

Supply chains and recycling processes

Dr. Herena Torio



Agenda

- **Supply chains**
- **Circular economy**
- **The digital pass**
- **Recycling**

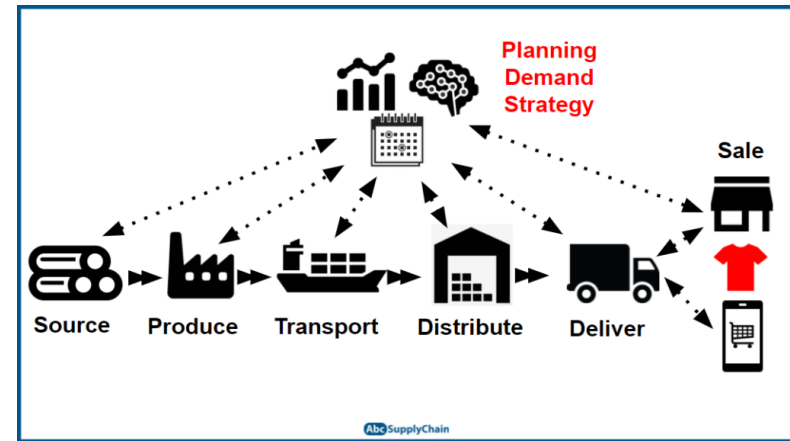
Supply chains

Definition

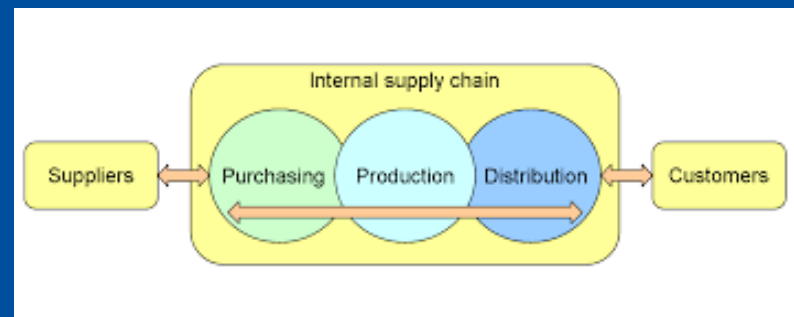
Network of all activities and stages that a product undergoes from the processing of raw material resources it requires until it reaches the final user.

Includes:

- Resources
- Actors
- Processes
 - Purchasing
 - Manufacturing
 - Production
 - Distribution



Once upon a time....



Source: Wikipedia.org

Supply chains

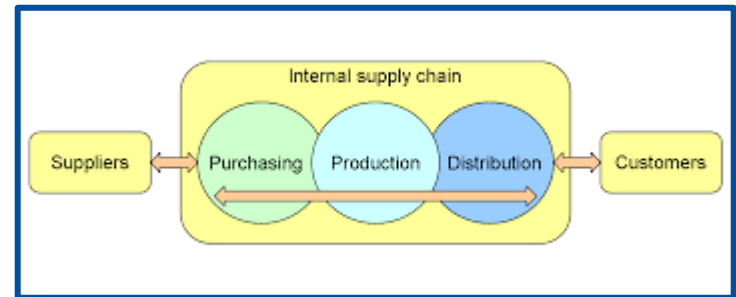
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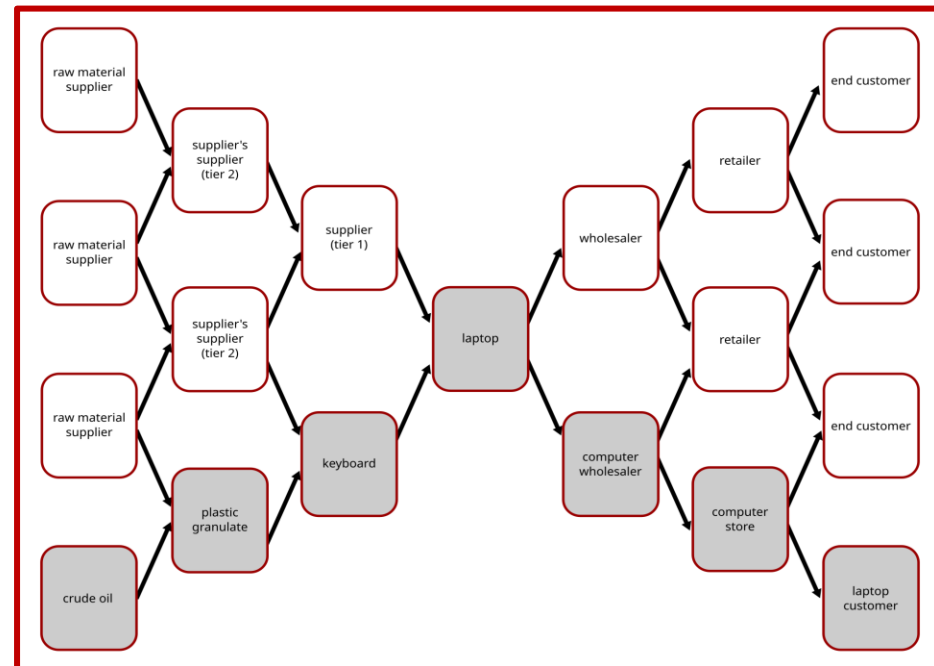
Micro-level



Source: Wikipedia.org



Macro-level



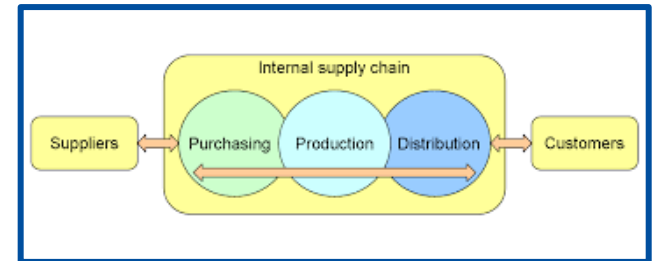
Supply and demand network (en) - Supply chain - Wikipedia

Supply chains

Definition



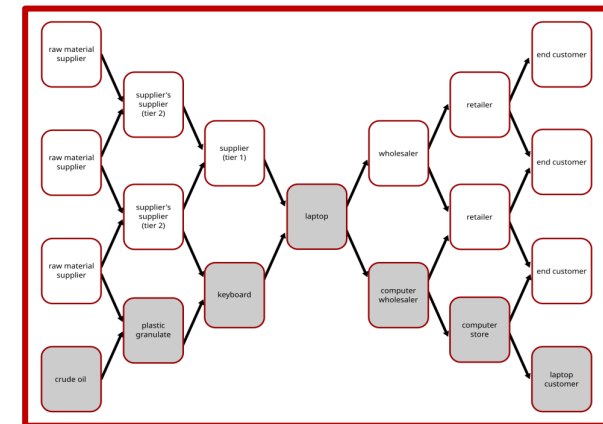
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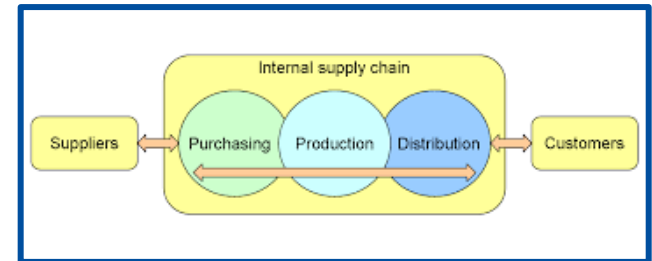
Macro-level



Supply chains

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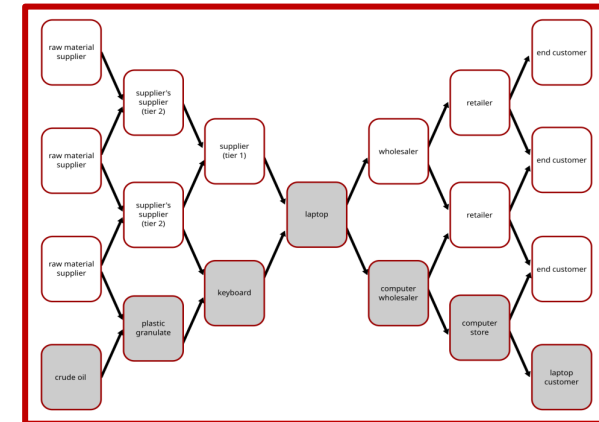
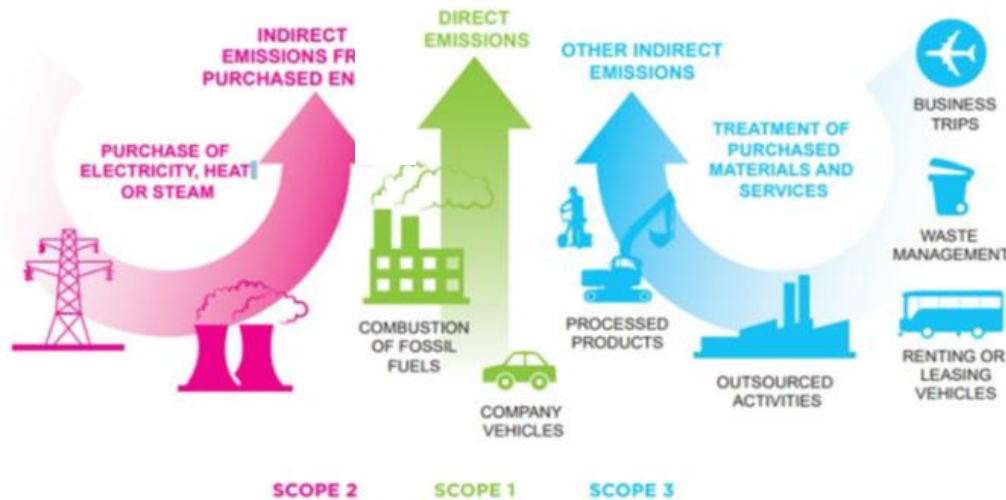
Micro-level



Source: Wikipedia.org



Macro-level

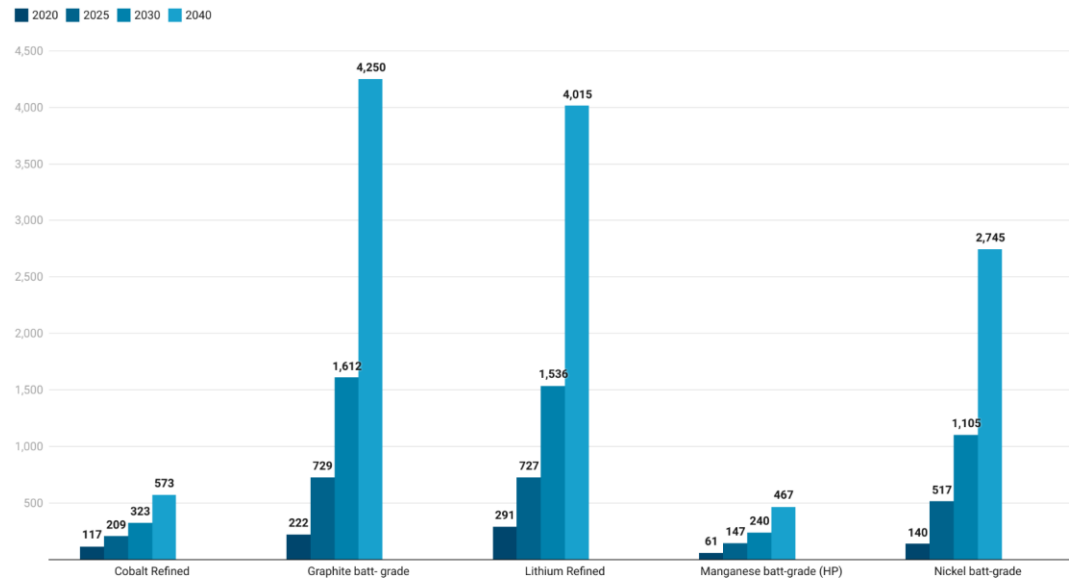


Supply chains

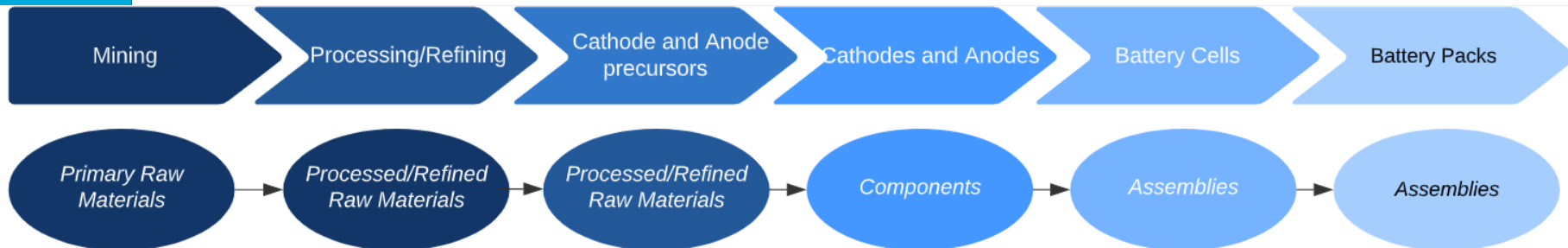
Current status

LINEAR:
Cradle to grave

Figure 1 – Forecast of battery demand globally from processed raw materials [kt]



Source: JRC analysis.



Source: <https://rmis.jrc.ec.europa.eu/analysis-of-supply-chain-challenges-49b749>

Supply chains

Characterization

No single indicator, not very standardized

Micro-level: traditional issues

Service (customer facing perf.)

Customer satisfaction

Time & speed (flow eff.)

Responsiveness, agility

Inventory & capacity (stock health)

Availability vs excess stock

Finance & cash-flow (economic health)

Profitable, capital efficient

Transportation & logistics

Bottlenecks and cost drivers

Planning & demand (predictive quality)

Inventory swings, delays



Source [1]

Supply chains

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Source [1]

Macro-level: growing issues

Sustainability and ESG

(environmental, social, governance)

Environmental and social impact

- CO2 emissions (Scope 3)
- Supplier compliance
- Resource usage (water, energy)

Resilience and disruptions

Shock handling, not routine efficiency

- SC flexibility & adaptability
- Supplier risk / diversification (e.g., single-source exposure)
- Exception rates / disruption frequency
- Time to recover (TTR)

Supply chains

Characterization

- No standard indicators

Sustainability and ESG

- CSDDD: corporate sustainability due diligence directive & CSRD: corporate sustainability reporting directive
 - Only applicable to some companies (e.g. large nr. of employees and turnover)
- Forced Labour
- Deforestation
- Carbon Border Adjustment Mechanism:
e.g. 10-50 € /unreported ton

→ DPP: digital product-passport



Supply chains

Characterization

- No standard indicators



Source [1]

Resilience and disruptions

- **Global Supply Chain Pressure Index (GSCPI)**
“The GSCPI integrates transportation cost data and manufacturing indicators to provide a gauge of global supply chain conditions” [1].
 - real-time proxy for systemic supply chain risk
 - **Macro-level SC indicator**

Includes indicators from following realms:

- **Delivery time:** extent to which supply chain delays in the economy impact producers
- **Backlogs:** volume of orders that firms have received but have yet to either start working on or complete; and, finally,
- **Purchased stocks:** which measures the extent of inventory accumulation by firms in the economy.

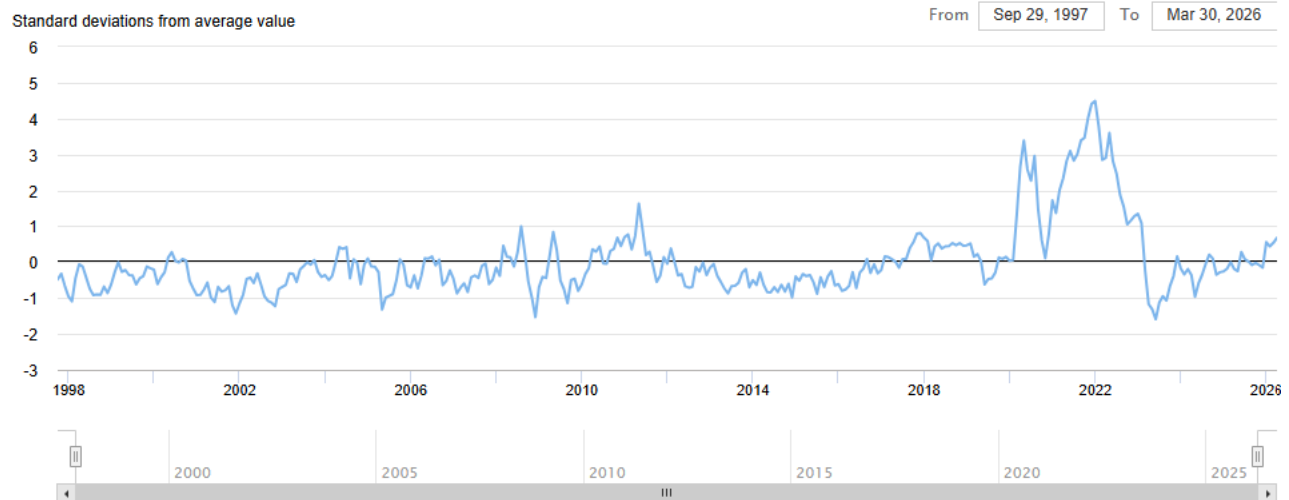
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Latest Update March 2026

Enter a date range to see monthly estimates or use the slider below to view a specific date range.



Source: Global Supply Chain Pressure Index (GSCPI) - FEDERAL RESERVE BANK of NEW YORK

Supply chains

Challenges and Opportunities

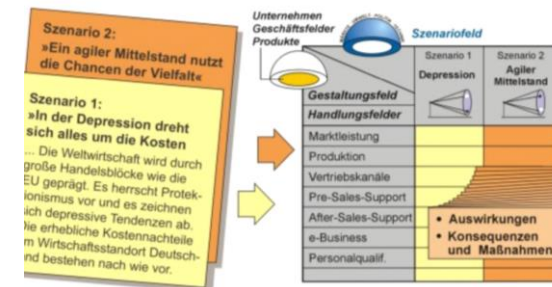
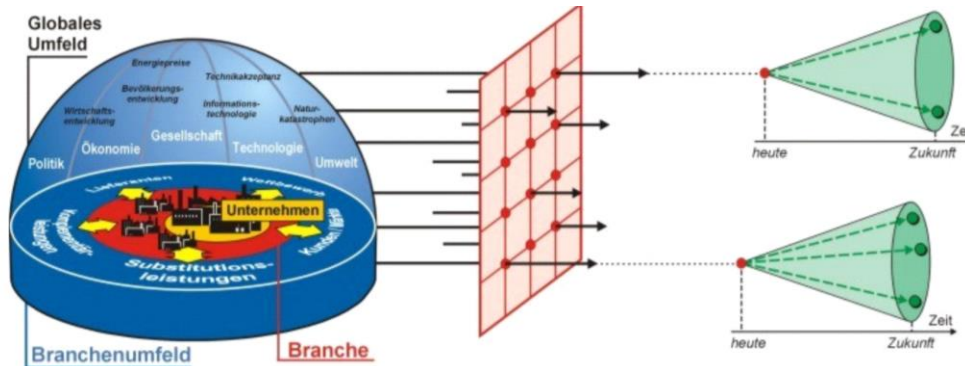
Identify influential factors

Analyse interactions and main drivers

Describe future/ possible trends

Scenarios

SWOT analysis



Supply chains

Challenges and Opportunities

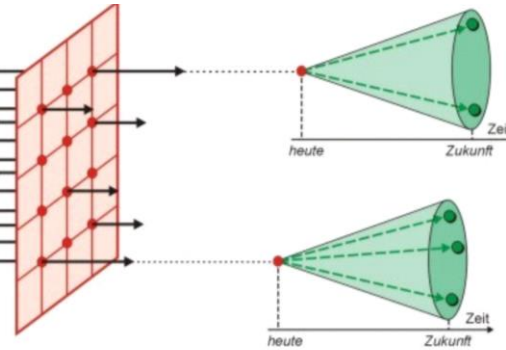
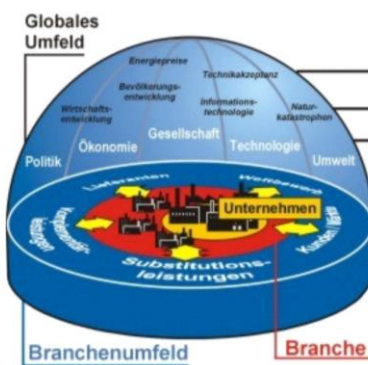
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SWOT analysis



Szenario 2:
»Ein agiler Mittelstand nutzt die Chancen der Vielfalt«

Szenario 1:
»In der Depression dreht sich alles um die Kosten«
... Die Weltwirtschaft wird durch große Handelsblöcke wie die EU geprägt. Es herrscht Protektionismus vor und es zeichnen sich depressive Tendenzen ab. Die erhebliche Kostennachteile im Wirtschaftsstandort Deutschland bestehen nach wie vor.



Strengths

Tech. innovation
Global scope
Reputation & sustainability
Standardized processes

Weaknesses

Dependency on crit. materials
Complexity & Intransparent Supply chains
Costs of sust. measures
Lacking Flexibility

Opportunities

Circular economy & Recycling
New laws as comparative advantage
Tech. Innovation
Aware consumers

Risks

Geopolitical Risks
Global warming
Regulations (CS3D,...)
Greenwashing claims

Supply chains

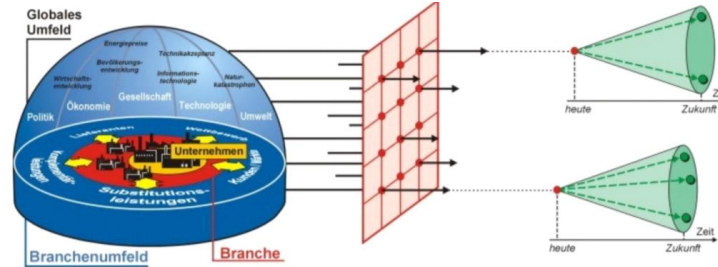
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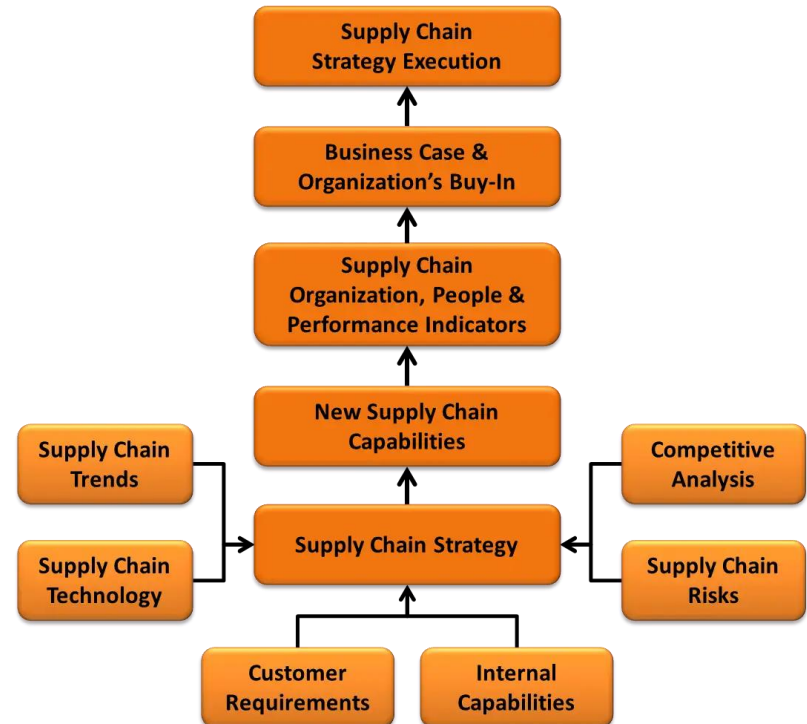
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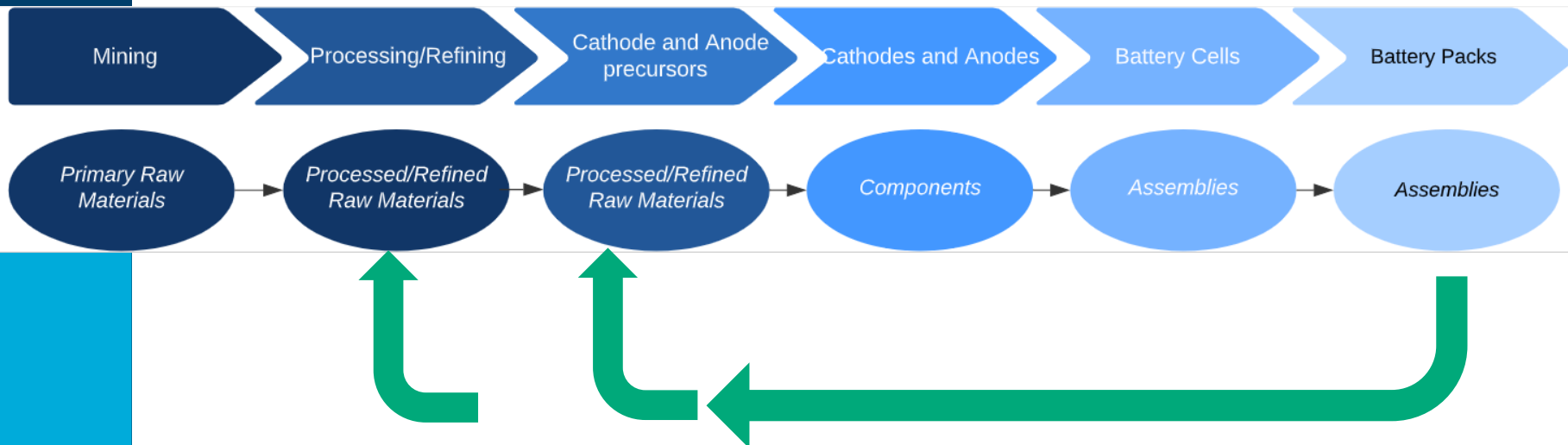
Agenda

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- **Recycling**

Supply chains and circular economy

Concepts coming closer

CIRCULAR:
Cradle to cradle

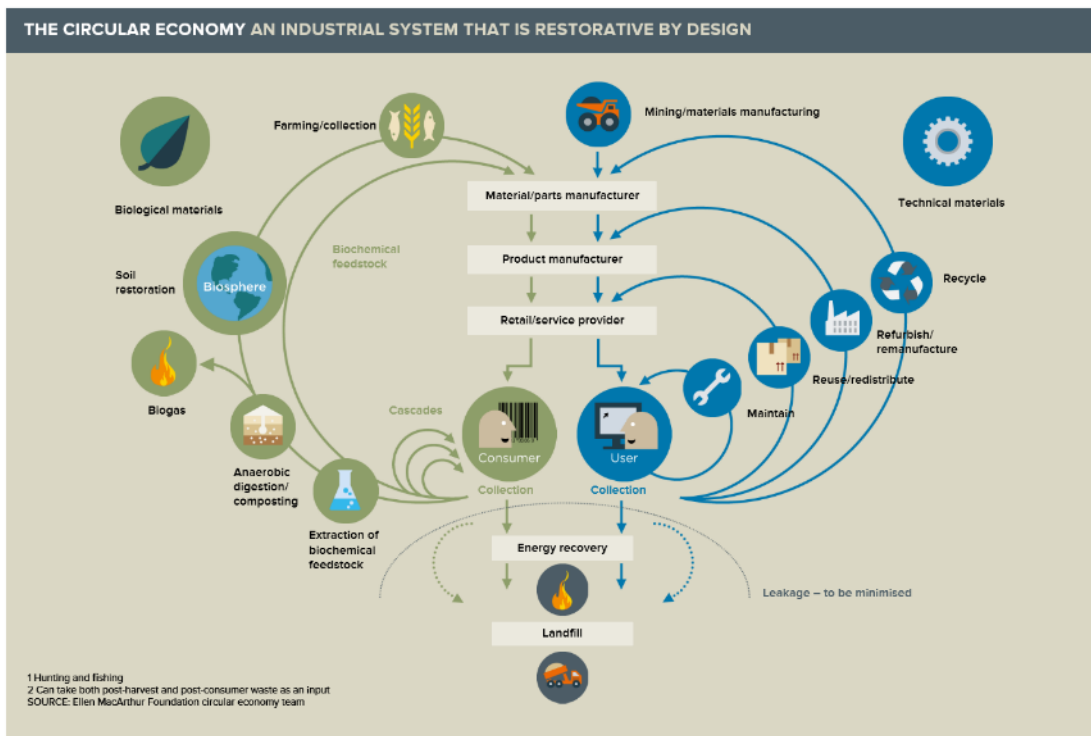


Circular economy

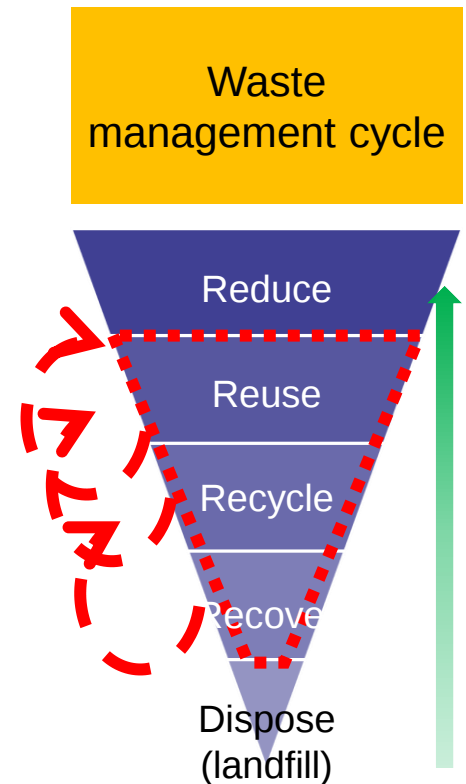
From linear to circular supply chains

Product during lifetime

Service vs. product



Sources: Ellen MacArthur Foundation (<http://www.ellenmacarthurfoundation.org/circular-economy/circular-economy/interactive-system-diagram>)



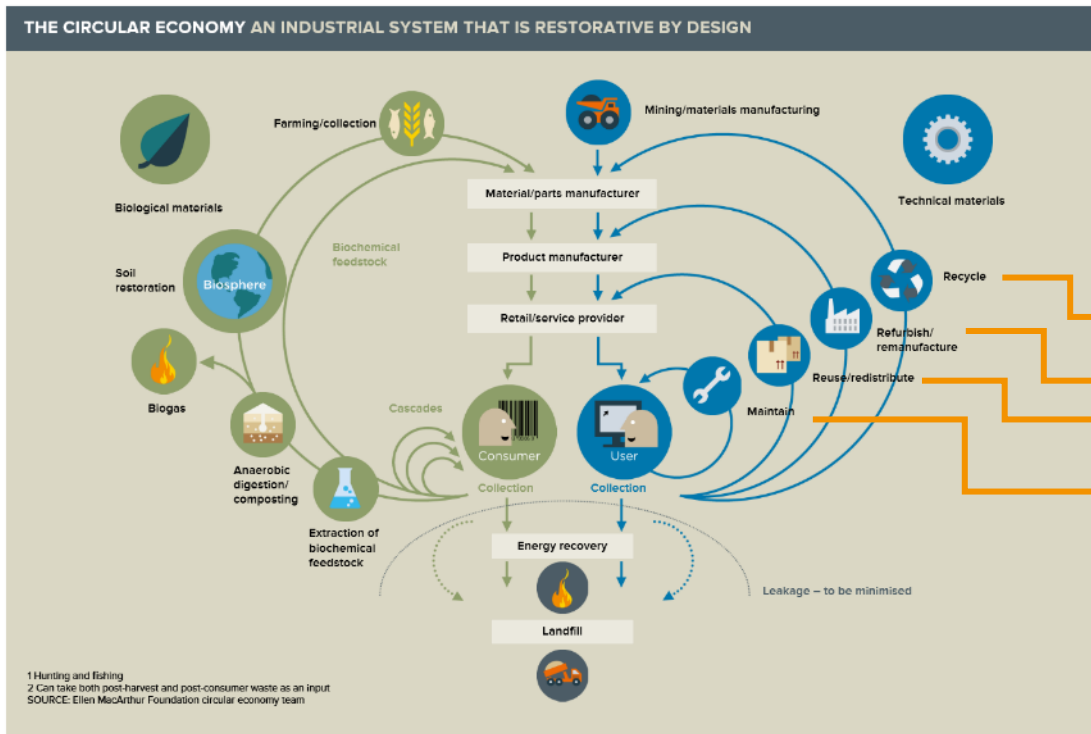
Source: Pehlken, Strategisches Management. Slide Set. Universität Osnabrück (modified)

Circular economy

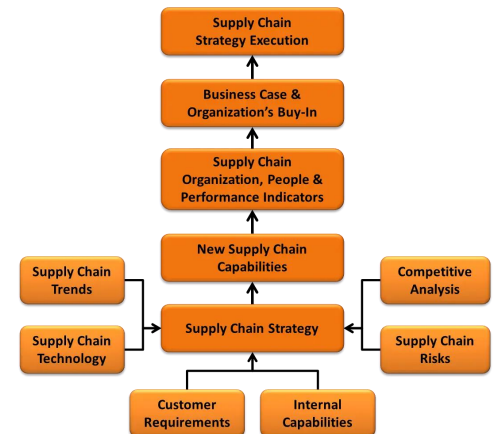
From linear to circular supply chains

Product during lifetime

Service vs. product



Product management cycles



Sources: Ellen MacArthur Foundation (<http://www.ellenmacarthurfoundation.org/circular-economy/circular-economy/interactive-system-diagram>)

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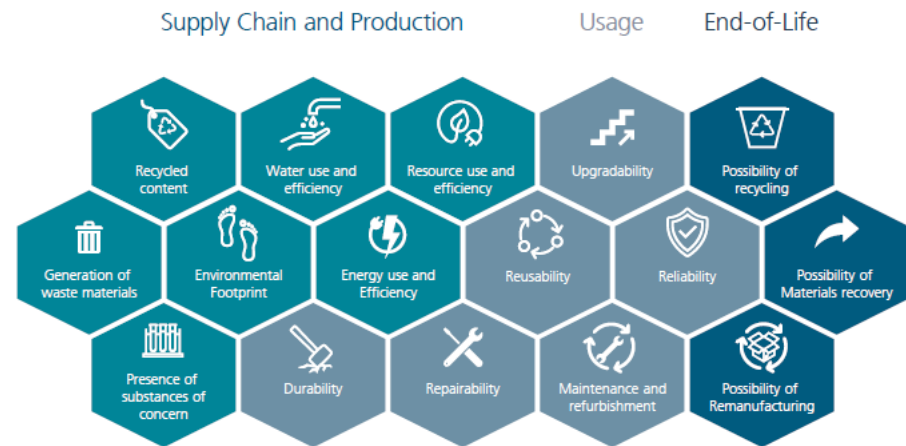
DPP

Digital Product Passport

Compulsory in Feb. 2027

Includes great amounts of data in the **different life-phases** of the battery

2023	2023	BATTERIEN
2026	2027	EISEN UND STAHL
2025	2027	TEXTILIEN
2027	2028	ALUMINIUM
2027	2028	REIFEN
2027	2028	BAUSTOFFE / -PRODUKTE
2027	2028	ELEKTRONIKPRODUKTE
2028	2029	MÖBEL
2028	2029	UMWELTFAHRZEUGPASS
2028	2029	UNTERHALTUNGSELEKTRONIK
2030	2032	KREISLAUFFAHRZEUGPASS
20XX	Erwarteter delegierter Rechtsakt je Produktgruppe	
20XX	Erwartete verpflichtende Umsetzung von Pässen für Unternehmen	



DPP-Datenkategorien aus der ESRP (Quelle: EU Kommission)

DPP

Digital Battery Passport

Compulsory in Feb. 2027

Digital Battery Passport

Battery Regulation:

Battery Passport mandatory from **18 Feb 2027** for:

- Electric vehicle (EV) batteries;
- Light means of transport (LMT) batteries;
- Industrial batteries > 2 kWh.

Responsibility:

- Economic operator¹ placing the battery on the market
- Indirectly: suppliers

DPPs in the EU

Ecodesign for Sustainable Products

Regulation (ESPR) sets the technical framework + several other legislations include DPPs

Single Market Strategy:

- “The EU needs a paradigm shift from a document-based to a **data-based Single market** [...]”
- **DPP** will become the main tool across **all future product legislation**



Objectives of DPPs



Drive **digitalisation** in B2B, B2C and B2G (incl. burden reduction)



Enable shift from linear to **circular** business models



Support **sustainable** and transparent value chains



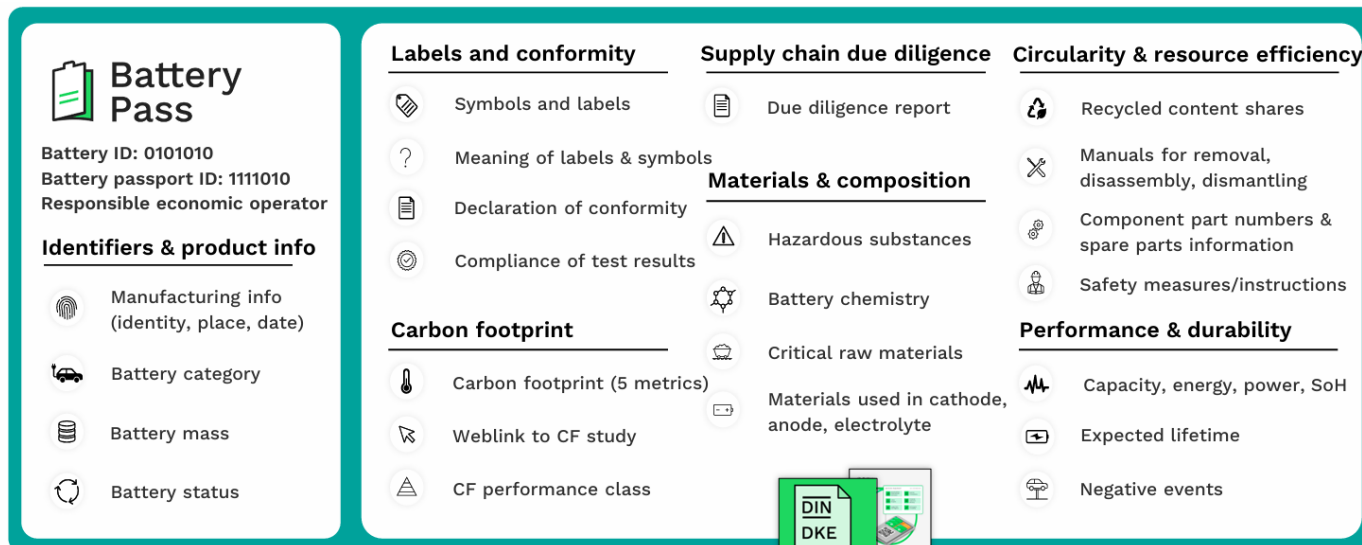
Much more than compliance

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Integrated
in test
procedures

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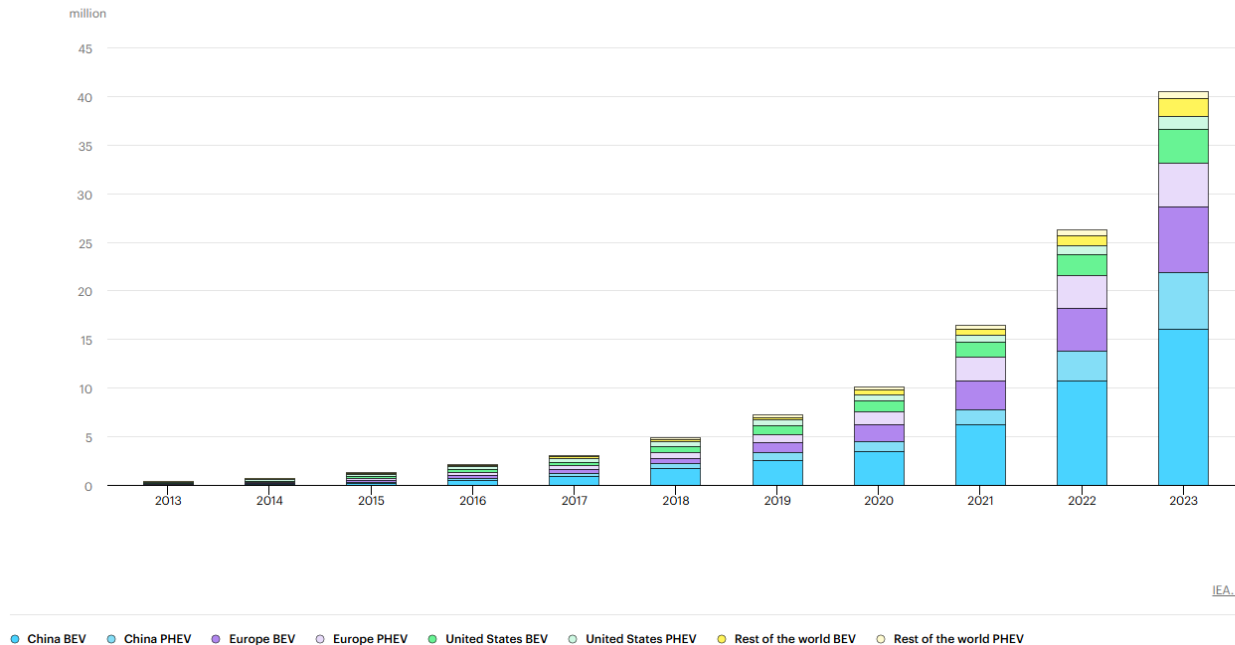
Recycling

Drivers – Demands

- Exponentially growing: 14 million new EV in 2023! (35% more than 2022)
- Until ca. **2035** recycling for **scrap** from production

Global electric car stock, 2013-2023

Open 

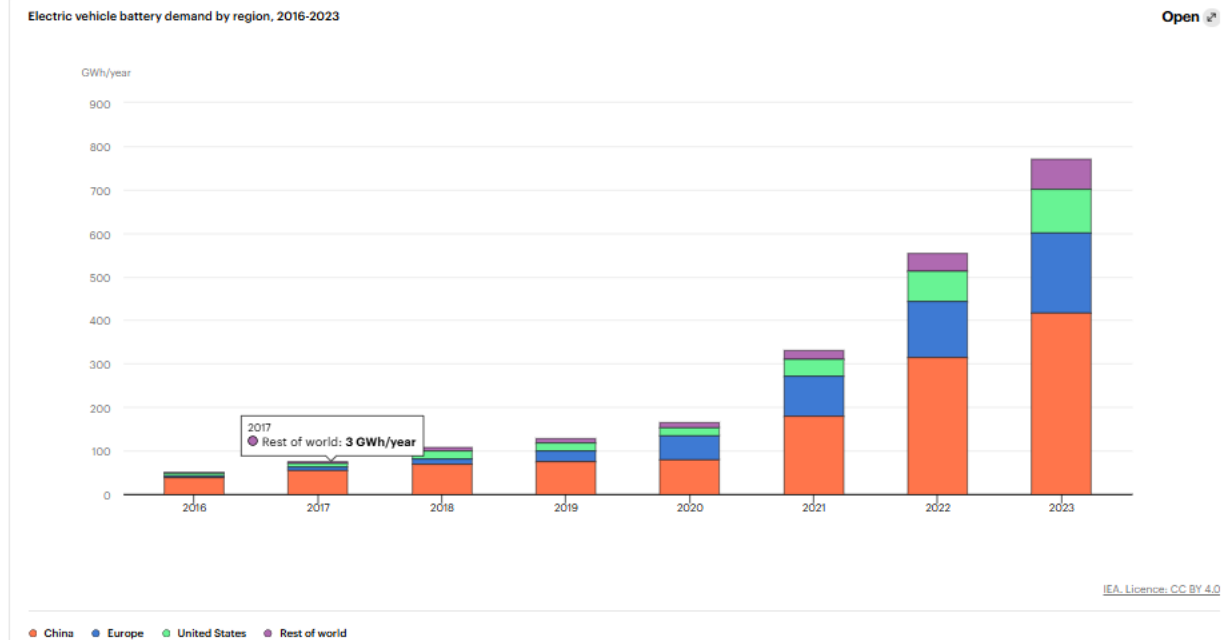


Source: <https://www.iea.org/reports/global-ev-outlook-2024/trends-in-electric-cars>

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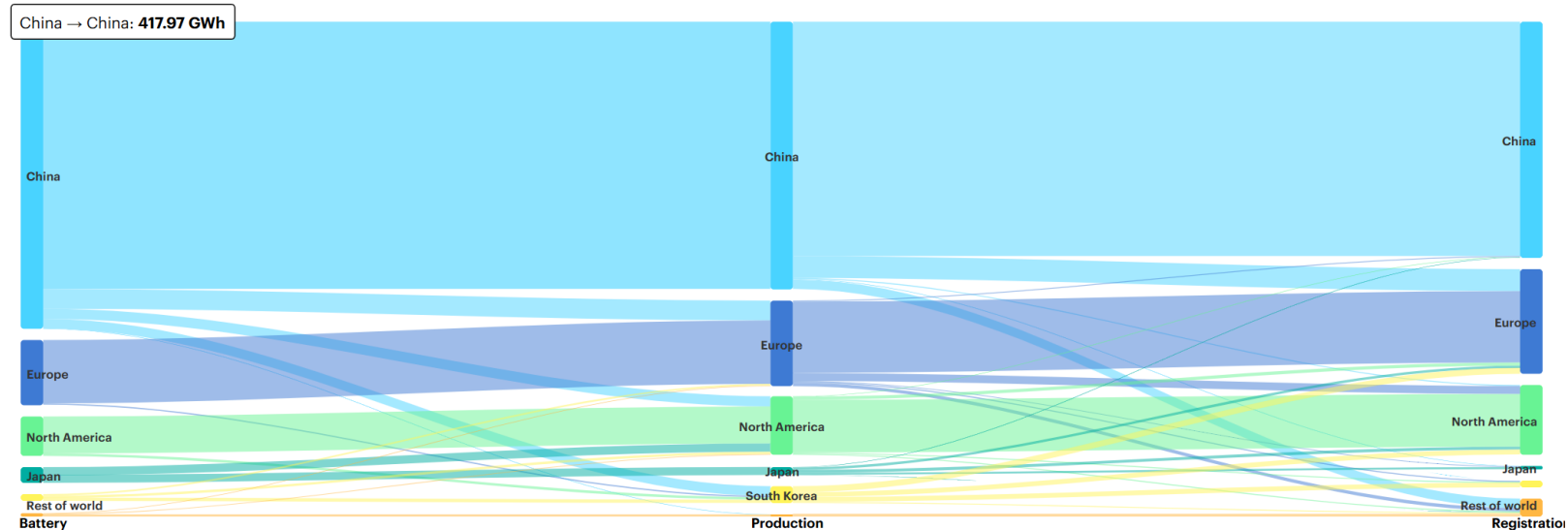
Source: Trends in electric vehicle batteries – Global EV Outlook 2024 – Analysis - IEA

Recycling

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Global trade flows for lithium-ion batteries and electric cars, 2023



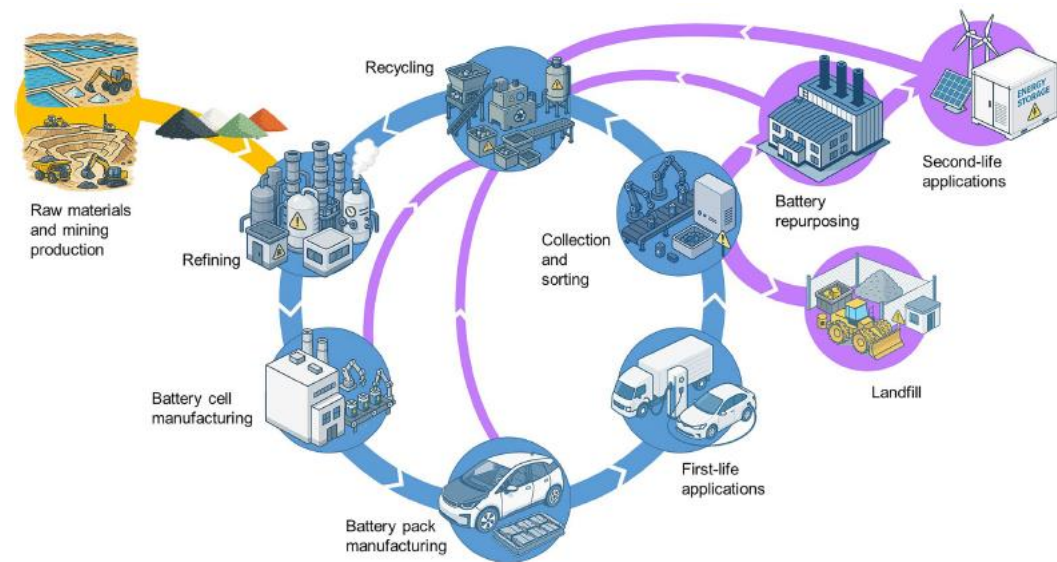
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- Until ca. **2035** recycling for **scrap from production**
 - 2030: 1.2 Mio. Batteries retired each year (Chacana-Olivares et al. 2025)
 - 2040: 14 Mio. Batteries retired each year (Chacana-Olivares et al. 2025)

→ Recycling to **supply main battery properties**

→ Flexible battery process design



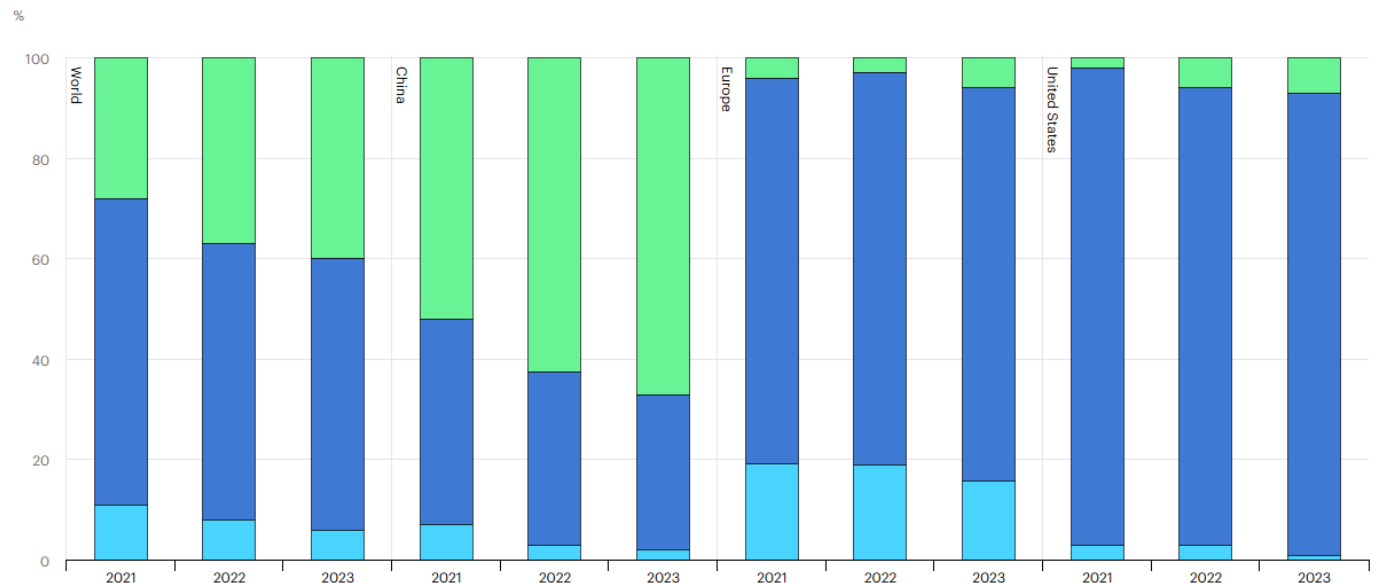
Recycling

Drivers – Demands and composition

- Different battery chemistries and properties (energy density, lifetime,...)

Share of battery capacity of electric vehicle sales by chemistry and region, 2021-2023

Open 



IEA, Licence: CC BY 4.0

● Low-nickel ● High-nickel ● LFP

Source: Trends in electric vehicle batteries – Global EV Outlook 2024 – Analysis - IEA

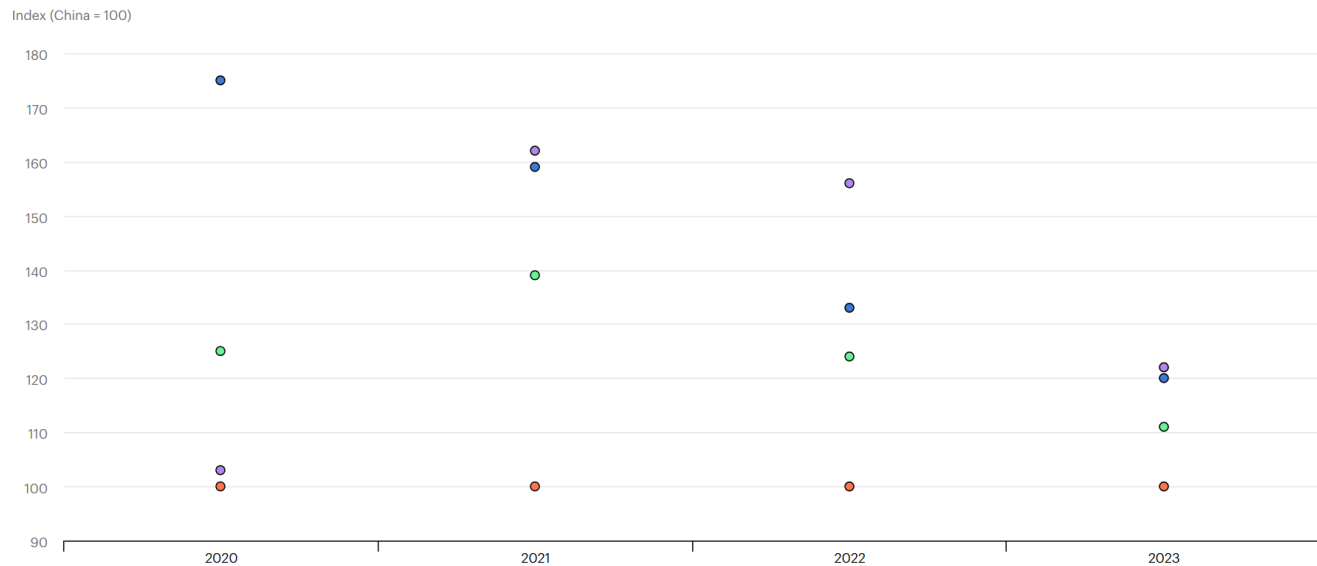
Recycling

Drivers – Demands and composition

- Cost concerns!

Battery price index by selected region, 2020-2023

Open 

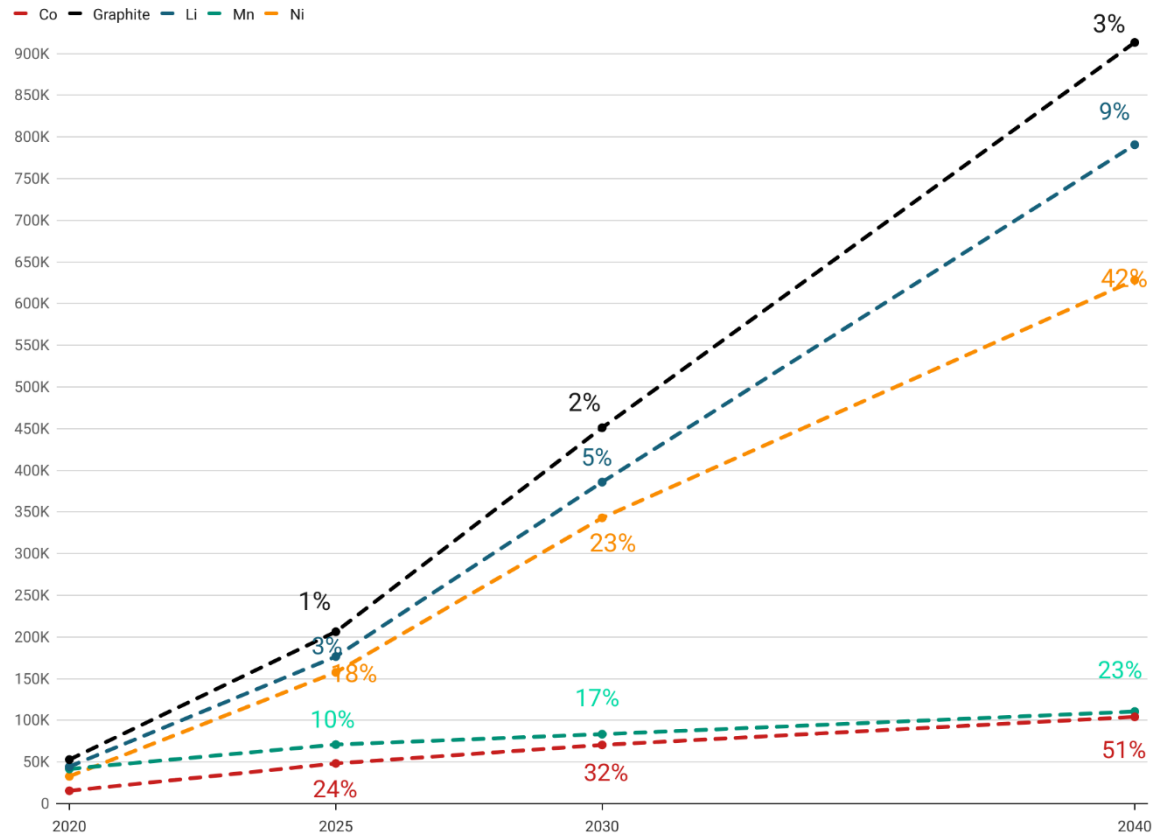


IEA. Licence: CC BY 4.0

● China ● Asia Pacific ● North America ● Europe

Recycling

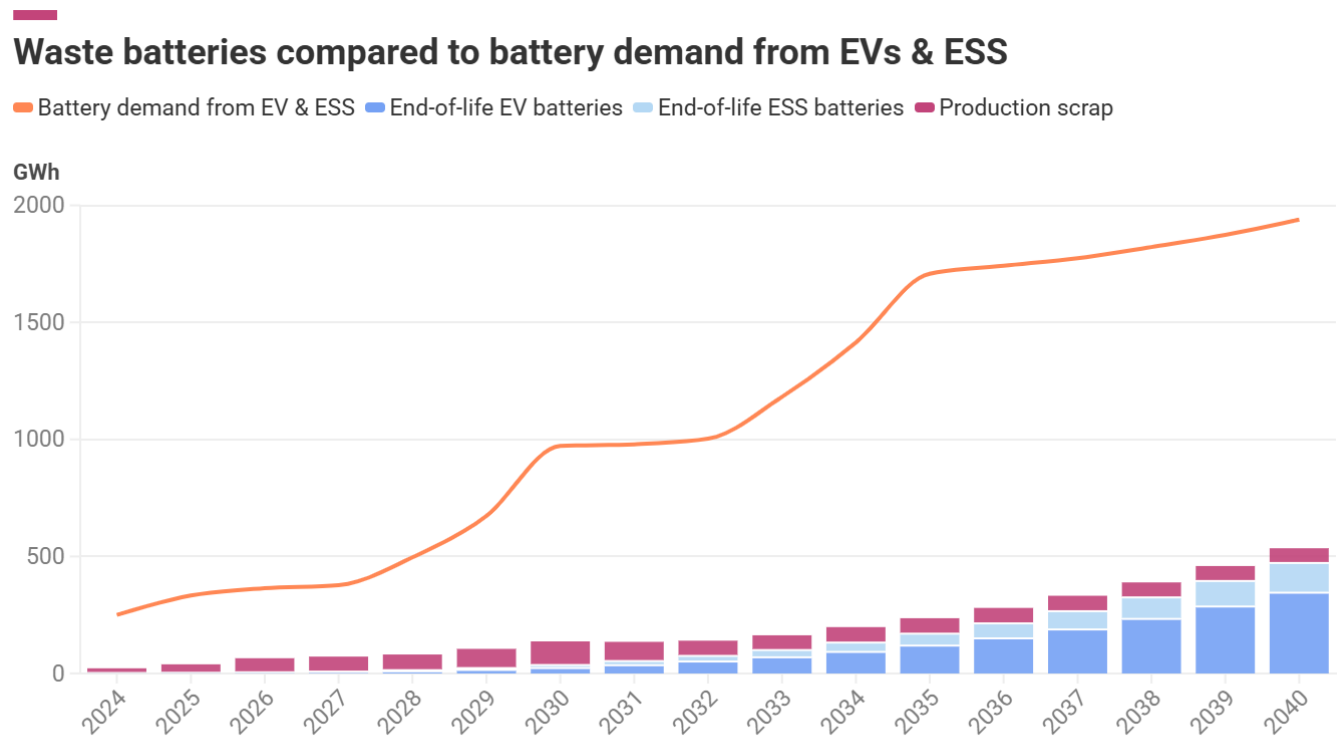
Potential – Materials, processes and costs



Recycling

Potential – Materials, processes and costs

- Recycling potential accelerates steeply after 2030
- Right now mainly **scrap** available



Source: T&E analysis

Recycling

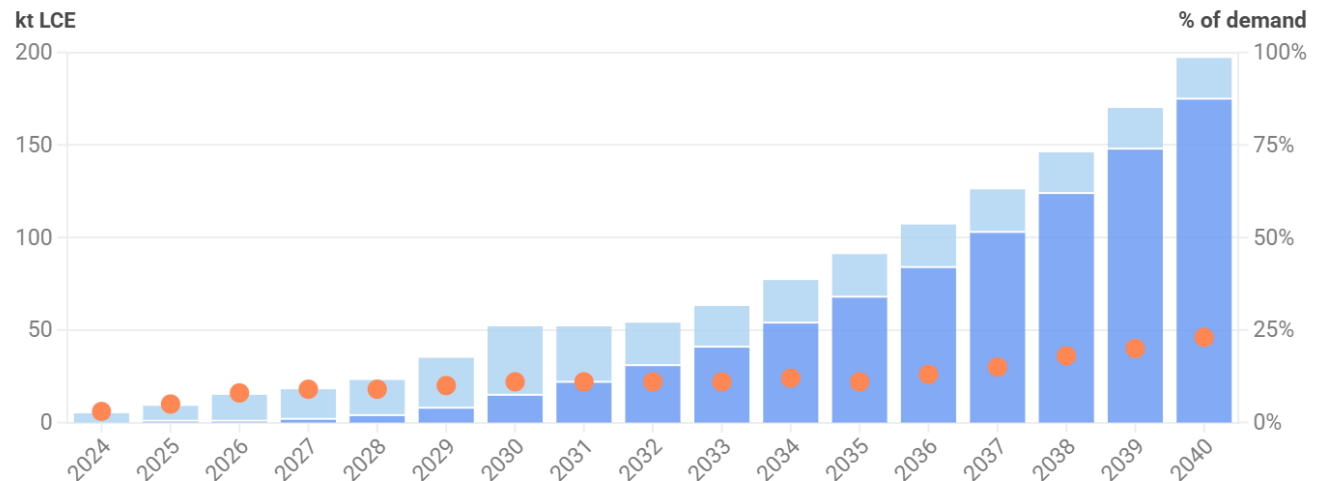
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- The volume of recycled lithium from scrap is projected to peak around 2030 and then stabilize as gigafactories reach full operational efficiency.
- Recycled lithium to meet about 11% of demand during 2030-2035, increasing to 23% by 2040.

Recycled material from end-of-life batteries and production scrap relative to demand

Lithium

Recycled lithium as % of demand Recycled lithium from EoL batteries Recycled lithium from scrap



Source: T&E analysis

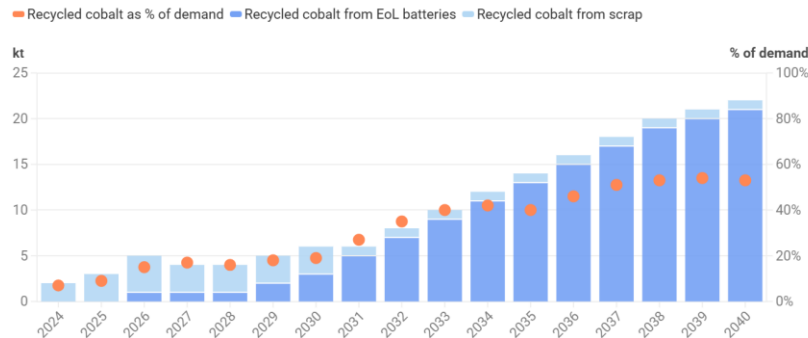
Recycling

Potential – Materials, processes and costs

- By early 2030s, recycled nickel is expected to cover 12% of demand, its share relative to demand is expected to increase to 16% by 2035 to 28% by 2040.
- Cobalt: expensive, ethical concerns, depletion and geographical concentration → displacement to Ni-rich chemistries (Co-poor)

Recycled material from end-of-life batteries and production scrap relative to demand

Cobalt



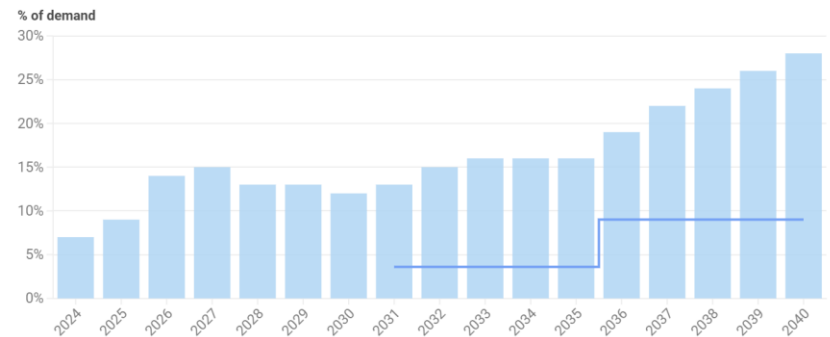
Source: T&E analysis

T&E

Recycled materials: targets vs. forecast

Nickel

Minimum recycled content required by the Battery Regulation Nickel recovered from recycling



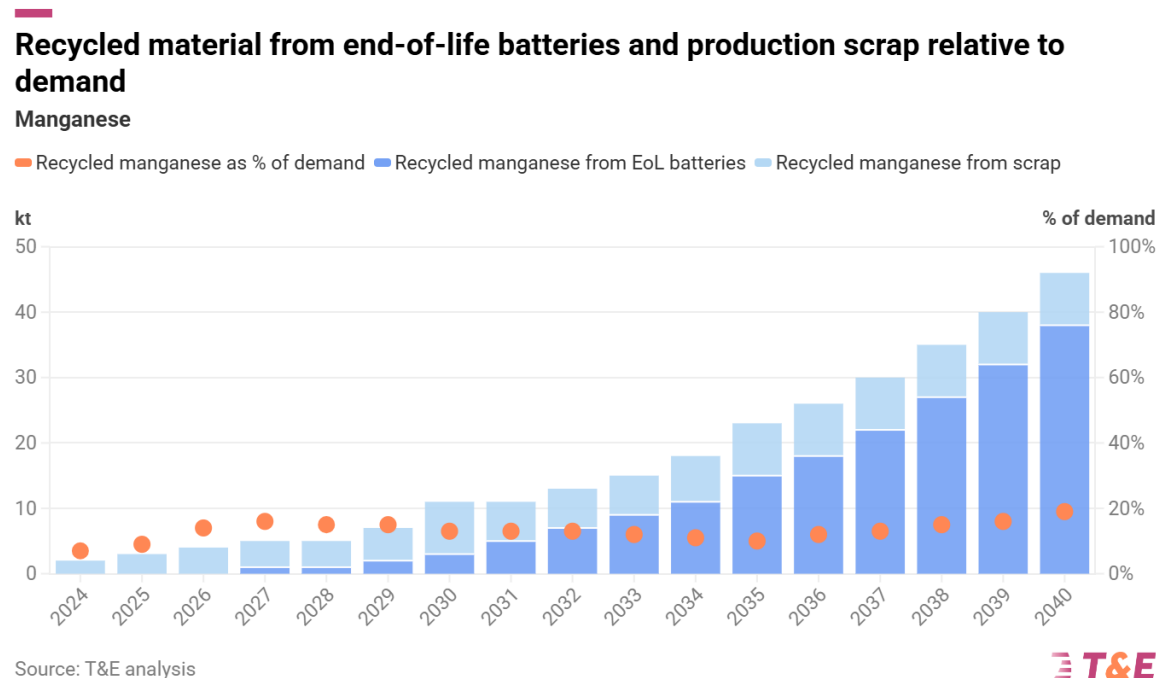
Source: T&E analysis

T&E

Recycling

Potential – Materials, processes and costs

- Manganese: lower cost alternative than Ni, and Co. But difficult to process (purity)
- Higher recycling rates possible (>95%)



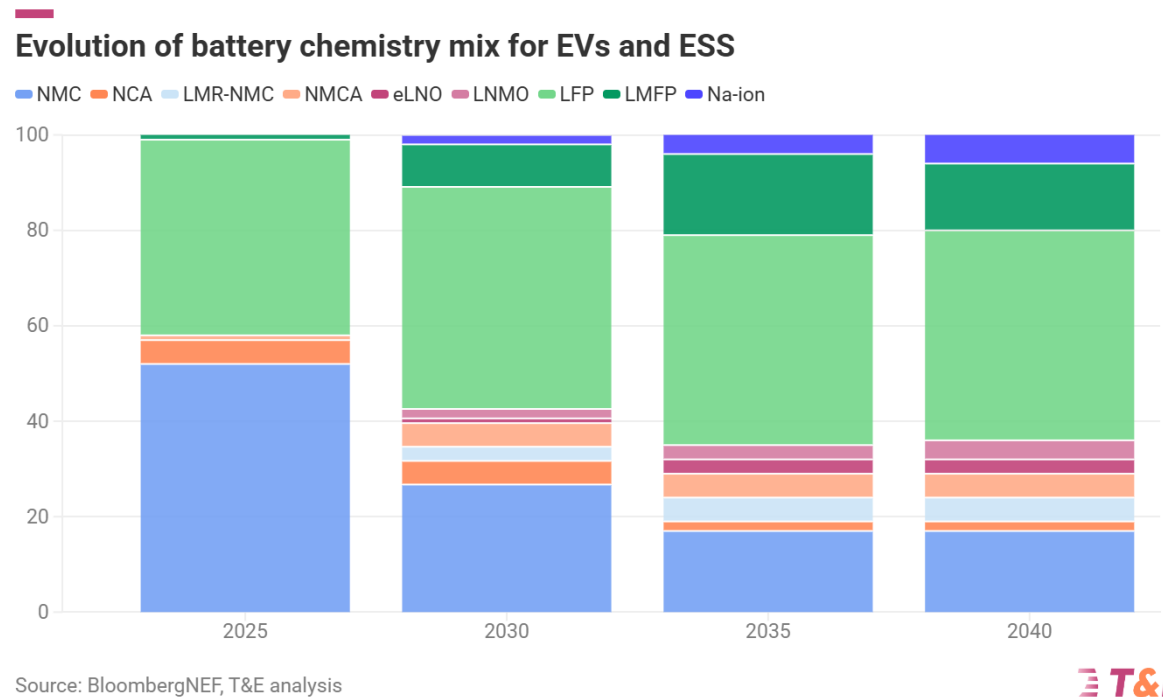
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Low Nickel

High Nickel



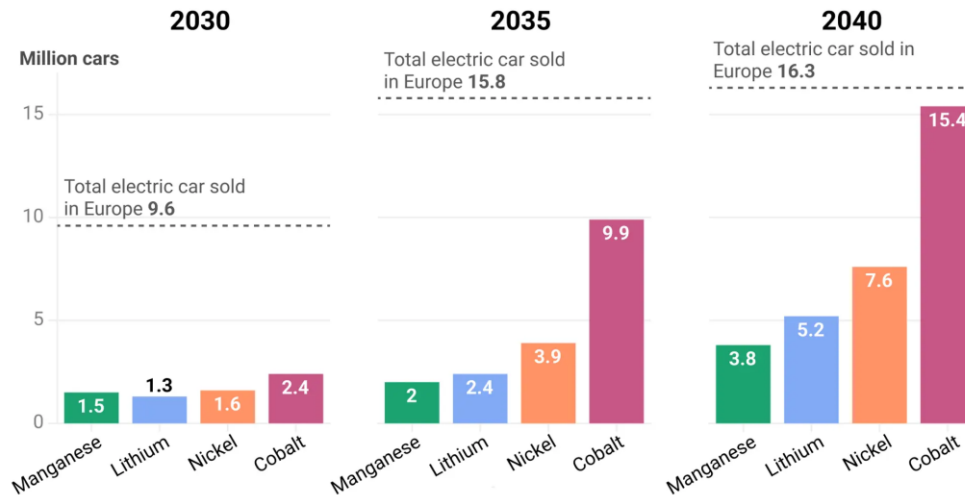
Recycling

Potential – Materials, processes and costs

- End-of-Life batteries and scrap from battery gigafactories in Europe have potential to provide 14% of all lithium, 16% of nickel, 17% of manganese, and a quarter of cobalt demand by 2030 already.
- These materials will be enough to build between 1.3 and 2.4 million EVs locally in 2030, up to 10 mln in 2035, and up to 15 mln EVs by 2040.

Potential BEV production from recycled materials in Europe

Recycled material used to produce electric cars



Source: T&E analysis • Assuming a medium electric car with 74 kWh battery capacity
Scope: EU, UK, Norway and Switzerland



19%

CO2 saving of recycling lithium in Europe compared to extracting it in Australia and refining in China

44%

of recycling capacity that has been announced for Europe is on hold or uncertain to go ahead

Recycling

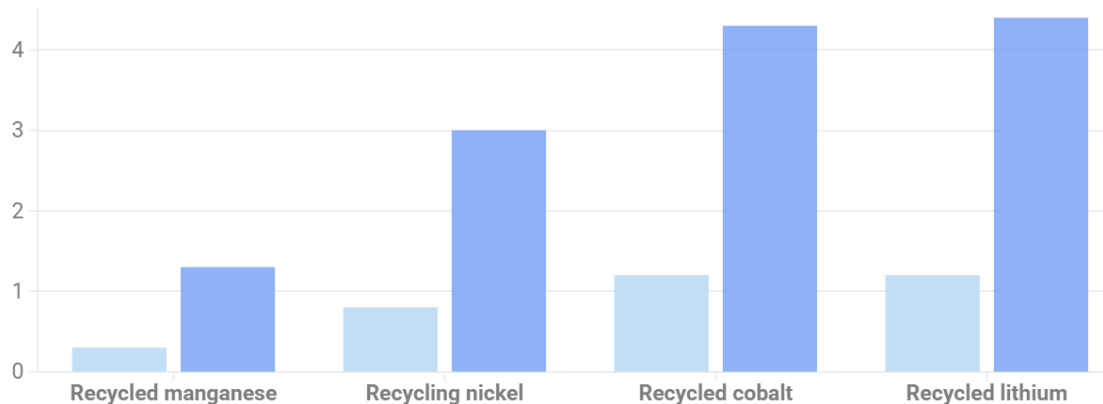
Potential – Materials, processes and costs

- **Lithium:** 2/3 from spodumene (hard metal mining), 1/3 from brine (salt-deserts)
- **Cobalt:** mainly RDC (recently Indonesia!)
- **Nickel:** currently mainly sulphide ores (Canada, AU), but also ever more laterite ores (tropical regions, high environmental impacts!)
- **Manganese:** mainly from South Africa, recovery rates increasing (batt. Chemistries)

Mines replaced through recycling

2030 2040

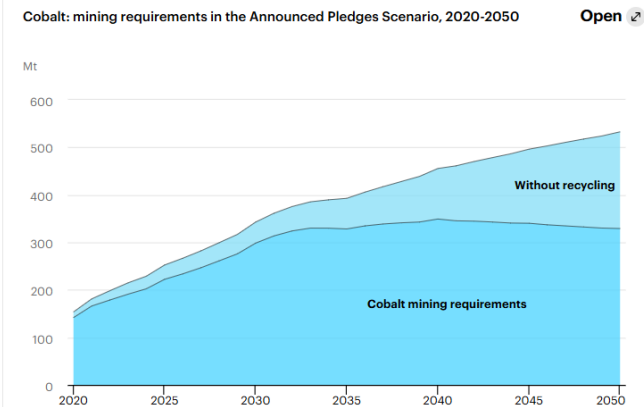
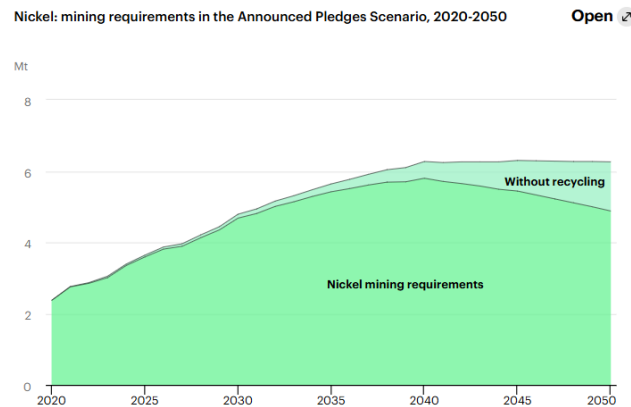
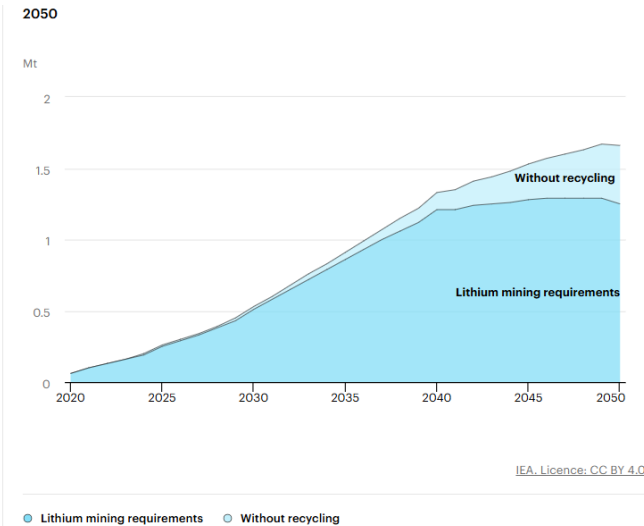
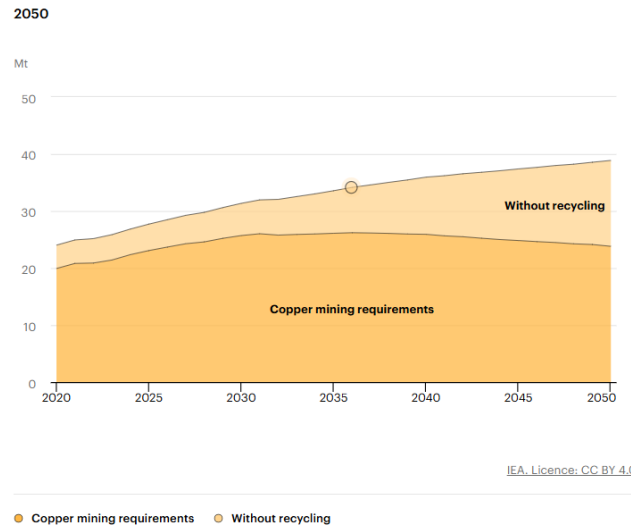
Number of mines replaced



Source: T&E analysis, Benchmark Mineral Intelligence • Average mine size assumptions: 45 kt LCE annual output for lithium, 42 kt for nickel, 5 kt for cobalt and 35 kt for manganese. 

Source: From waste to value: the potential for battery recycling in... | T&E

Recycling Potential –



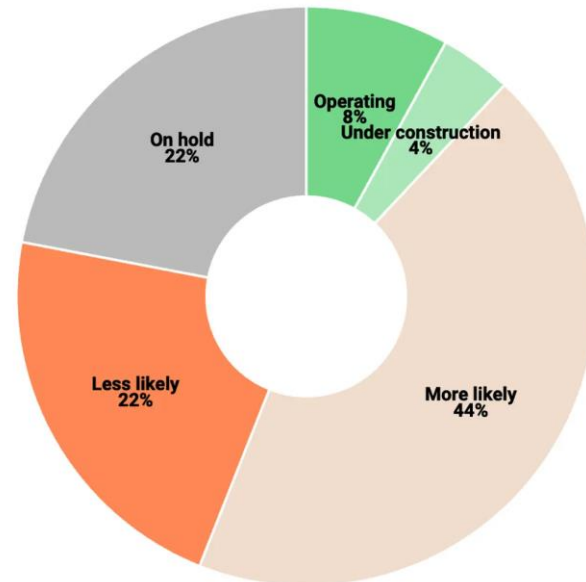
Recycling

Potential – Materials, processes and costs

Main challenges: project complexity and high capital and operating costs in a still-developing market

Almost half of Europe's battery recycling plans at risk

Operating Under construction More likely Less likely On hold



Source: T&E analysis, Circular Energy Storage • Based on total capacity of 781 kt batteries equivalent by 2030 (November 2024 assessment). Analysis does not include the expansion of Umicore Belgium project, which is planned for 2032

Recycling

Overview of main processes

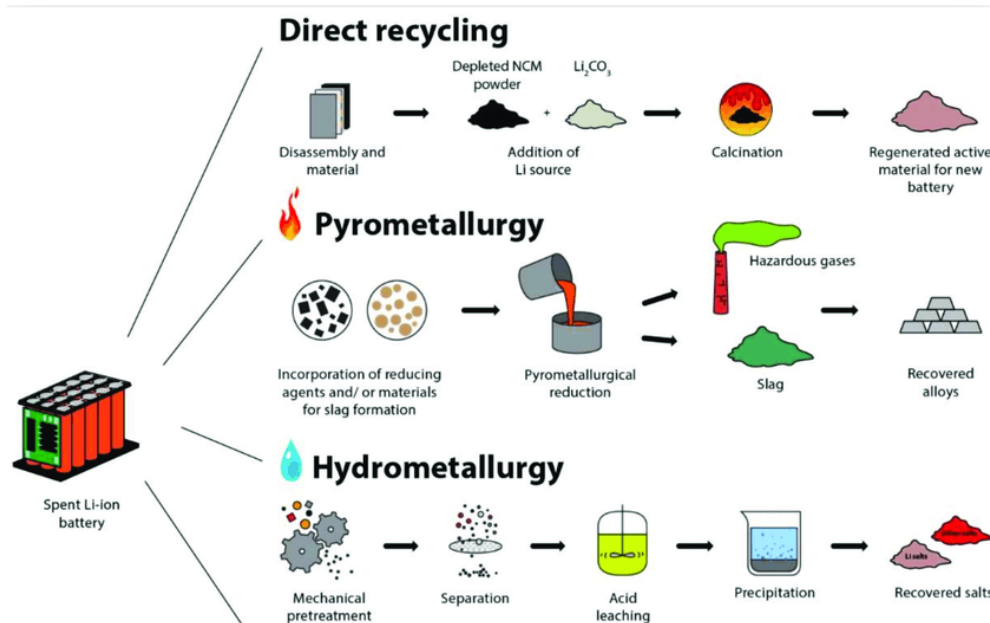
Pyrometallurgy

Main process, also followed by hydrometallurgy

Hydrometallurgy

CAPEX and OPEX costs are significant (electricity and labour):

- 14 \$/kWh in Europe vs 11 \$/kWh in China



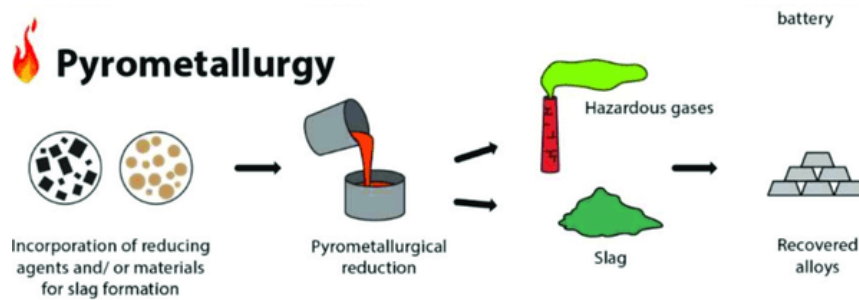
Factors	Pyrometallurgy	Hydrometallurgy
Initial capital investment	high	low
Relative energy requirements	moderate	high
Primary waste products	solids and air	liquids and solids
Rate of chemical reaction	high	low
Production costs	low	intermediate
Level of separations	low	high

DOI: 10.1016/B978-0-12-803581-8.03609-2

Recycling

Overview of main processes

Pyrometallurgy



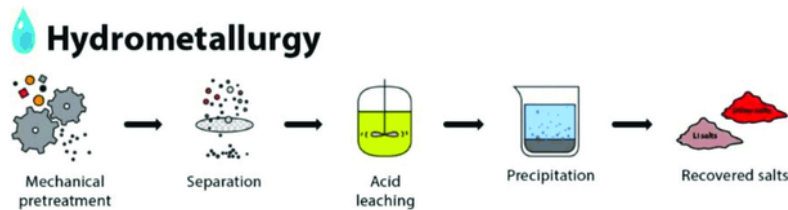
- Recovery rates for Ni, Co & Cu and copper can reach 95%.
- Li and Mn lost in the remaining slag → require additional processing through hydrometallurgy, where lithium recovery can exceed 70%.
- Graphite from anode is typically burned off

Source: Hydrometallurgical Battery Recycling Plant Quotation - Guanma Machinery

Recycling

Overview of main processes

Pyrometallurgy



- Recovery rates of up to 95% for Co, Mn, Ni present from the black mass.
- Lithium recovery has also been improving, on average up to 90% at commercial scale, achieving even 95%
- Efforts to target graphite recycling

Source: Hydrometallurgical Battery Recycling Plant Quotation - Guanma Machinery

Recycling

Flexible recycling process design

Comminution (shredding)

Industry scale

Most batteries currently enter comminution and shredding processes.



In many recycling processes, batteries are first discharged through brine discharge or ohmic discharge.

Currently: shredding

- mainly for scrap from production
- Mixing all materials
- Afterwards separating some of them

- Applicable on all chemistries
- Standard general procedure

Recycling

Flexible recycling process design

Alternative: disassembly route

- Higher yield of material recovery
- Recovery at higher value state
- Specific for battery composition
- Labour intensive
- Robotic disassembly in infancy state

Disassembly (robotics, automation)

Laboratory scale

Laboratory-scale recycling processes focus on either disassembly of cells for cleaner separation, or taking shredded material and applying more advanced separation techniques that are currently used by industry. Disassembly at scale could unlock different approaches to recycling in the future.

Currently, the dismantling of battery packs takes place at small scale. To be economical at scale, the process needs to be automated, but robotic disassembly is challenging given the variety of battery packs on the market.



Recycling

Flexible recycling process design

Comminution (shredding)

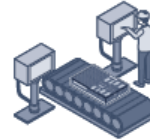
Industry scale

Most batteries currently enter comminution and shredding processes.



In many recycling processes, batteries are first discharged through brine discharge or ohmic discharge.

Gateway testing and triage



Received batteries are tested to determine which cells and modules are suitable for repair, remanufacture, reuse or recycling. Cells and modules with no further economic use pass into the recycling process.

Pack

Disassembly (robotics, automation)

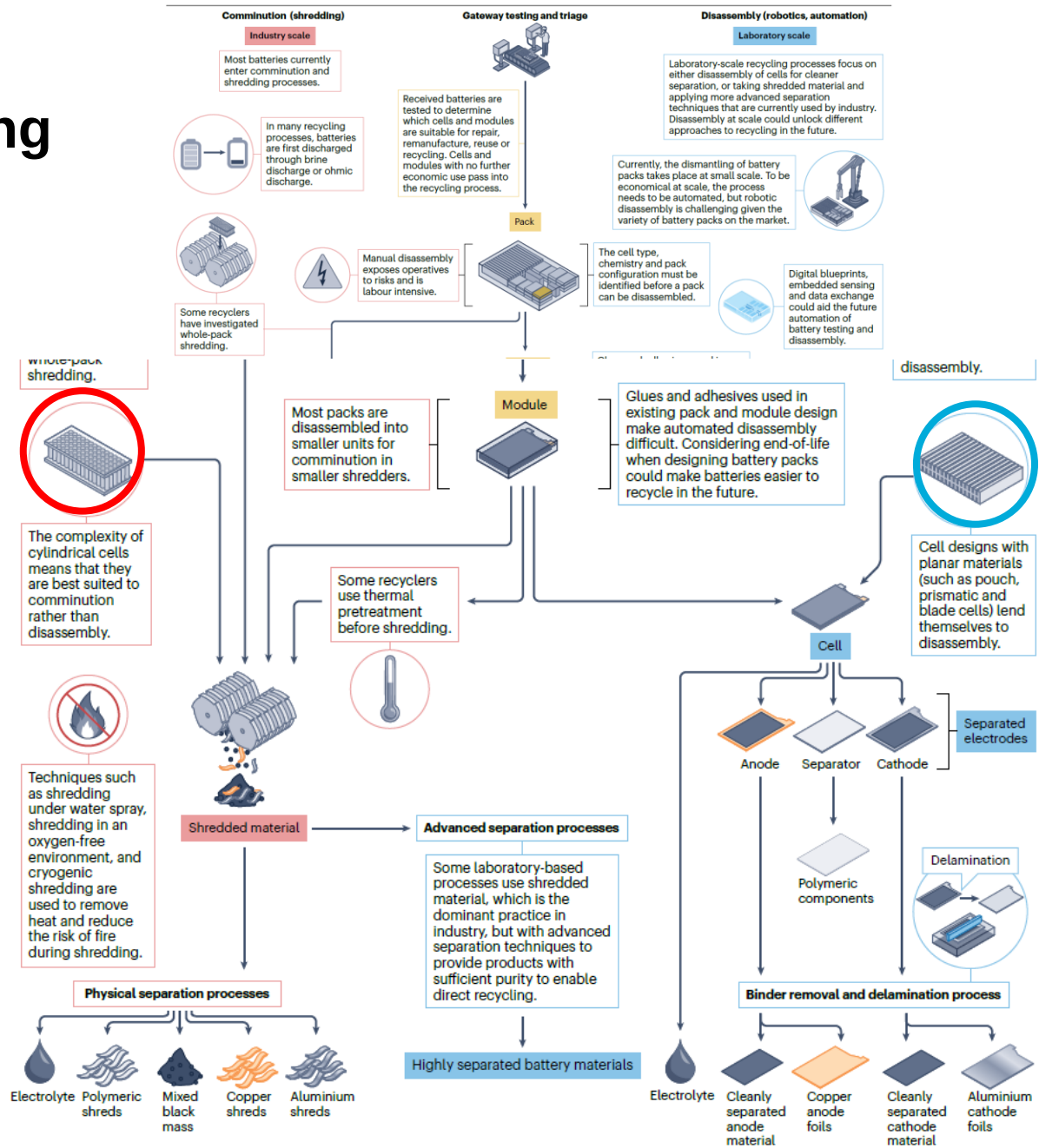
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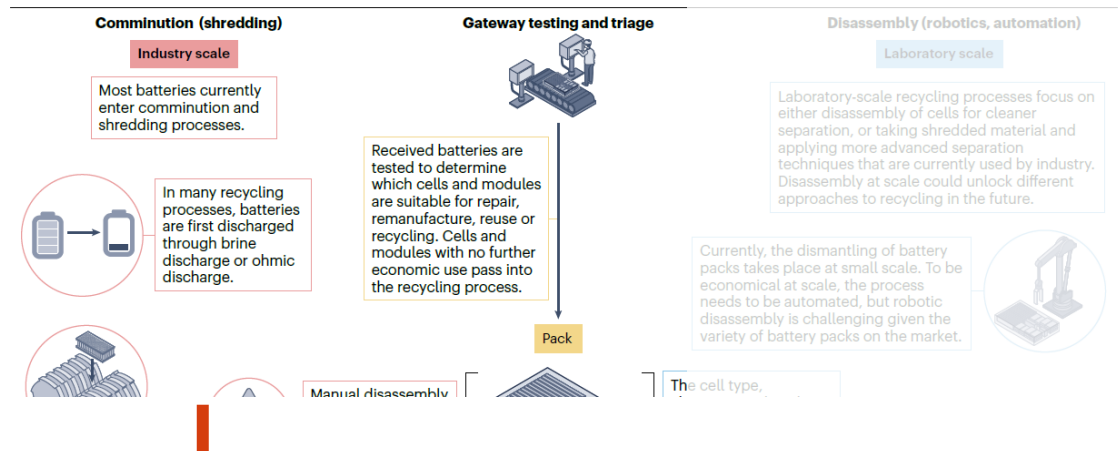


Recycling



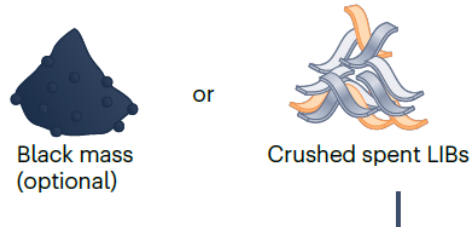
Source: The evolution of lithium-ion battery recycling. Ma et al., 2025. Nature Reviews,
<https://doi.org/10.1038/s44359-024-00010-4>

Recycling

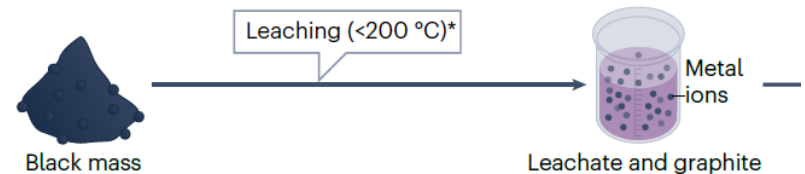


- Battery design determines recycling success
- Production, pre- and post-processing processes need to be developed / adapted

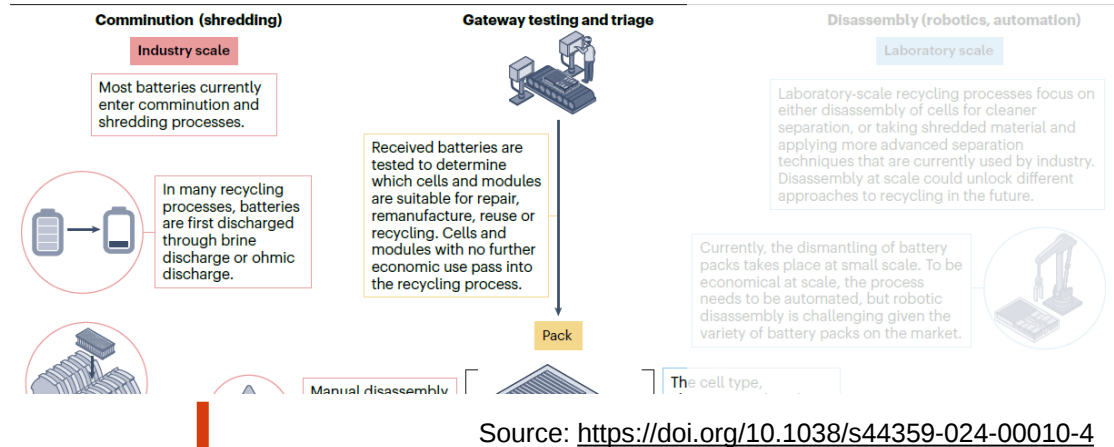
a Pyrometallurgical



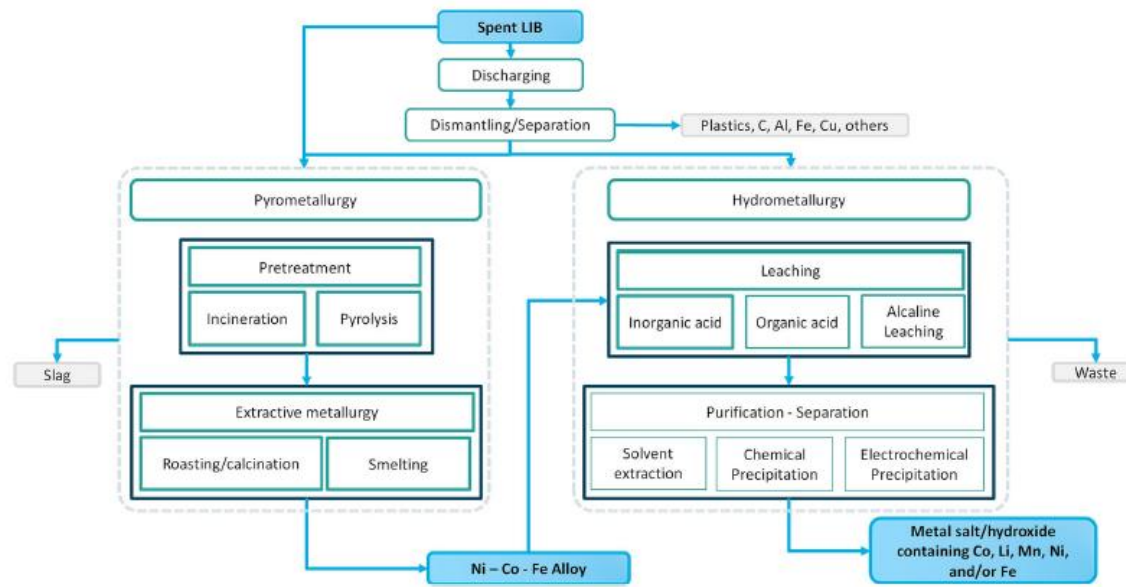
b Hydrometallurgical



Recycling



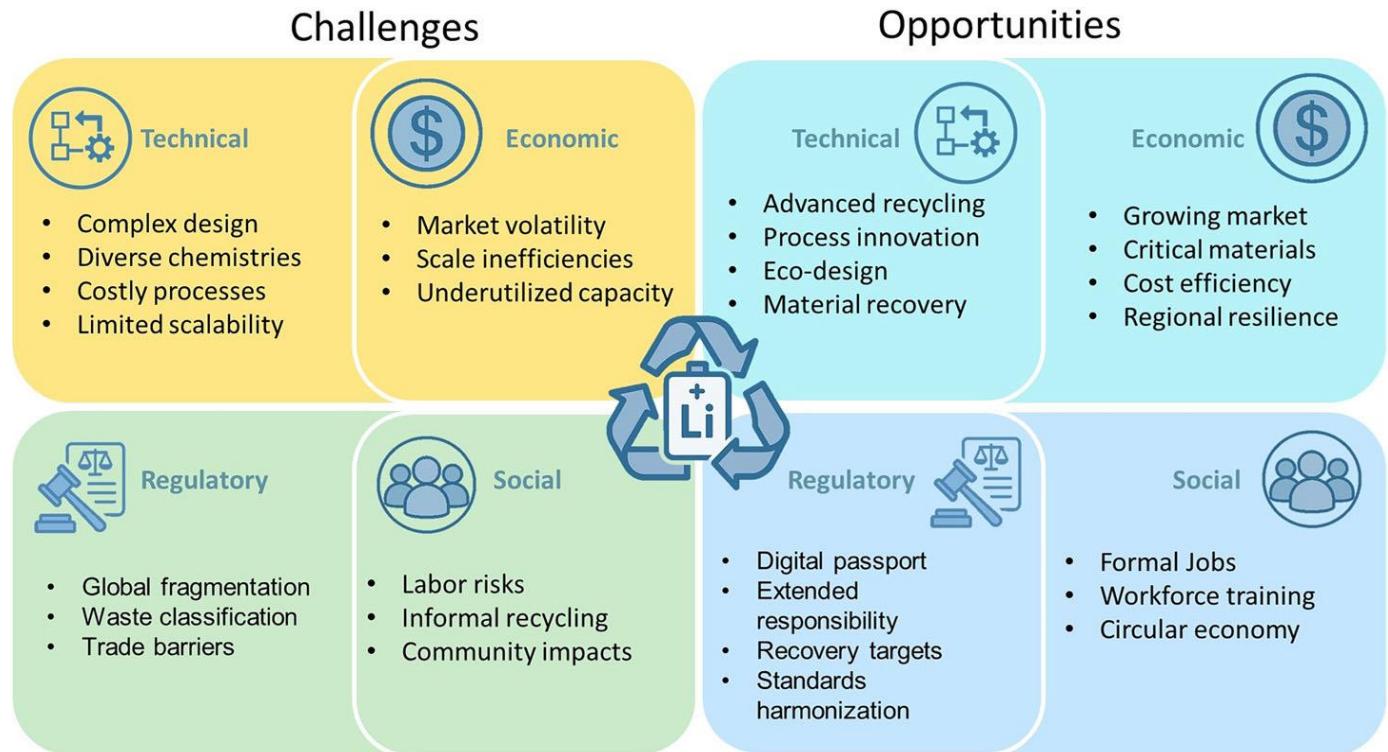
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Closing the loop

Sustainability – Supply Chain Characterization

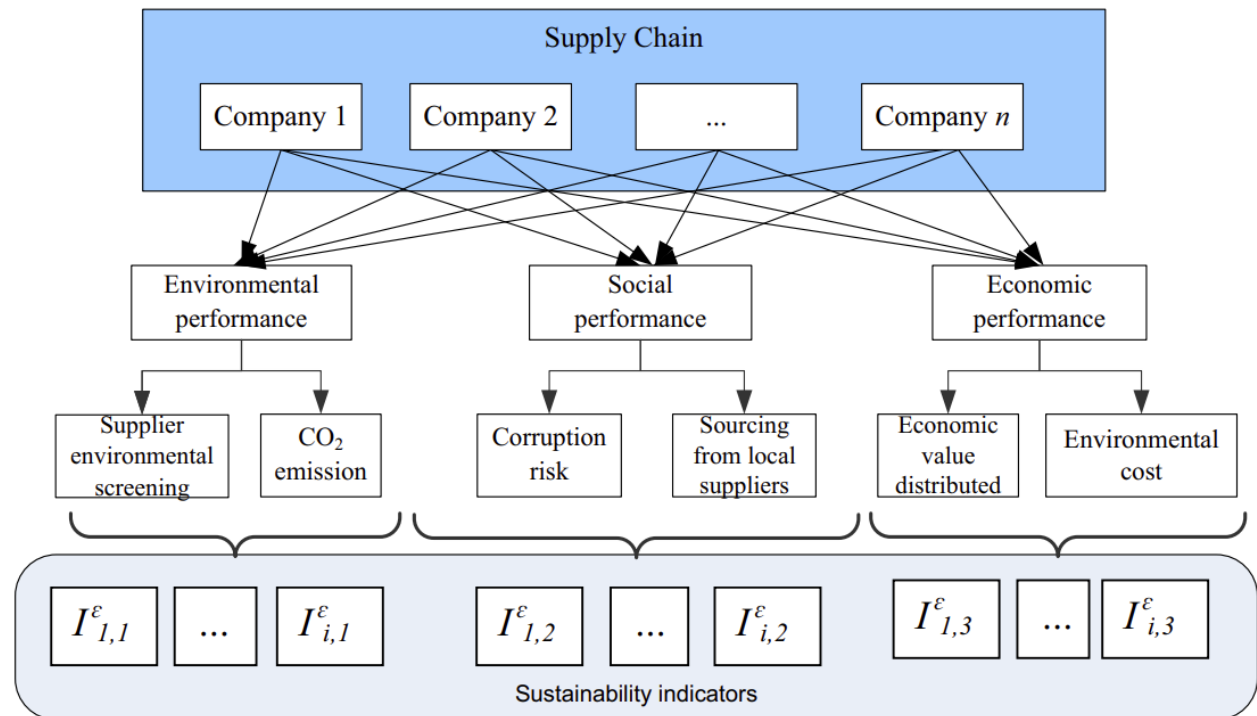
SWOT analysis (reloaded)



Closing the loop

Sustainability – Supply Chain Characterization

Hierarchical approach



--> Link to MCDM methods