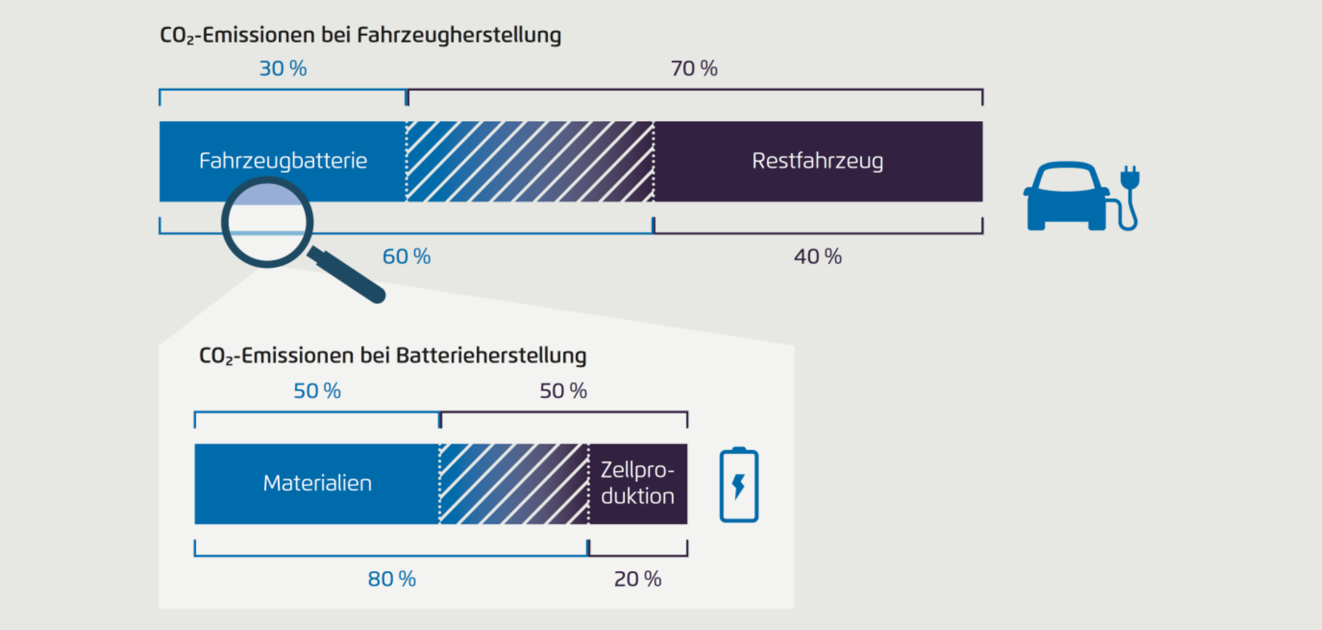
CO2-Emission reduction potentials

similar footprints from materials to cells to products (EVs)



Europe	Raw material situation	Energy and CO2-footprint	Local (environmental) impact	Independence and sovereignty	Cost and scale
Cell production	- scrap for new (EU) players - access to materials	+ EU with better energy mix (but differing across MS) (technologies and scale effects not specific to EU)	- Shift of emissions to EU	+ self sufficiency (but with Asian producers)	0 (- newcomers in EU, e.g. with less scaled production + rules of origin)

Sustainability pathways in a future European battery ecosystem

Dresden Battery Days 2023

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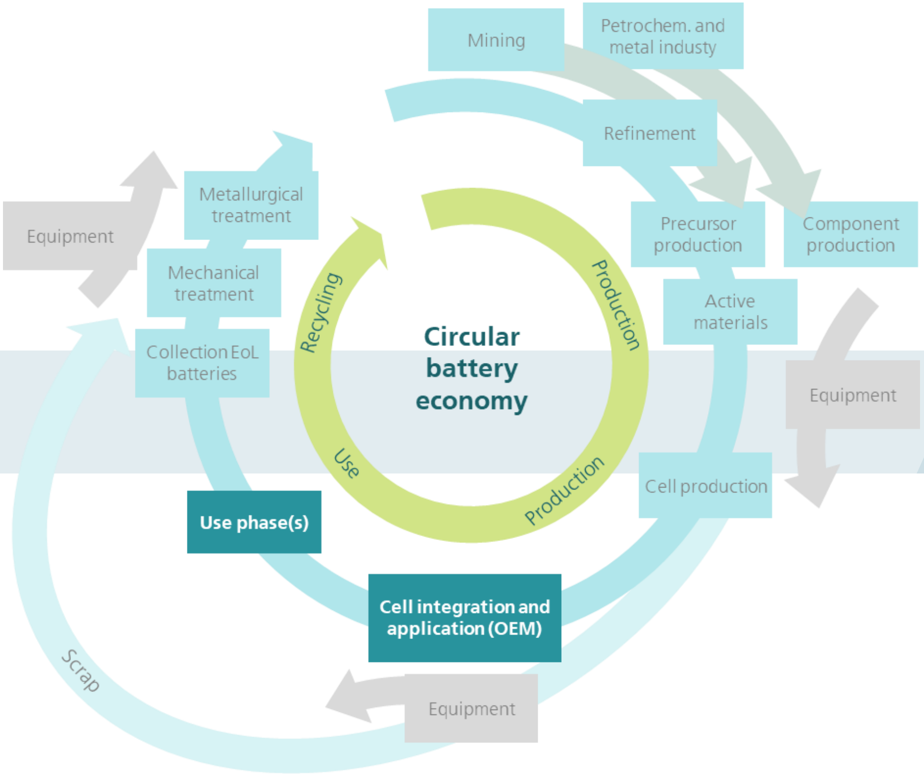

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Reducing no. of cars helps reducing overall impacts on environment & society

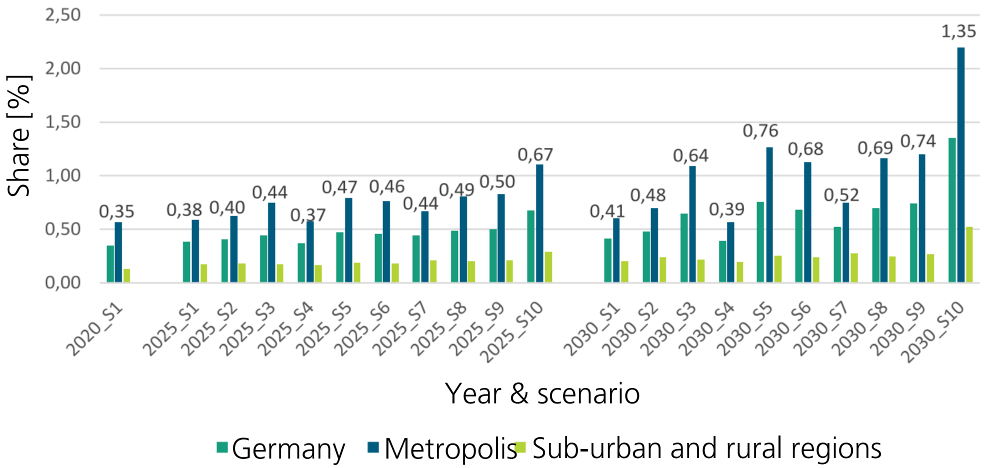
Reducing car usage can lead to a reduction in cars owned (Krauss et al., 2022)

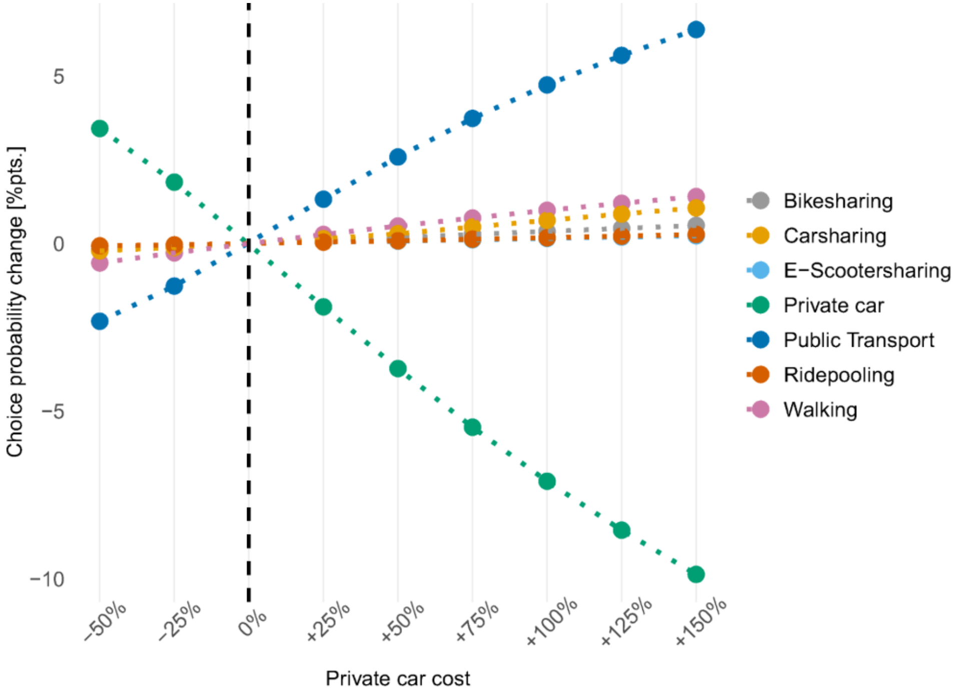
→ Increasing private car cost reduces the demand for car usage

→ Public transport and shared services can be one crucial element to reduce private car usage, which can then result in less cars owned

→ Carsharing can capture ca. 1.4 % of transport demand (private car km) in 2030 in the best case

Carsharing: share of transport demand





Simulated probability changes in choosing respective modes due to an increase in private car costs Public transport and shared mobility service capture the transport demand from the private car

Europe	Raw material situation	Energy and CO2-footprint	Local (environmental) impact	Independence and sovereignty	Cost and scale
Demand/ use	+ potential reduction of demand with mobility concepts (large cities)	+ potentially less emissions due to lower absolute demand	+ potential lower demand due to shift in mobility concept	+ limit demand	0/-? put effort in mobility research, concepts and frame conditions

Effects of better battery use (2nd life, smart charging, etc.) can have postive impacts but not specfic to EU)

Sustainability pathways in a future European battery ecosystem

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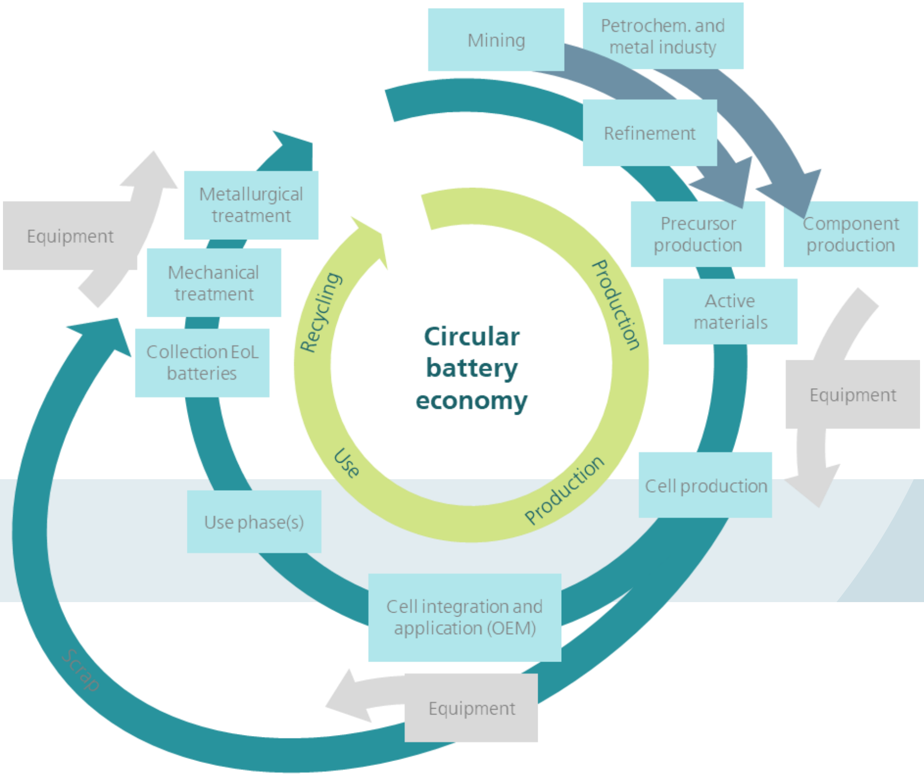


Effects of localization of supply chains

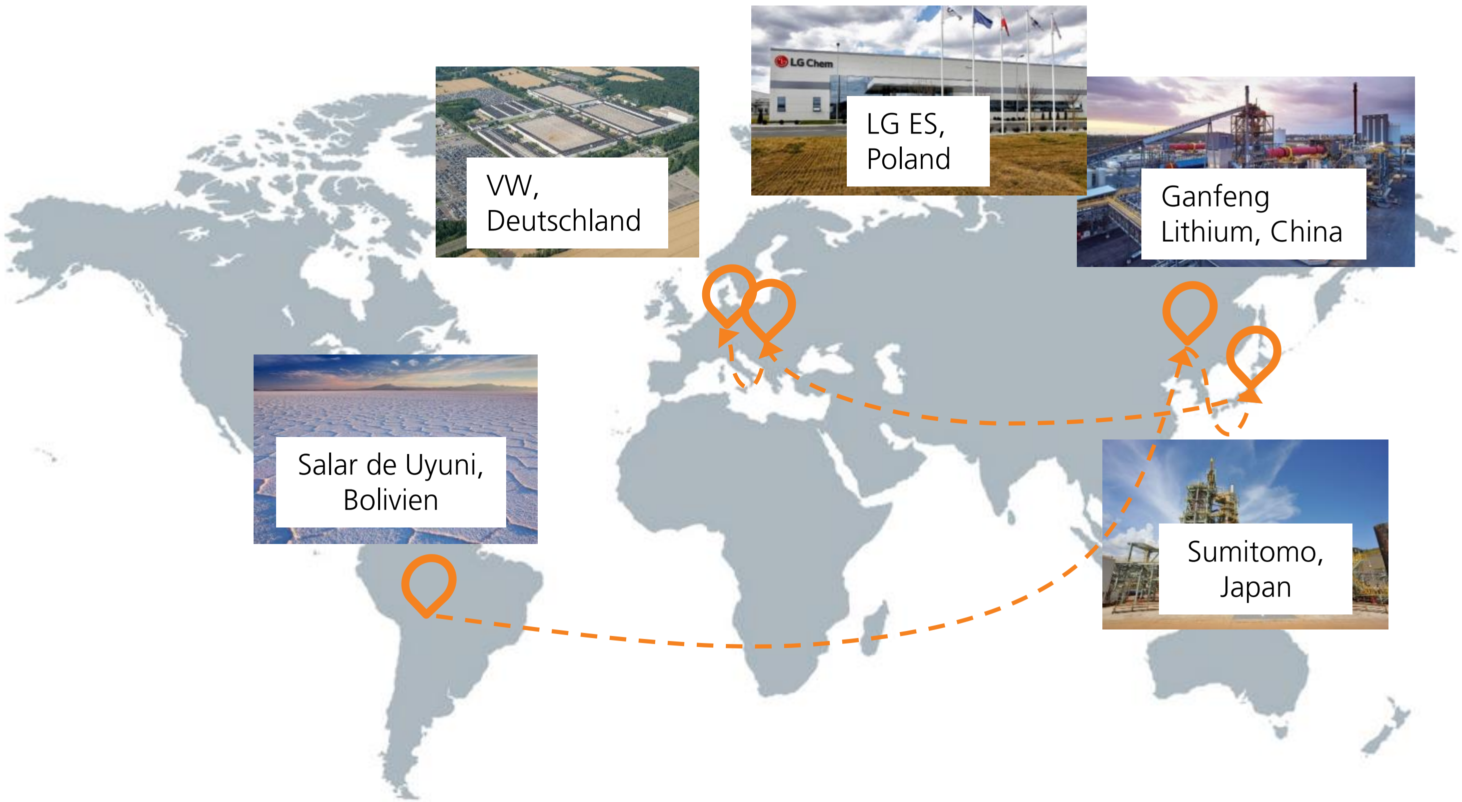
International supply chain

Hypothetical international supply chain for Lithium for CAM and LIB cells:

- South America (mining)
- China (refinement, pCAM), Japan (CAM)
- Hungary (cells)
- Germany (integration)

- ~40.000 km by sea
- ~4.000 km road transport
- **0.4-0.5 kg_CO_{2eq} / kWh** (most of it for transport of Li_2CO_3, does not include other CAM components!)

Assumption: 15-20 kg_CO_{2eq} / ton / km for sea freight and 100-150 kg_CO_{2eq} / ton / km for road freight



Effects of localization of supply chains

International supply chain

Hypothetical European supply chain for Lithium for CAM and LIB cells:

- Portugal (mining, refinement)
- Poland (pCAM, CAM)
- Sweden (cells)
- Germany (integration)

- ~6000 km road (can be optimized by including sea transport)
- **0.2-0.3 kg_CO_{2eq} / kWh** (most of it for transport of Li_2CO_3, does not include other CAM components!)

Raw material situation	Energy and CO_2-footprint	Local environmental impact	Independence and sovereignty	Cost and scale
-- (lower supply with purely European prod.)	+ (although minor share in total cell budget)	- (shift of emissions to Europe)	++ (less vulnerable due to "Panama events")	+ (lower transportation cost)

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Sustainability pathways in a future European battery ecosystem

Dresden Battery Days 2023

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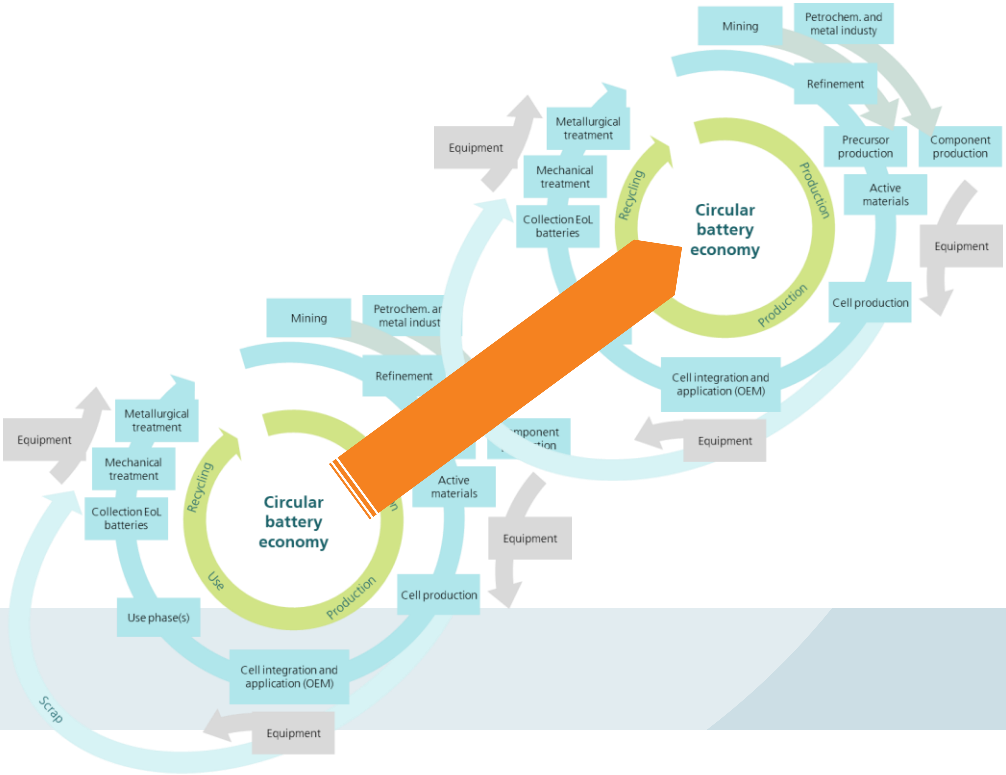
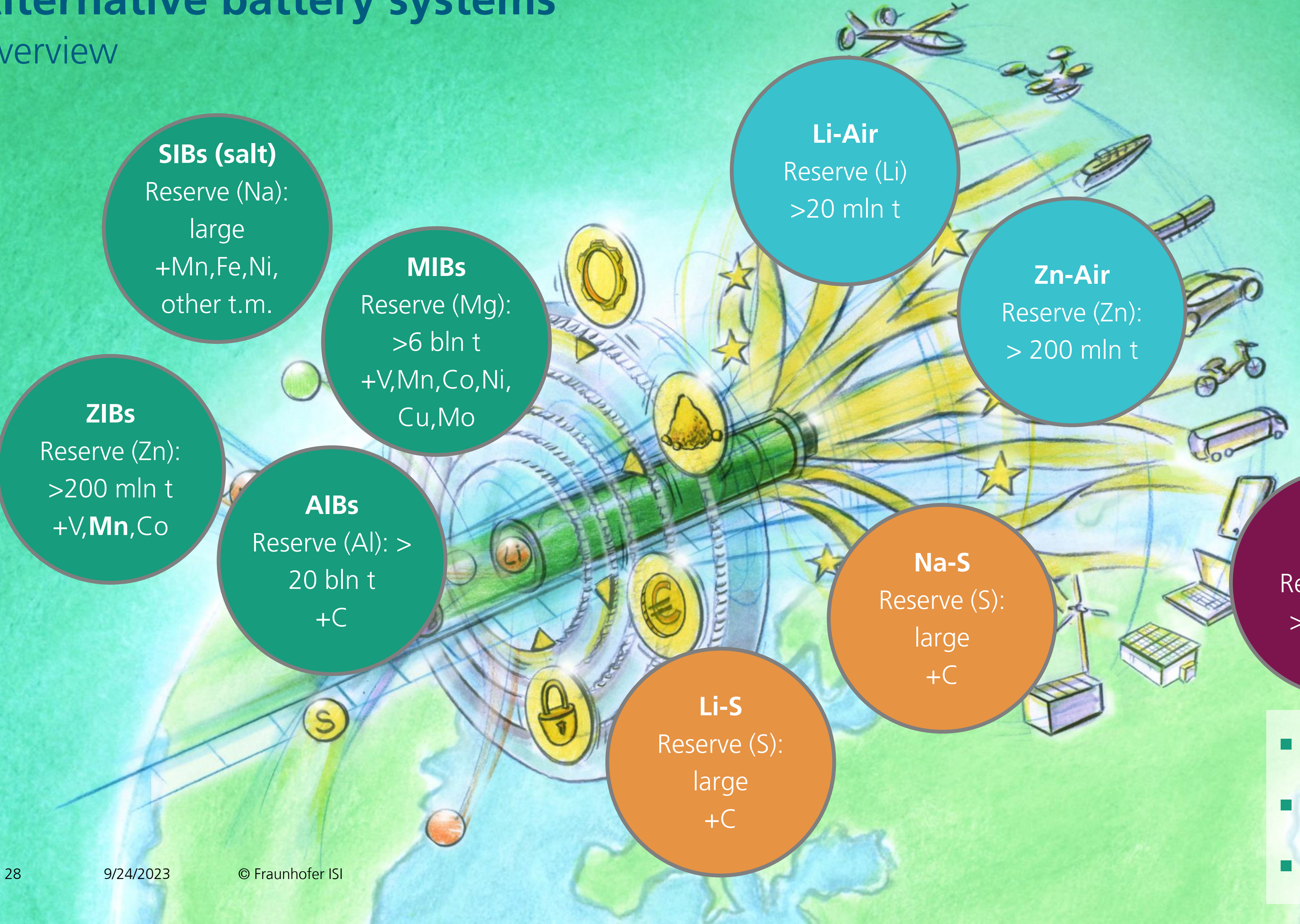
6. **Alternative battery technologies**



Alternative battery systems

Overview



SIBs (salt)
Reserve (Na):
large
+Mn,Fe,Ni,
other t.m.

MIBs
Reserve (Mg):
>6 bln t
+V,Mn,Co,Ni,
Cu,Mo

ZIBs
Reserve (Zn):
>200 mln t
+V,**Mn**,Co

AIBs
Reserve (Al): >
20 bln t
+C

Li-Air
Reserve (Li)
>20 mln t

Zn-Air
Reserve (Zn):
> 200 mln t

Li-S
Reserve (S):
large
+C

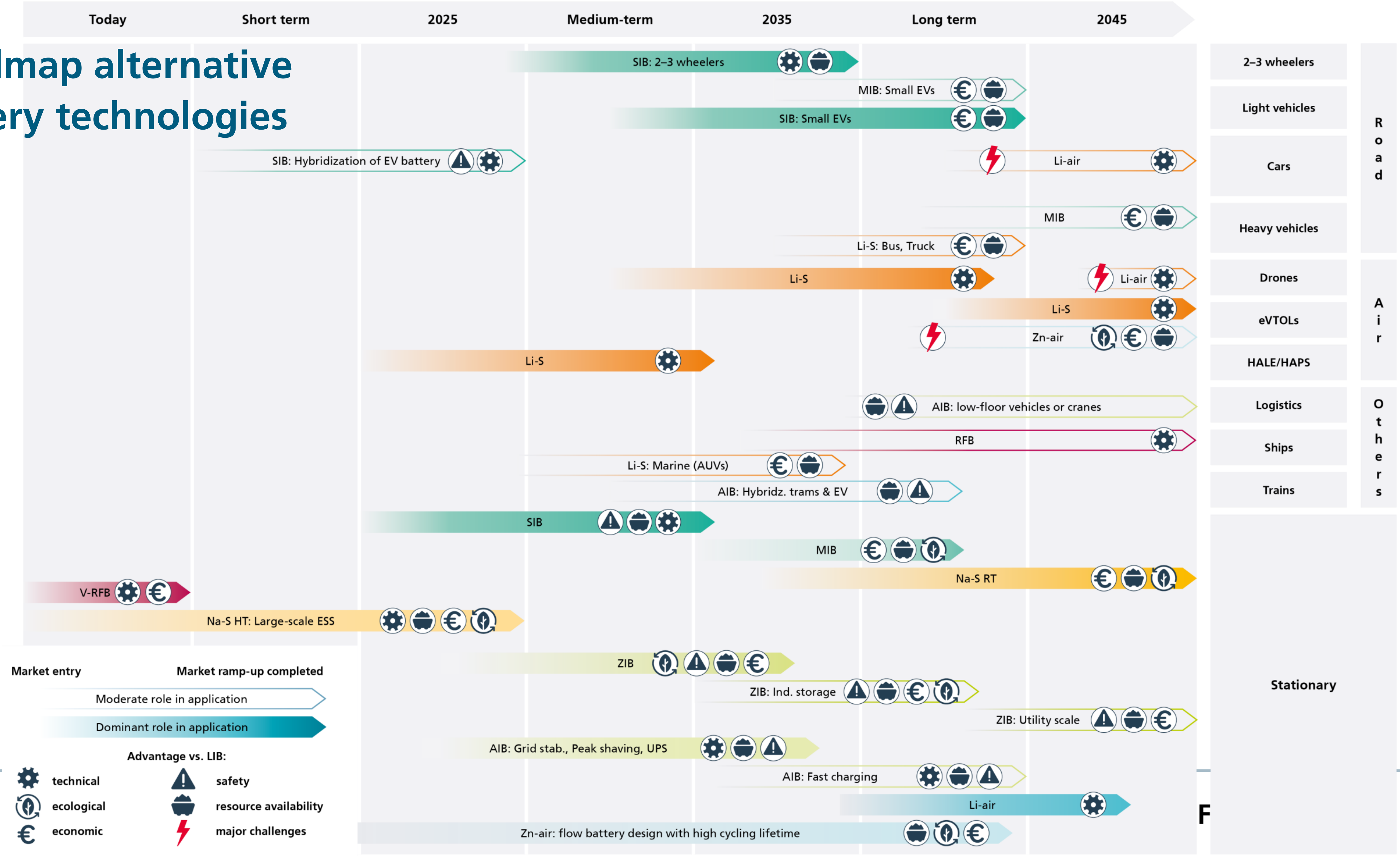
Na-S
Reserve (S):
large
+C

FeBr-RFB
Reserve
(Fe,Br): Large

V-RFB
Reserve (V):
>20 mln t

- Future cost?
- Application range?
- TRL / time to market?

Roadmap alternative battery technologies



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LIB Alternatives - Readiness, Market potential and sustainability impact

(red = much lower, yellow = lower, green = similar to LIB; for sustainability = yellow as benchm.)

Technology	Techn. Readiness	Market potential	Sustain. advantage
LIB			
SSB			
SIB (Na)			
MIB (Mg)			
ZIB (Zn)			
AIB (Al)			
LiS			
NaS RT			
NaS HT			
Li-air			
Zn-air			
RFB			

Evolutionary to LIB

Highest impact on sust.

Limited readiness and market (~percent level)

Solid-State Batteries (Li-based)

The evolutionary next step from LIB

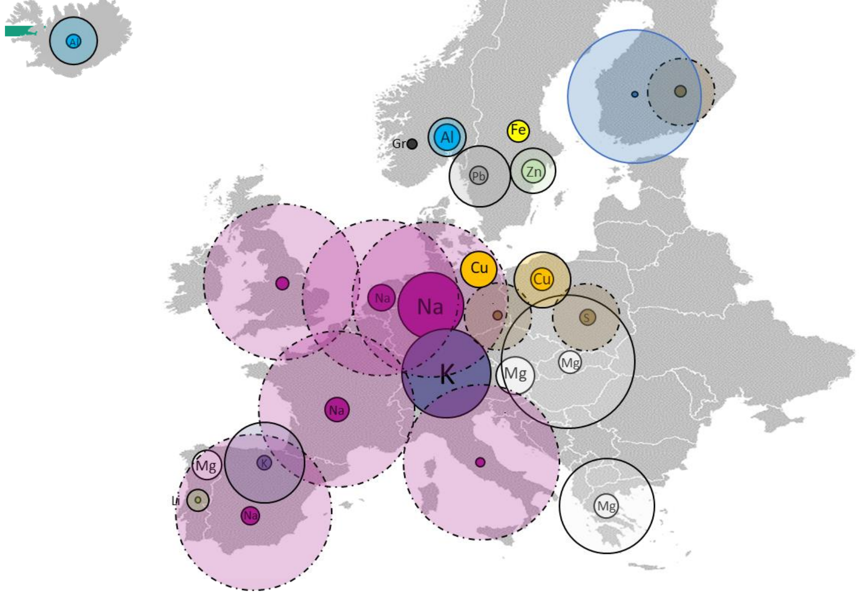
- SSB promise improvements in various KPI (e.g., energy density and specific energy, safety, cycle and calendar life)
- Similar (raw) materials as in liquid electrolyte (LE) LIB are being used:
- Evolutionary next step from LE LIB; intermediate step currently pursued are hybrid LE/SE LIB
- From sustainability perspective for most Li-based SSB no major change from LE LIB should be expected *(higher Li demand, might be compensated by higher cycle life)*

	Raw material situation	Energy and CO2-footprint	Local environmental impact	Independence and sovereignty	Cost and scale
SSB	• Depends on SSB technology considered • Most promising SSB technologies require a similar (e.g., Ni, Co) or even higher (Li) amount of critical raw materials • Some SE require rare or costly raw materials -> questionable, if these SE will play a role	• Materials combinations and production technologies are not clear, yet • Similar footprint compared to LE LIB can be expected • Possibly longer cycle life could reduce the footprint over lifetime	• Hard to assess as the materials and production technologies are still under development	• Upcoming technology that no one has mastered yet • Still the chance to be at forefront of this technology	• Upscaling efforts expected between 2025-2030 • Automotive market as main driver and application sector • Initially higher prices expected -> first premium products • Mass market diffusion will be decided by technical KPIs and price compared to LE LIB

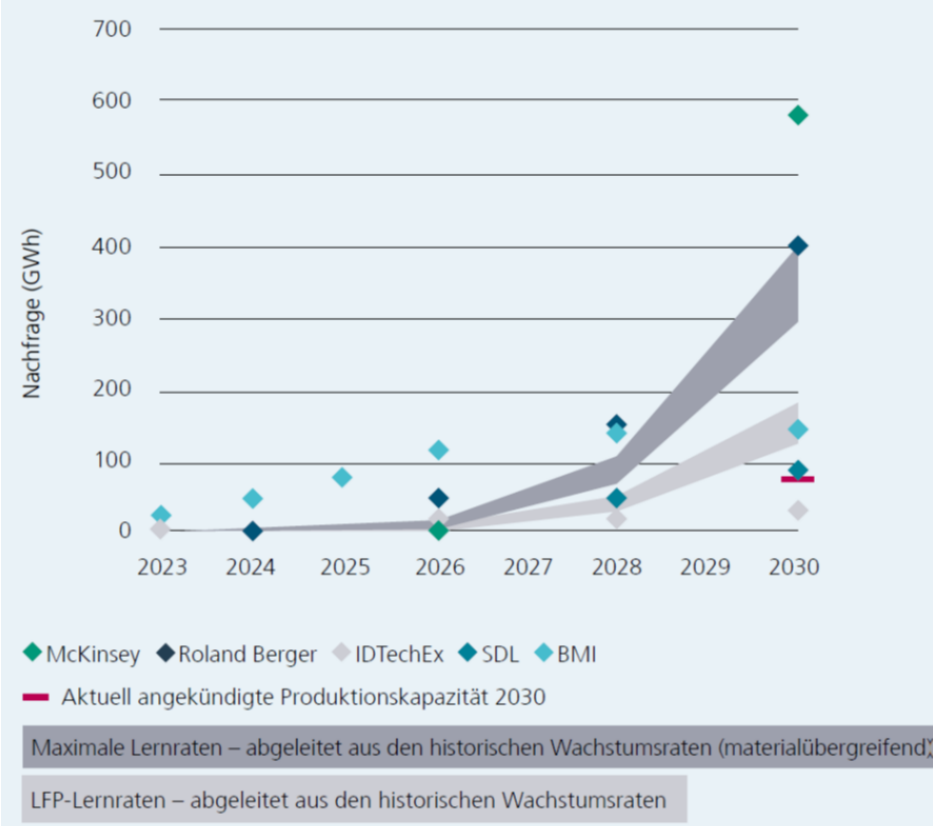
Ref.: "A Roadmap for Solid-State Batteries", T. Schmaltz, F. Hartmann, T. Wicke, L. Weymann, C. Neef, and J. Janek, *Adv. Energy Mater.*, just accepted

Sodium Ion Batteries

high material and market substitution potential



- **ESS:** Low cycle requirements / long life in UPS, Telecom
- **2W/3W:** low range eMotorcycles / eScooter
- **Small EV:** Low range and low cost
- **PHEV:** Potential use case but expiring technology
- **Hybridization:** Unclear cost effects
- Addressable market 2030+ → 200 – 600 GWh (10-20%)



Europe	Raw material situation	Energy and CO2-footprint	Local (environmental) impact	Independence and sovereignty	Cost and scale
SIB	++ (up to 20% less LIB demand e.g. with SIB) (e.g. Na availability and lower costs) - More Na/ materials due to lower energy density (but substitution of Cu, Co, Ni)	0 comparable to LB (50-90 kg CO_2/kWh cell) (higher energy for hard carbon anode but might level out, e.g. with cathode)	-	+ reduced LIB dependency but CN dominates SIB - Supply chains to be established	+ lower material costs (but more cells per kWh needed) - Less scaled technologies

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Sustainability impacts along the battery value chain

Summary

EU	Raw material situation	Energy and CO2-footprint	Local environmental impact	Independence and sovereignty	Cost and scale
Primary production	++ (0-20% self sufficiency depending on material)	-- (vs. South America, factor 3 to 4 higher CO_2-footprint of hardrock vs. brine) 0 (vs. other hardrock projects)	-- (shift of emissions to EU)	++ (0-20% self sufficiency depending on material)	+ scaled production less cost and potentially energy impact
Recycling	++ (10-20% self sufficiency depending on material)	+ (short transport distances, high share of renewables)	+ less primary production or dependencies with higher recycling rates	++ (10-20% self sufficiency depending on material)	+ scaled recycling increases economic adv. to primary production
Materials/ components	/	+ (higher average share of renewables compared to CN)	- (shift of emissions to Europe)	+ (higher degree of freedom for commercialization of own AM technologies)	? (higher energy cost, other regulative frame conditions)
Cell production	- scrap for new (EU) players - access to materials	+ EU with better energy mix (but differing across MS)	- Shift of emissions to EU	+ self sufficiency (but with Asian producers)	0 (- newcomers in EU, e.g. with less scaled production + rules of origin)
Demand/ use	+ potential reduction of demand with mobility concepts (large cities)	+ potentially less emissions due to lower absolute demand	+ potential lower demand due to shift in mobility concept	+ limit demand	0/-? put effort in mobility research, concepts and frame conditions
Logistics/ localisation	-- (lower supply with purely European prod.)	+ (although minor share in total cell budget), some %	- (shift of emissions to Europe)	++ (less vulnerable due to "Panama events")	+ (lower transportation cost)
Alternative technologies	++ (up to 20% less LIB demand e.g. with SIB) - More Na/ materials due to lower energy density	0 comparable to LB	-	+ reduced LIB dependency but CN dominates SIB - Supply chains to be established	+ lower material costs - Less scaled technologies
Total	**Half or higher relaxation of situation but potentially overlapping effects**	**Only primary production technologies critical with added footprint**	**Negative from local perspective but positive globally**	**All over positive impact to increase sovereignty**	**Positive impacts if scale effects are realized**

- first frame for assessment, better and consistent data to be expected in coming years, holistiv/systemic assessment beyond LCA, …

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