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Supply chains and recycling processes

Dr. Herena Torio

Agenda

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

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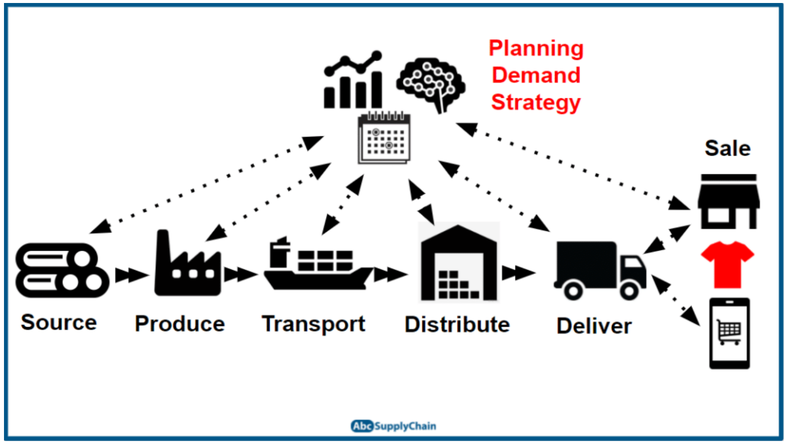
Supply chains

Definition

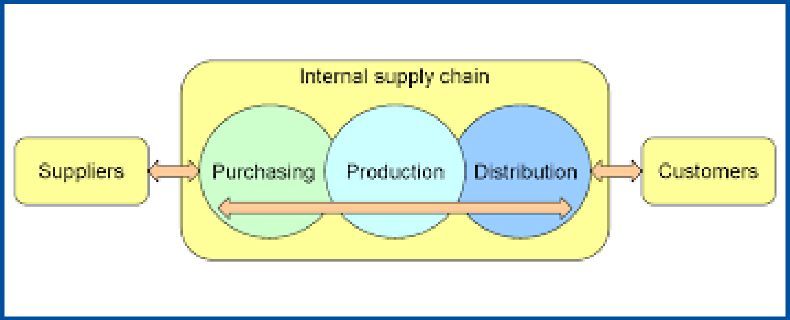
Network of all activities and stages that a product undergoes from the processing of raw material resources it requires until it reaches the final user.



Includes:

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

Once upon a time….



Source: Wikipedia.org

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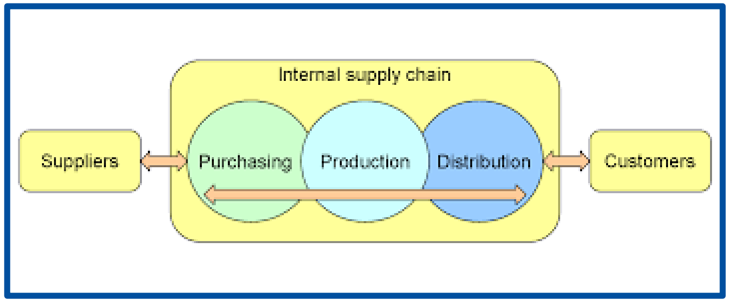
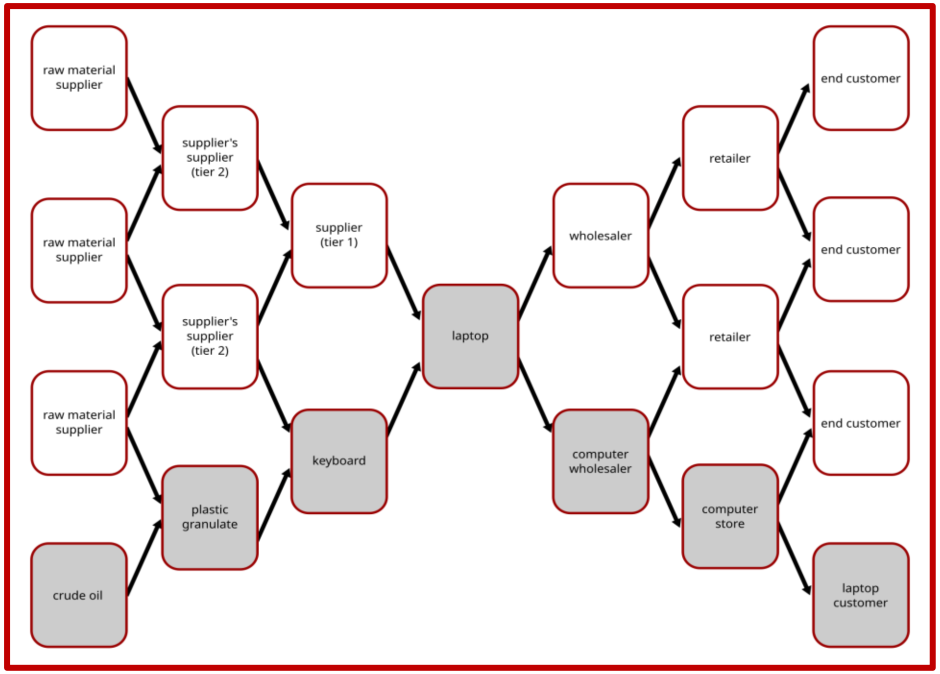


Source: Wikipedia.org

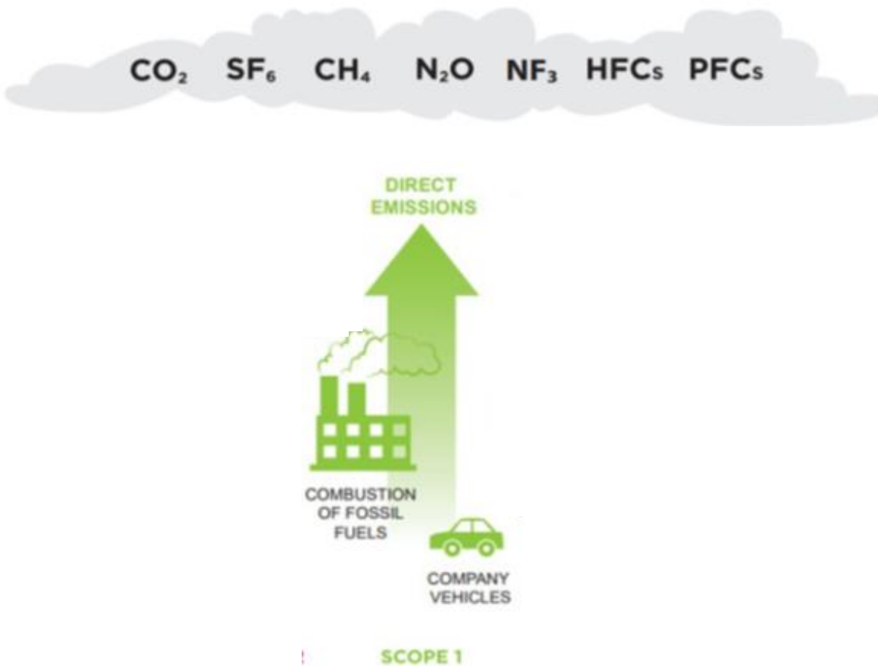
Macro-level



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

Supply chains

Definition



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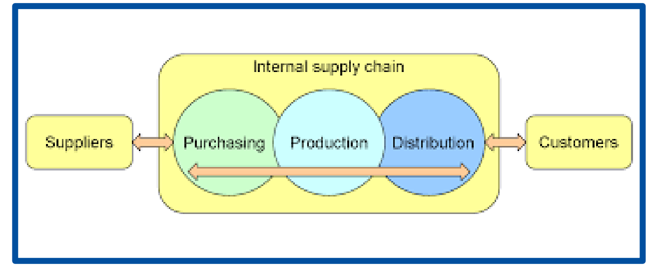

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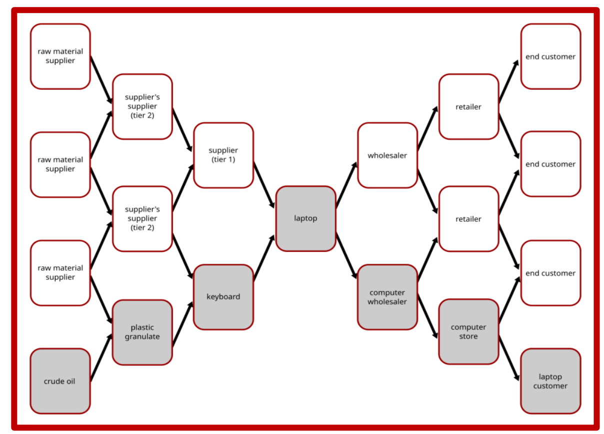

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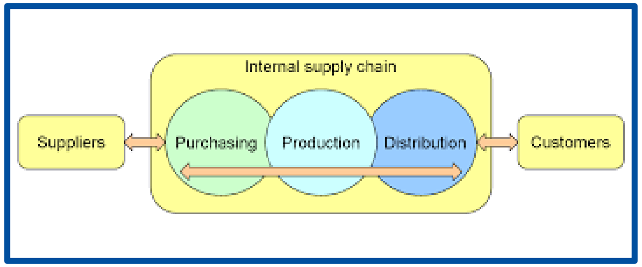

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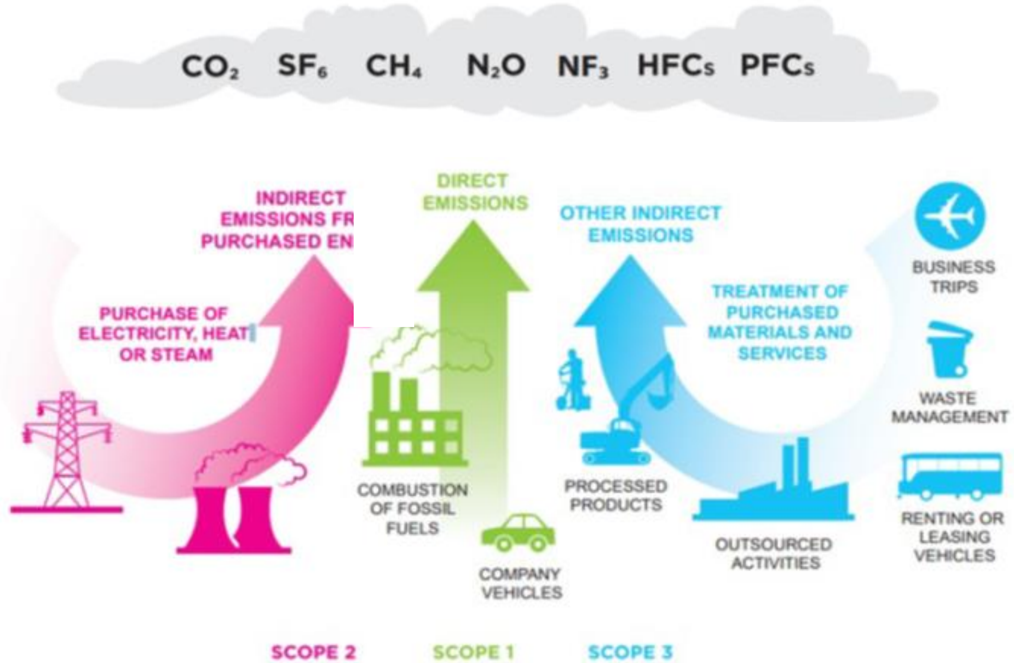

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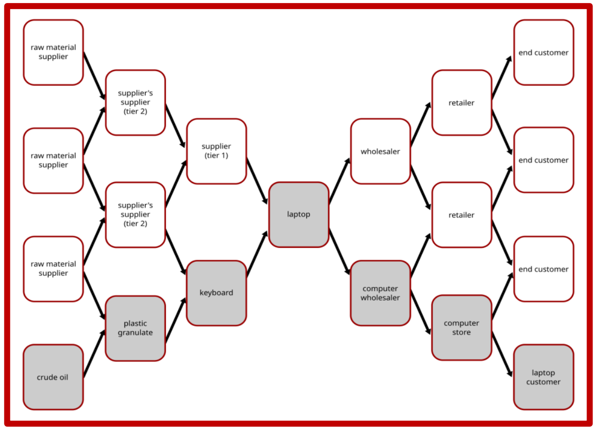


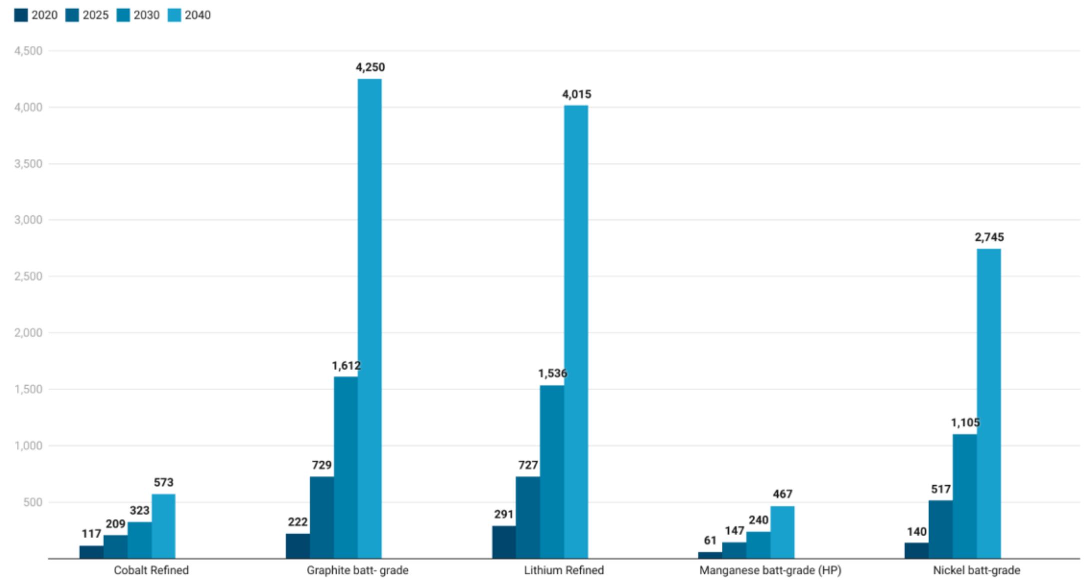
Supply and demand network (en) - Supply chain - Wikipedia

Supply chains

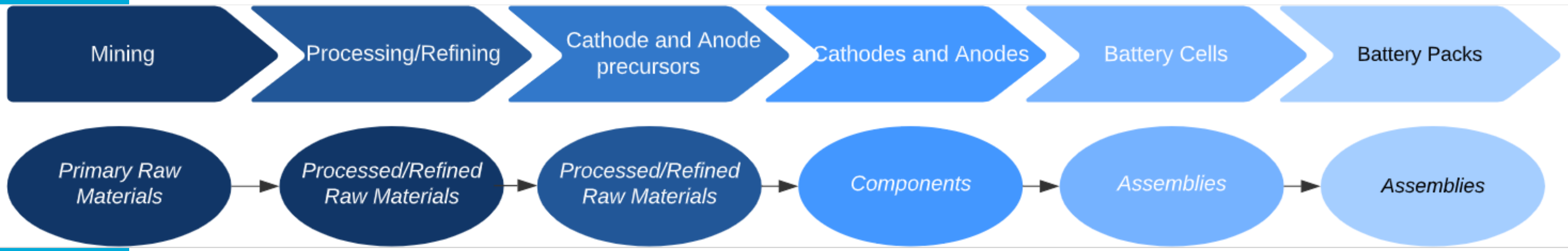
Current status

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

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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]

Source [1]: Global Supply Chain Pressure Index (GSCPI) - FEDERAL RESERVE BANK of NEW YORK

Supply chains

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Source [1]

Macro-level: growing issues

Sustainability and ESG
(environmental, social, governance)

Environmental and social impact

- CO_2 emissions (Scope 3)
- Supplier complieance
- Resource ussage (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)

Source [1]: Global Supply Chain Pressure Index (GSCPI) - FEDERAL RESERVE BANK of NEW YORK

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

Source: Navigating the ESG Regulatory Landscape, Stand: June 2025

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.

Source [1]: Global Supply Chain Pressure Index (GSCPI) - FEDERAL RESERVE BANK of NEW YORK

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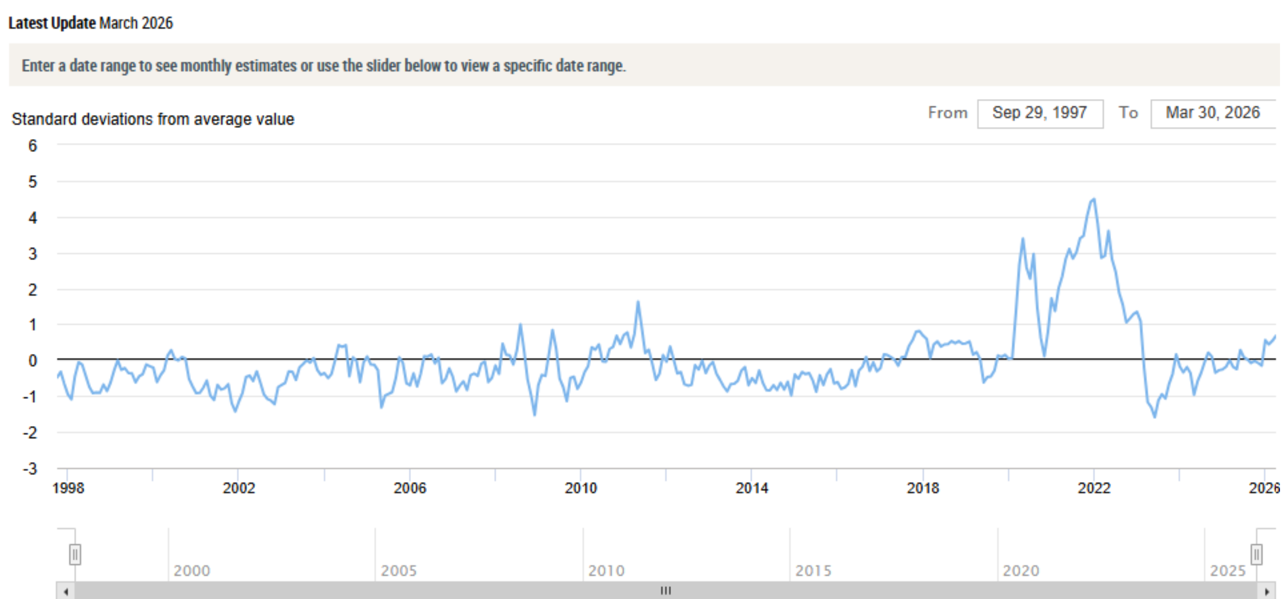

Source: Global Supply Chain Pressure Index (GSCPI) - FEDERAL RESERVE BANK of NEW YORK

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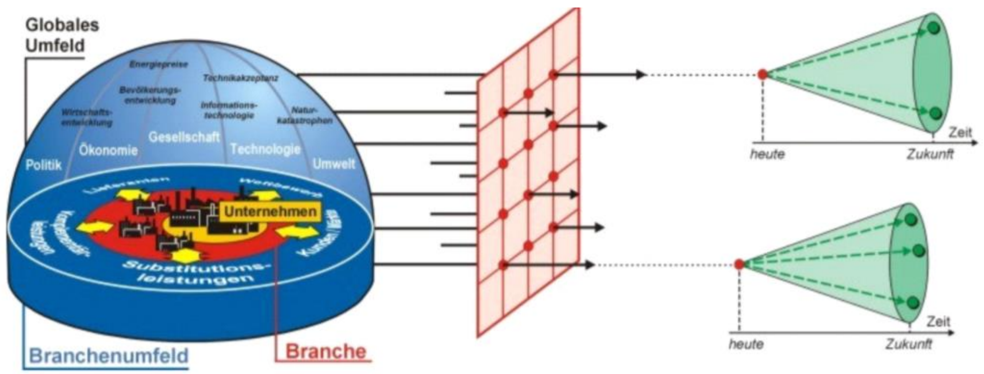
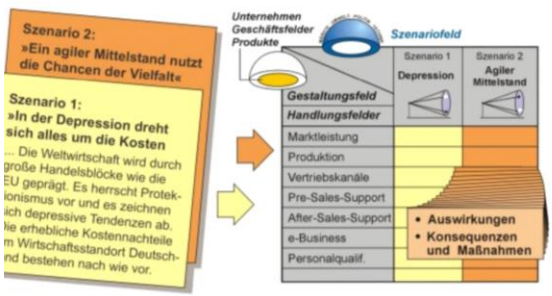
Supply chains

Challenges and Opportunities

Identify influential factors → Analyse interactions and main drivers → Describe future/ possible trends → Scenarios → SWOT analysis





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

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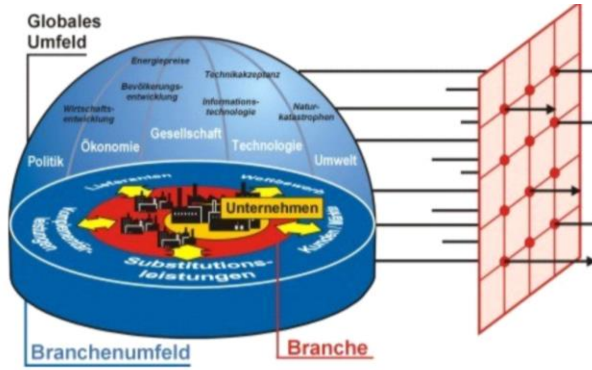

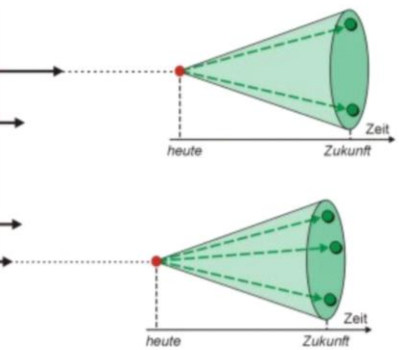

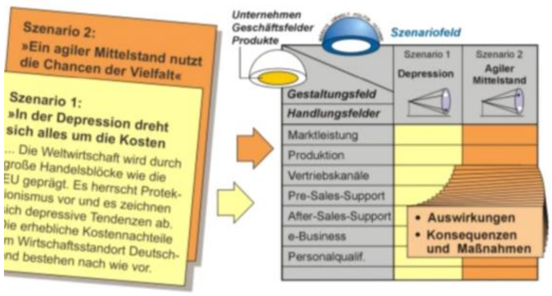

Strengths	Weaknesses
Tech. innovation	Dependency on crit. materials
Global scope	Complexity & Intransparent Supply chains
Reputation & sustainability	Costs of sust. measures
Standardized processes	Lacking Flexibility
Opportunities	**Risks**
Circular economy & Recycling	Geopolitical Risks
New laws as compartive advantage	Global warming
Tech. Innovation	Regulations (CS3D,…)
Aware consumers	Greenwashing claims

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

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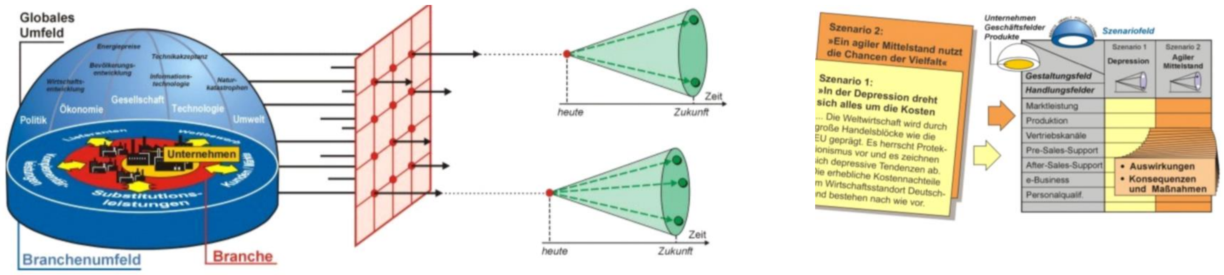

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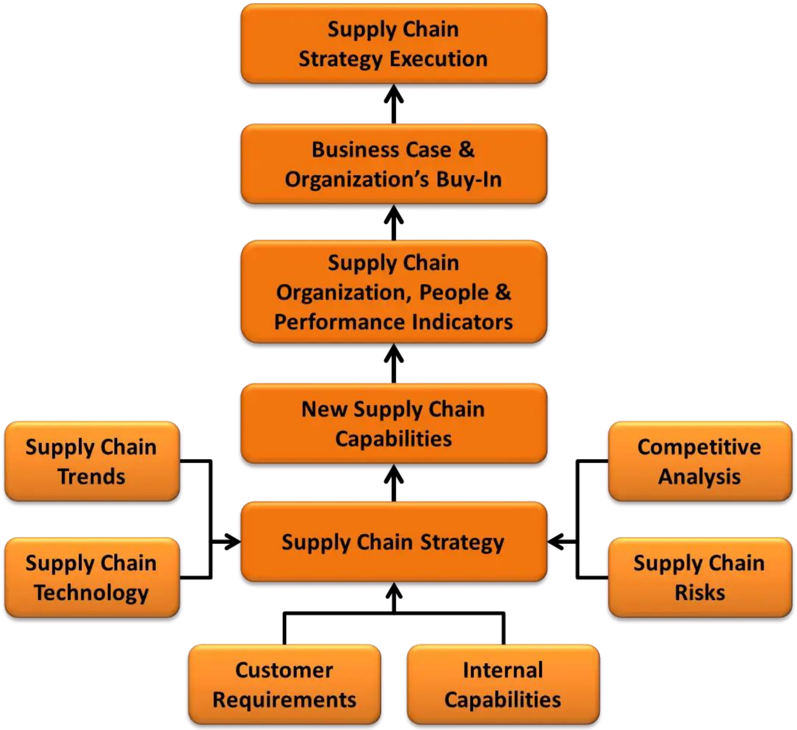

Source: How to develop a Supply Chain Strategy? | Operational Excellence Consulting LLC

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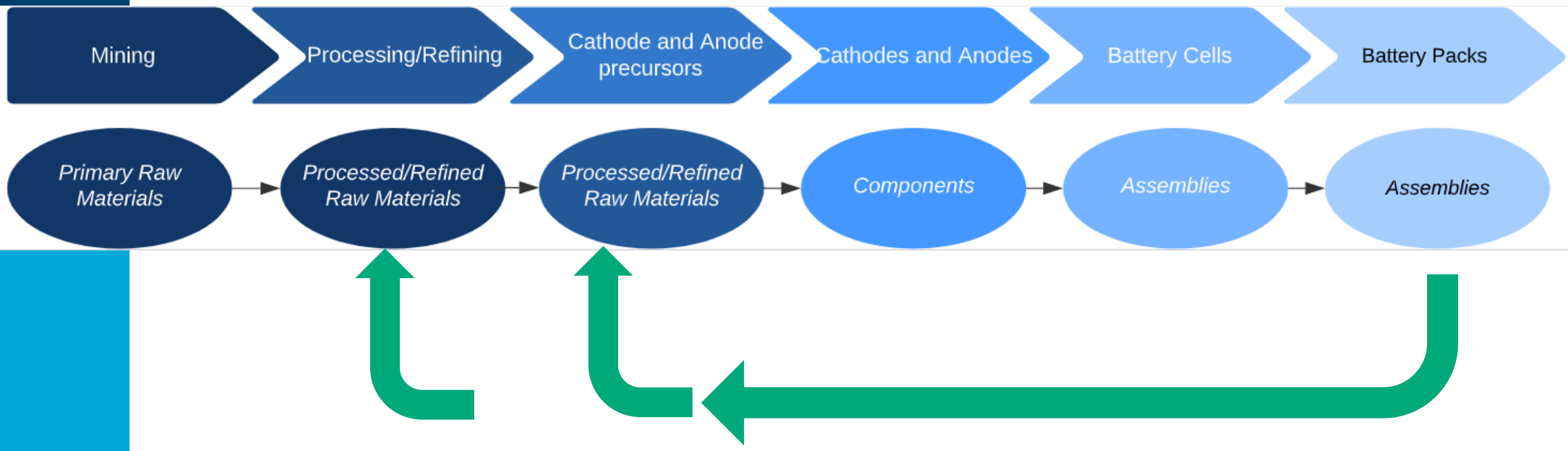
- Recycling

Supply chains and circular economy

Concepts coming closer

CIRCULAR:
Cradle to cradle



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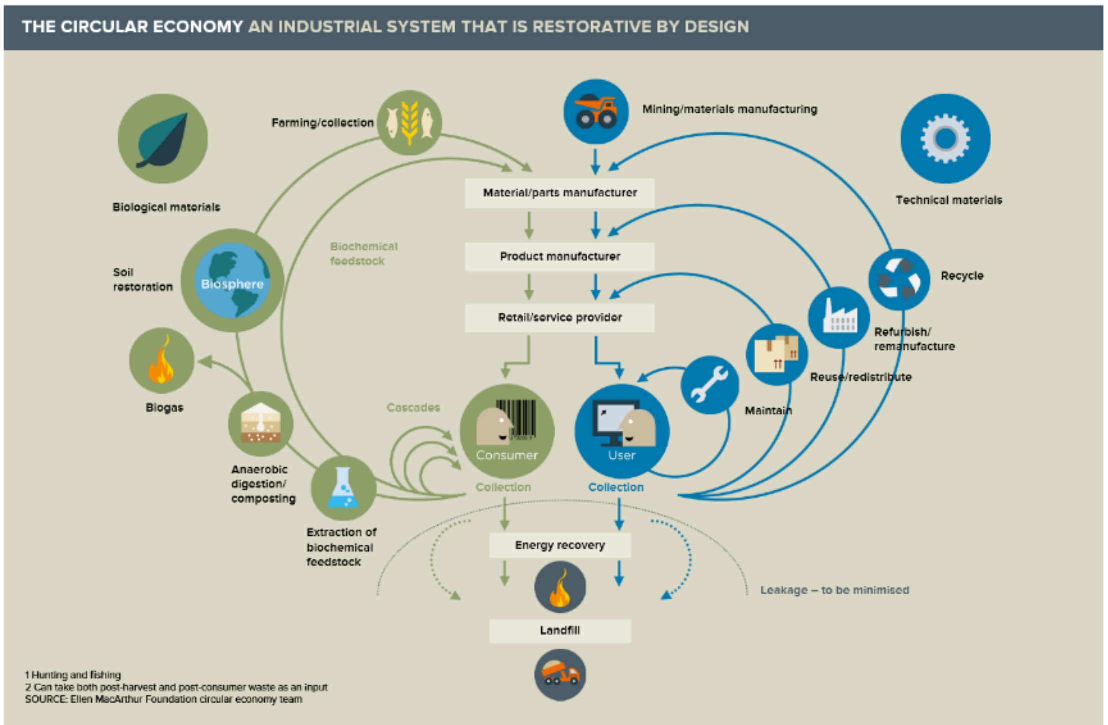
Circular economy

From linear to circular supply chains

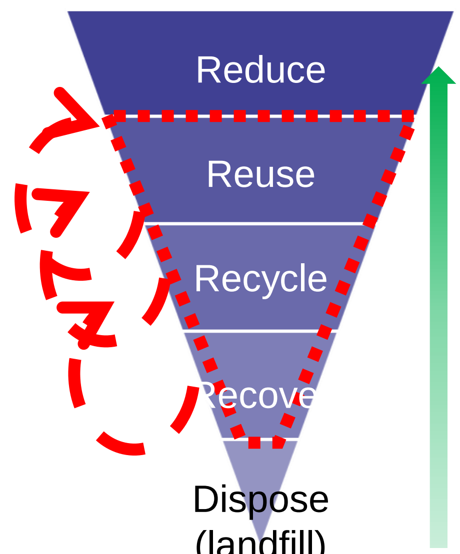
Product during lifetime

Service vs. product



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

Waste management cycle



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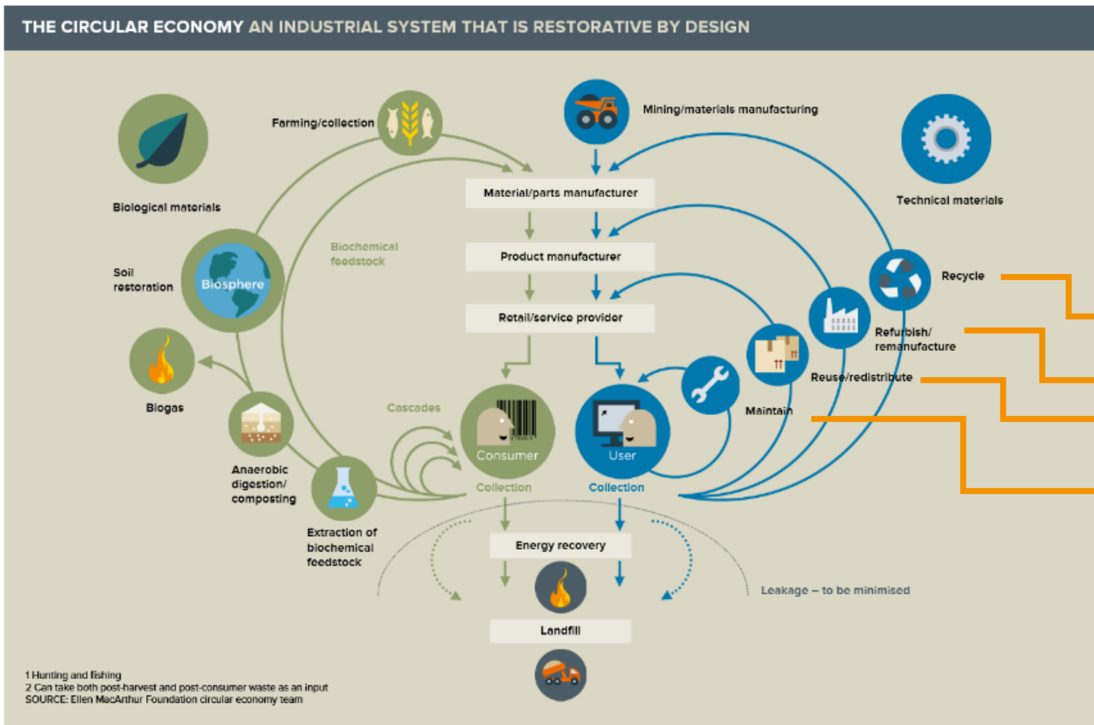
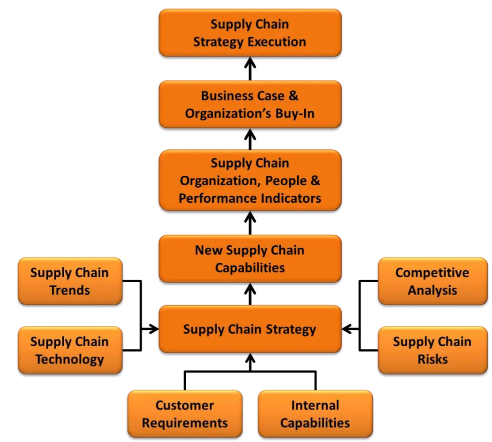


Product management cycles



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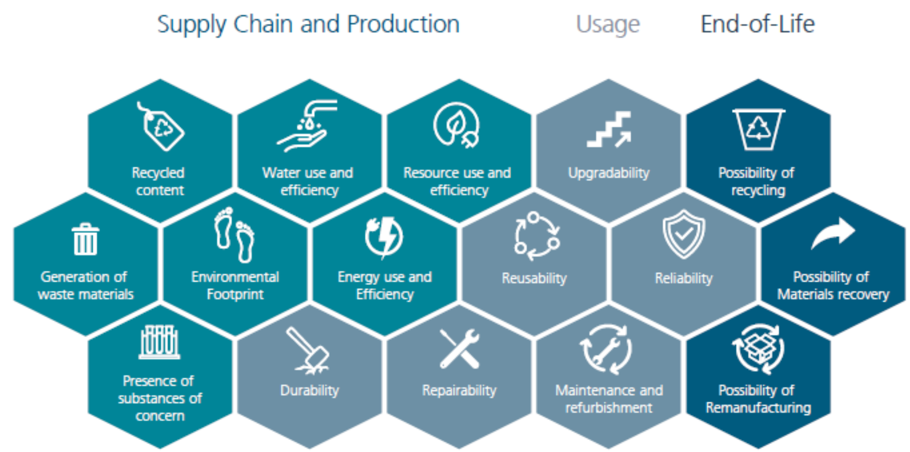
DPP

Digital Product Passport

Compulsory in Feb. 2027

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



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

Source: FhG-IPK. Whitepaper: Strategien für Unternehmen zur Umsetzung von digitalen Produktpässen.
Digitale Produktpässe (DPP) entlang des Lebenszyklus - Fraunhofer IPK

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 operator[1] 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

Source: BatteryPass-Ready_Project_Presentation-1.pdf

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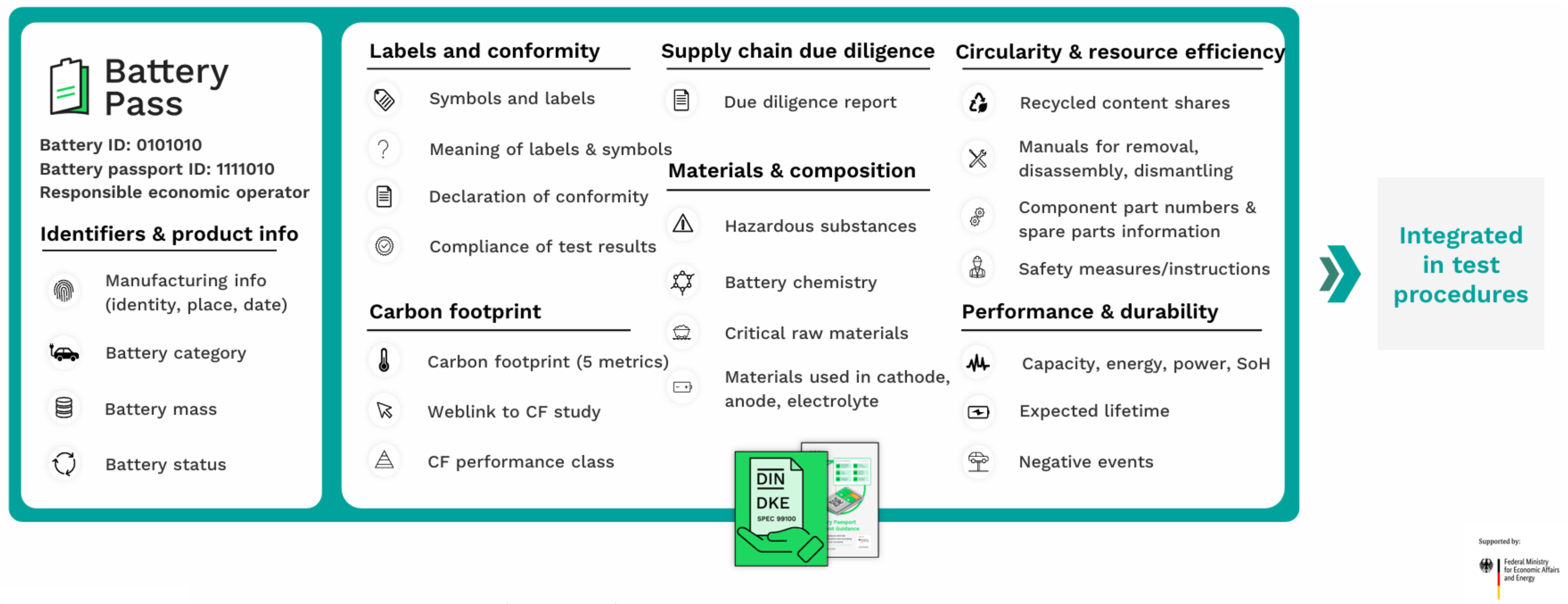

Source: BatteryPass-Ready_Project_Presentation-1.pdf

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Agenda

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

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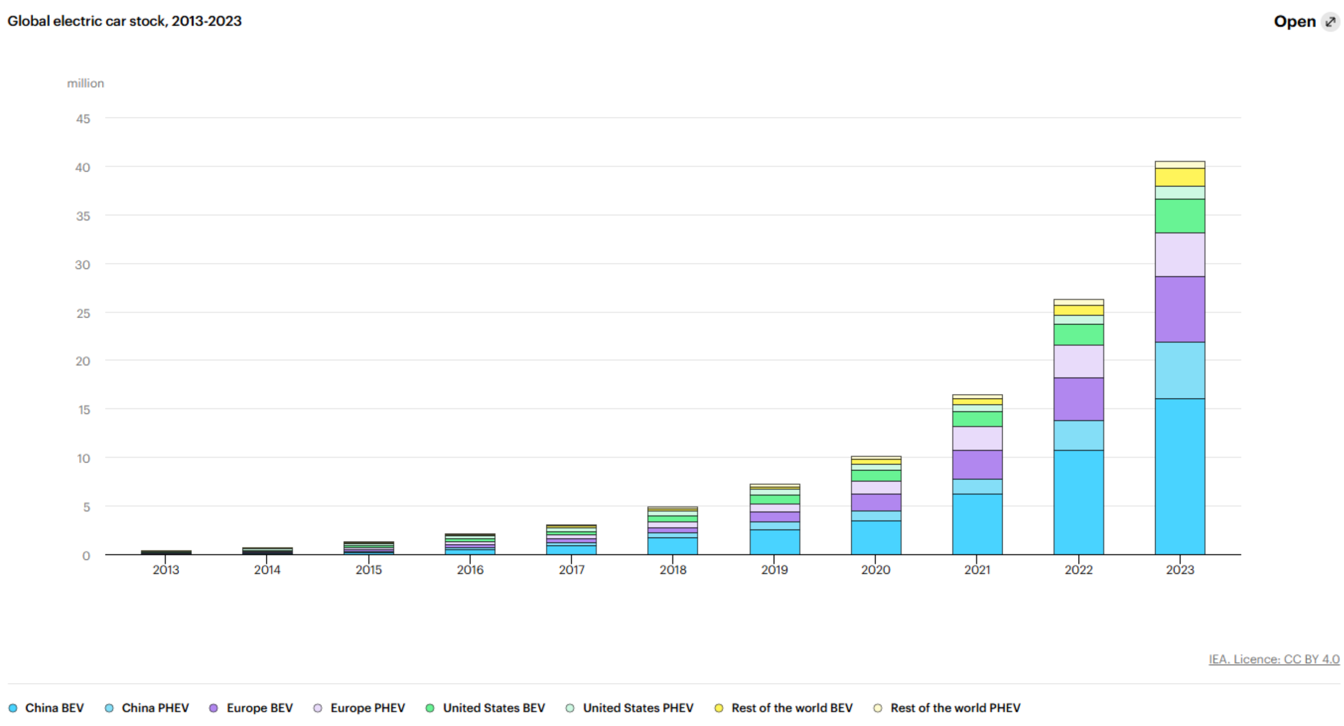
Recycling

Drivers – Demands

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



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

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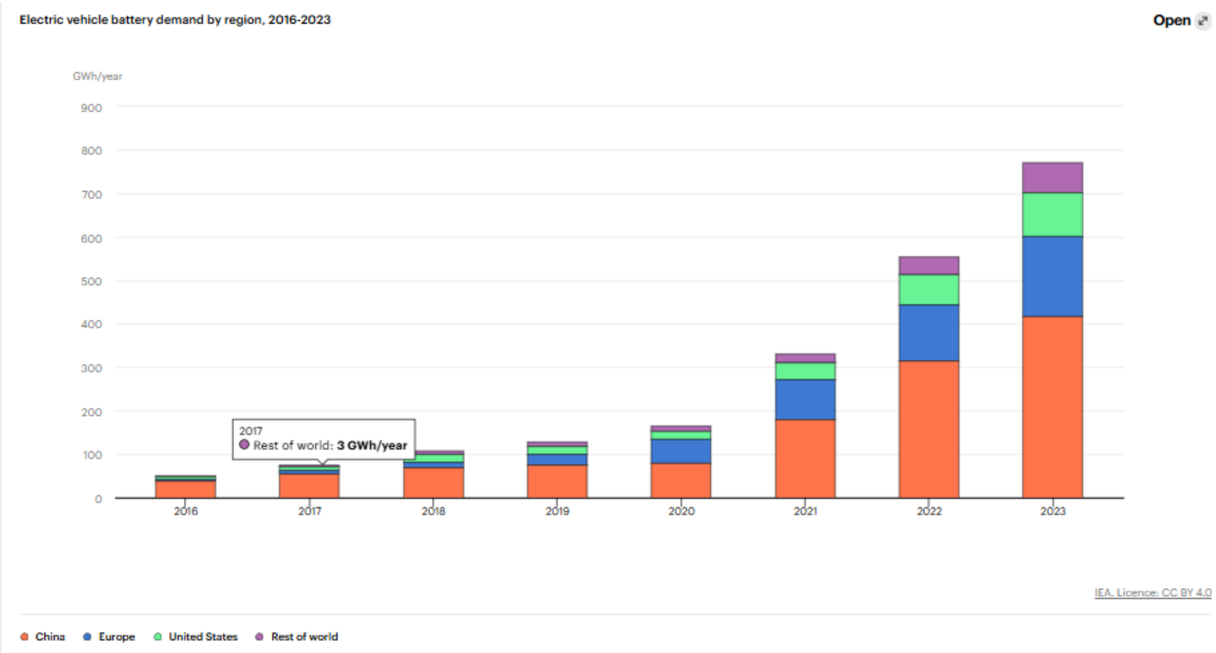

Source: Trends in electric vehicle batteries – Global EV Outlook 2024 – Analysis - IEA

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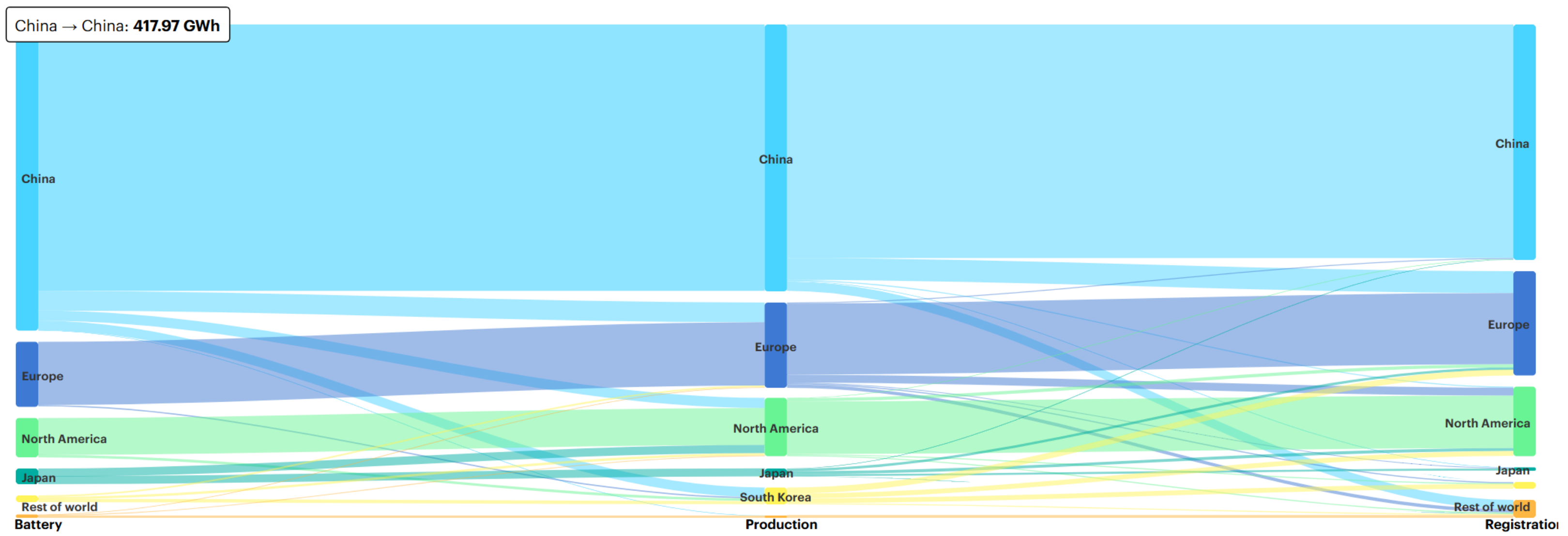
Global trade flows for lithium-ion batteries and electric cars, 2023



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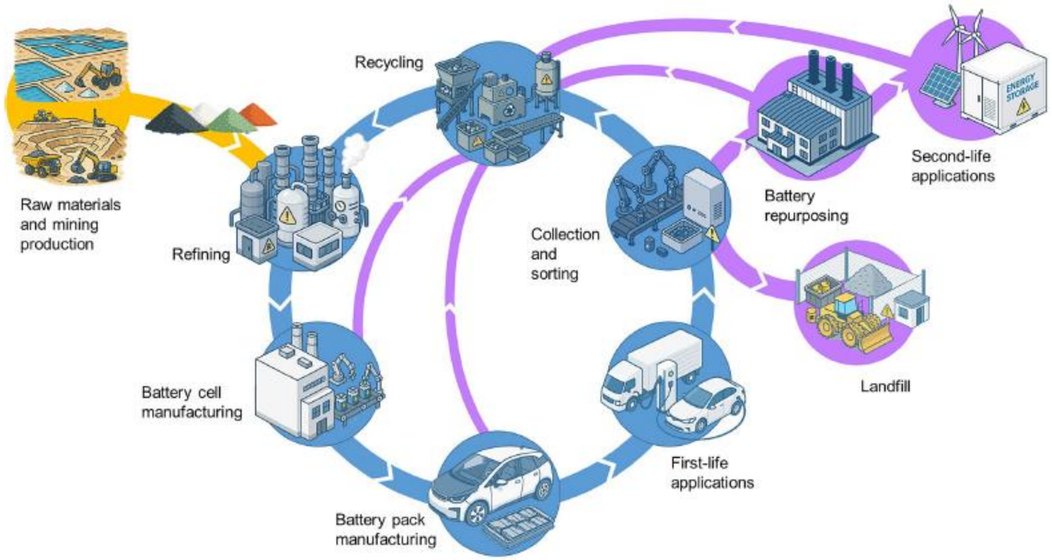
Drivers – Demands

- Exponentially growing: 14 million new EV in 2023! (35% more than 2022)
- 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

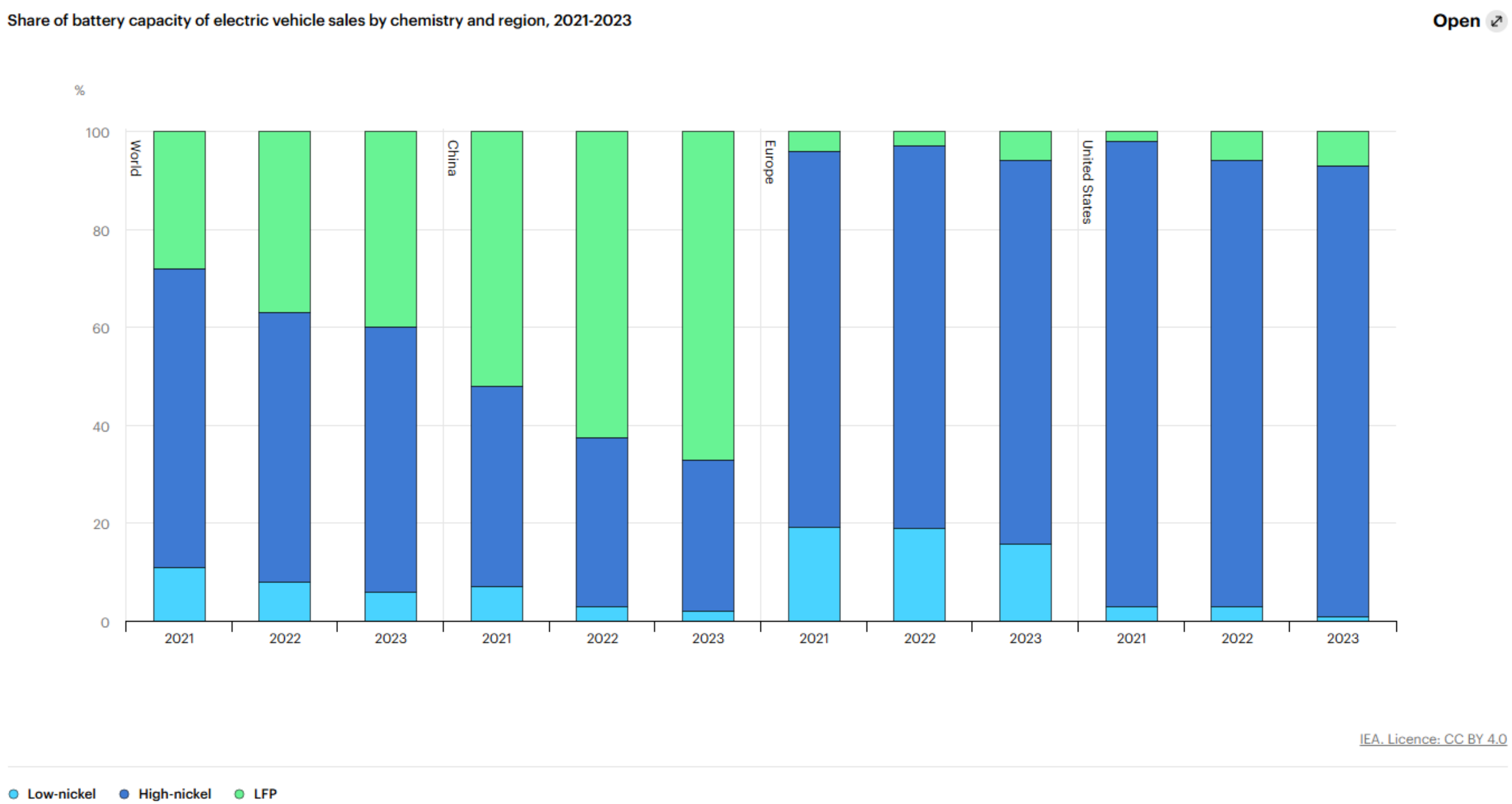


Source: Chacana-Olivares et al. 2025. Lithium-ion battery recycling: a perspective on key challenges and opportunities. Materials Sustainability. NPJ. https://doi.org/10.1038/s44296-025-00083-7

Recycling

Drivers – Demands and composition

- Different battery chemistries and properties (energy densitiy, lifetime,…)



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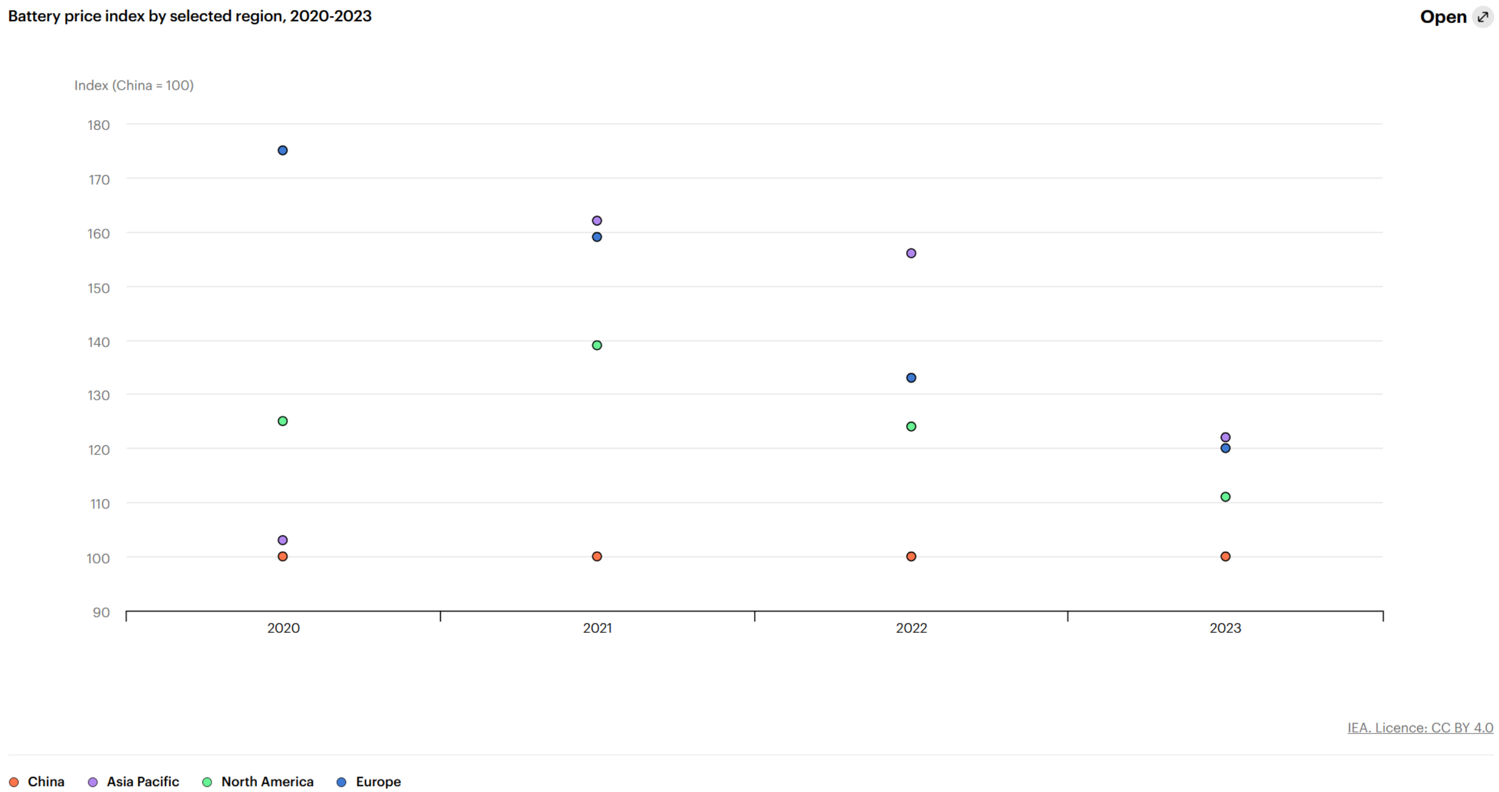
Recycling

Drivers – Demands and composition

- Cost concerns!



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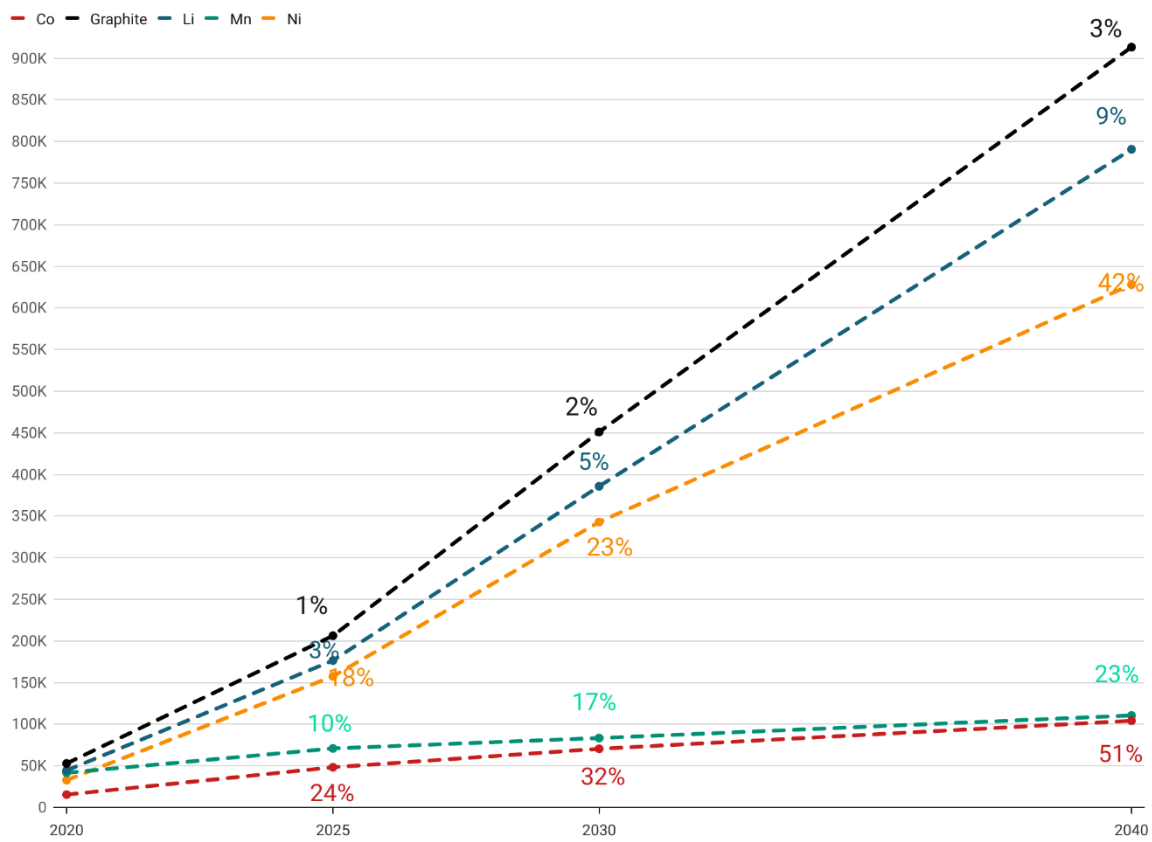
Recycling

Potential – Materials, processes and costs

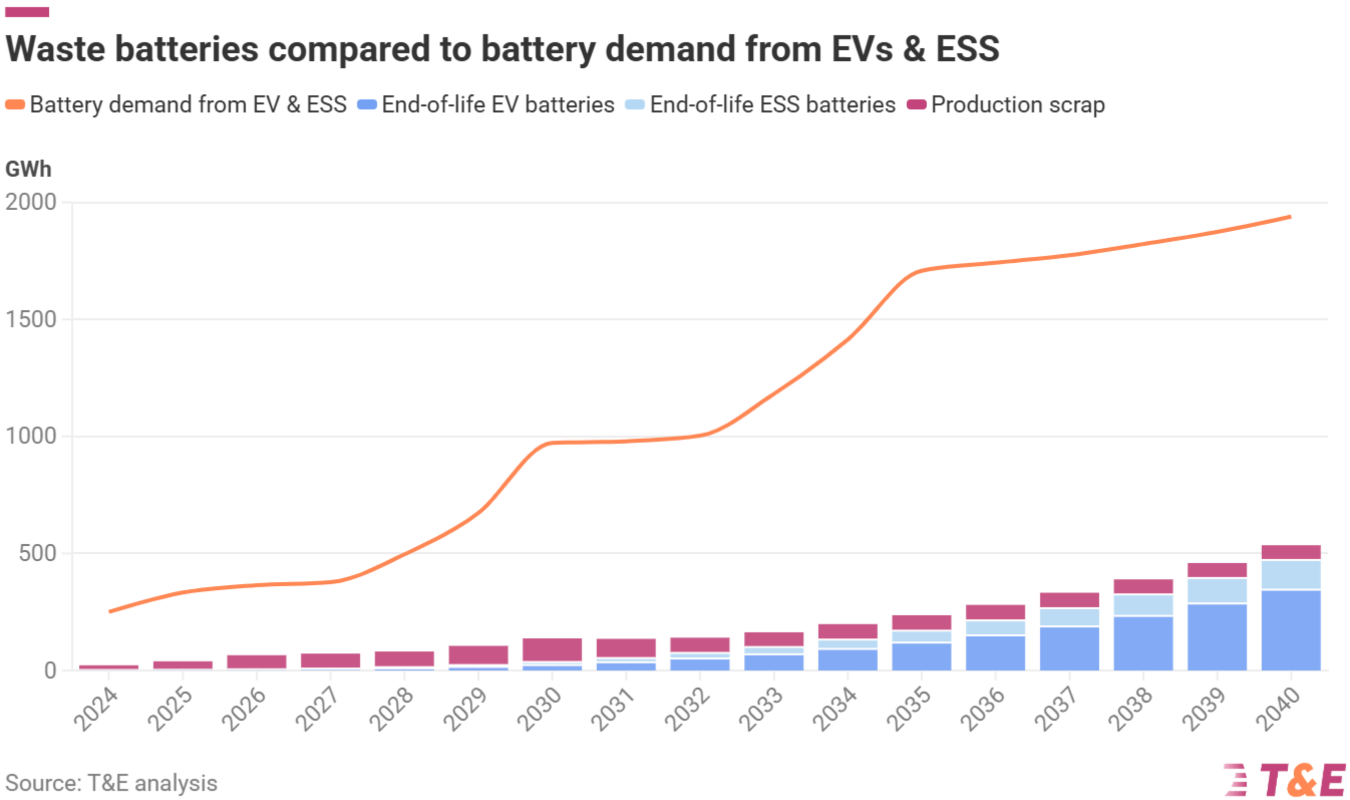


Source: RMIS - Lithium-based batteries supply chain challenges

Recycling

Potential – Materials, processes and costs

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



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

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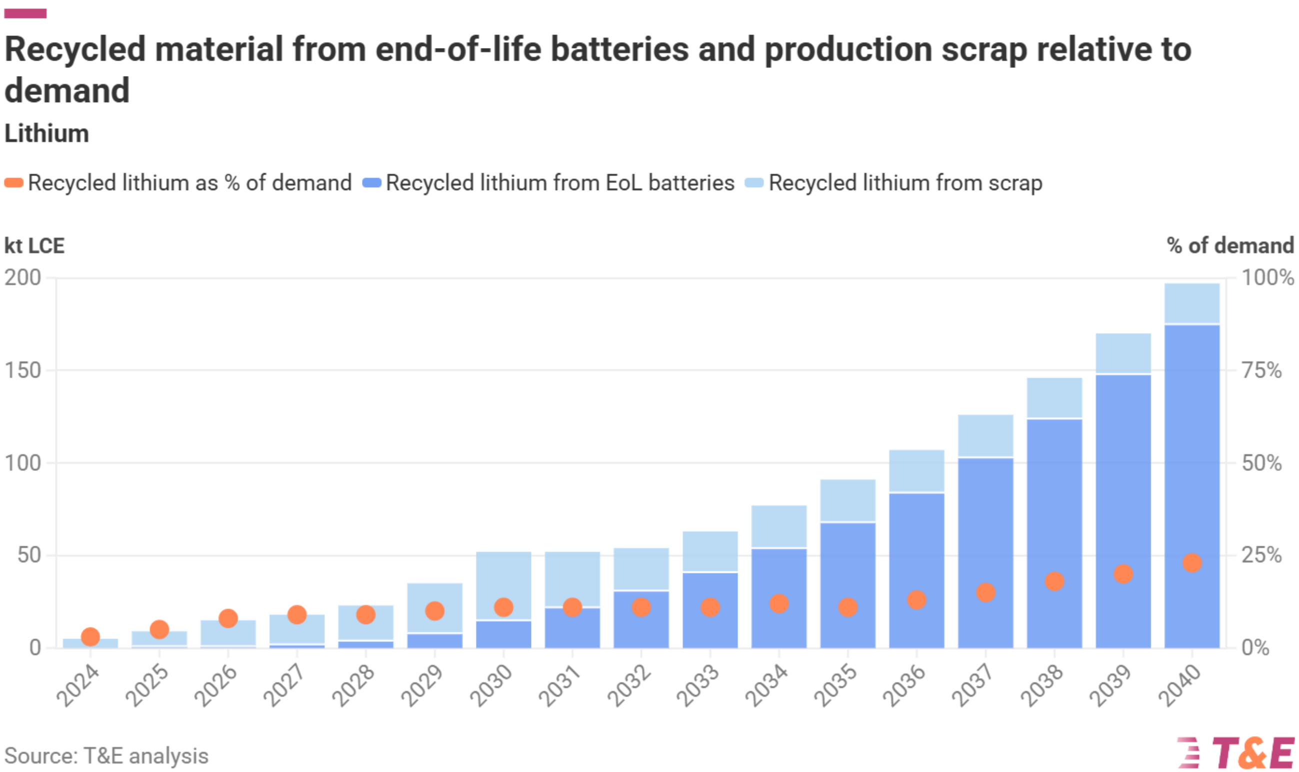
Recycling

Potential – Materials, processes and costs

- 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.



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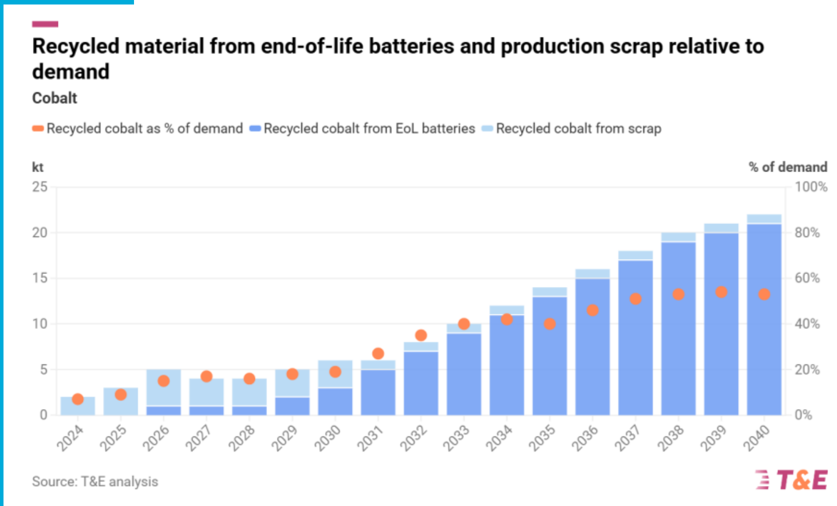
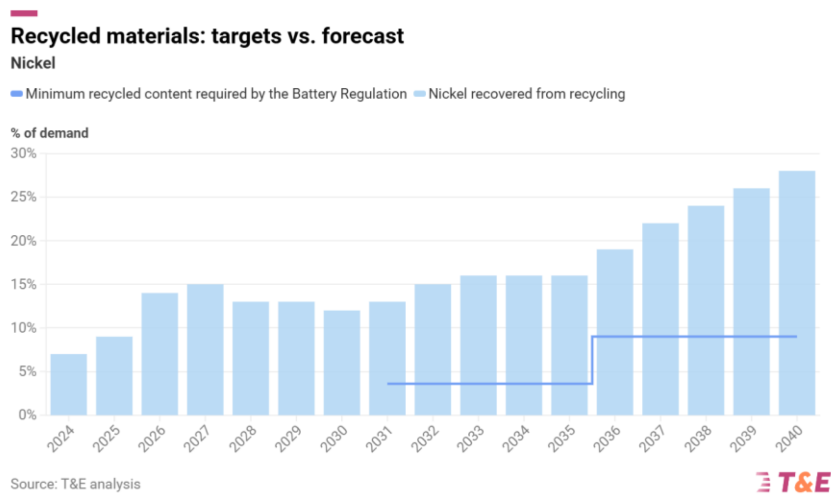
Recycling

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)





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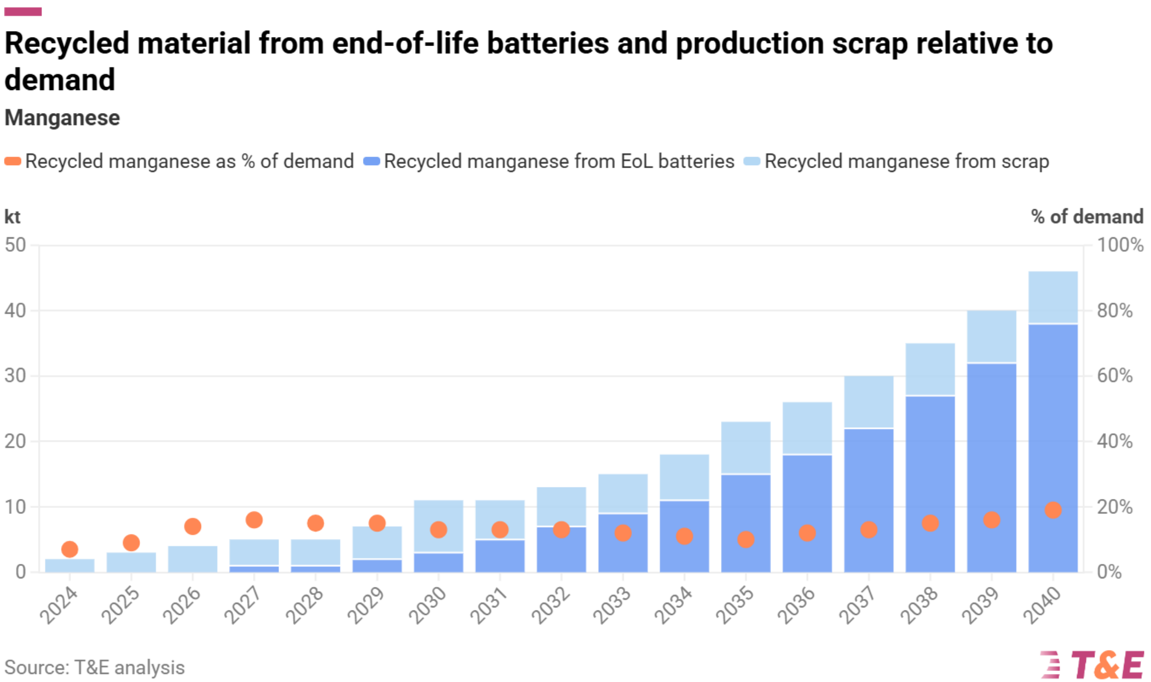
Recycling

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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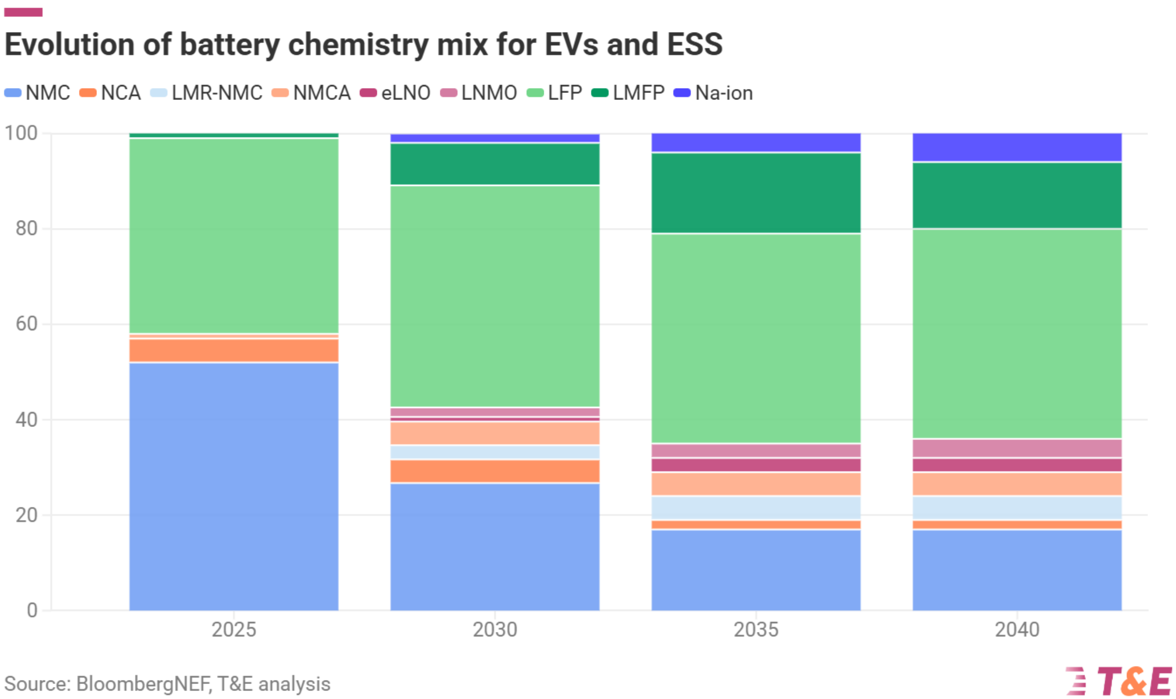
Low Nickel

High Nickel

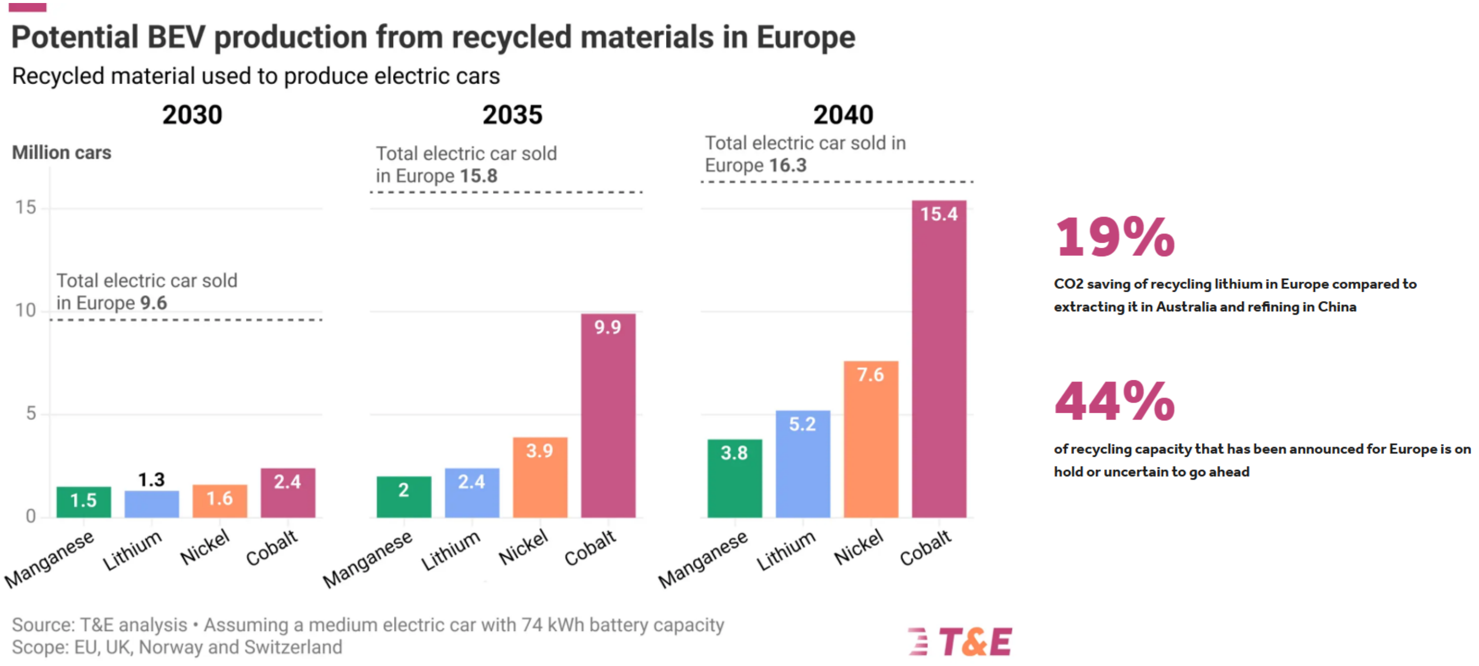


Source: From waste to value: the potential for battery recycling in… | T&E

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.



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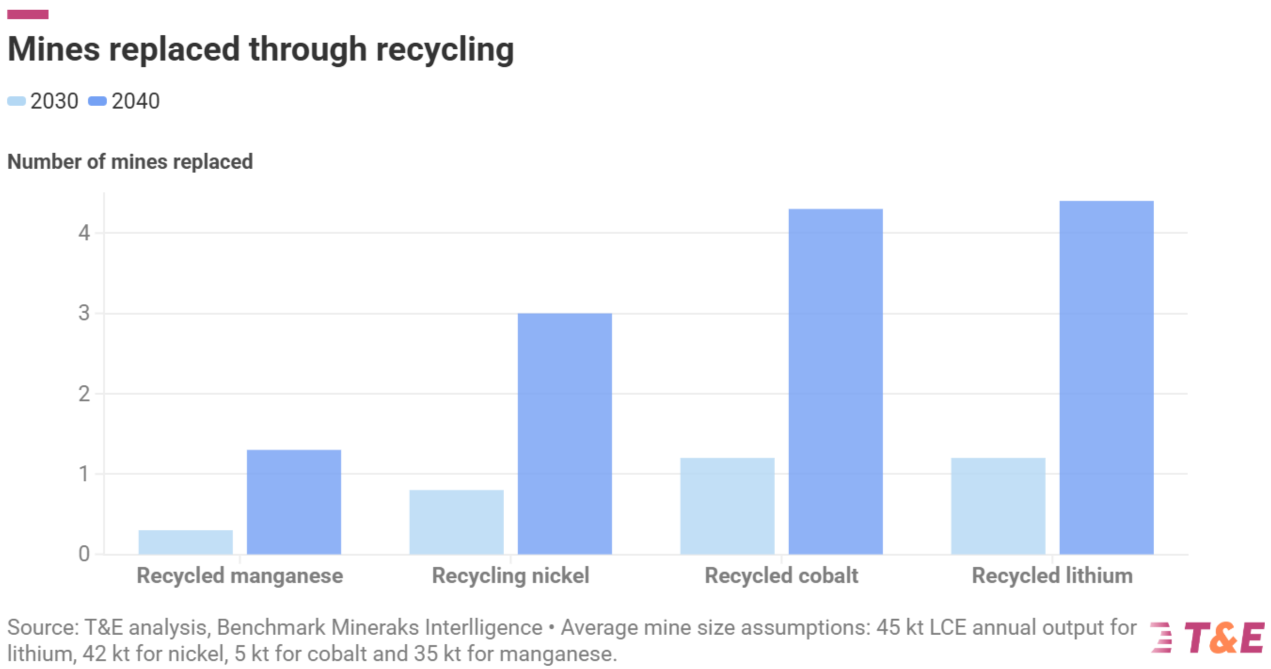
Recycling

Potential – Materials, processes and costs

- **Lithium**: 2/3 from sprodumene (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)



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

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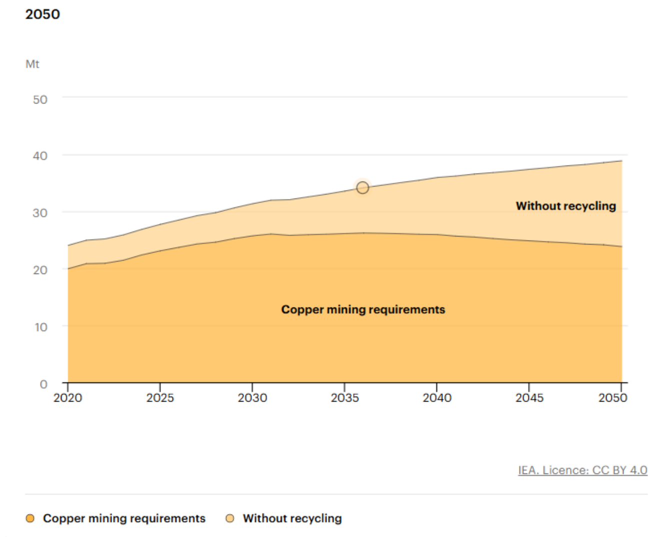
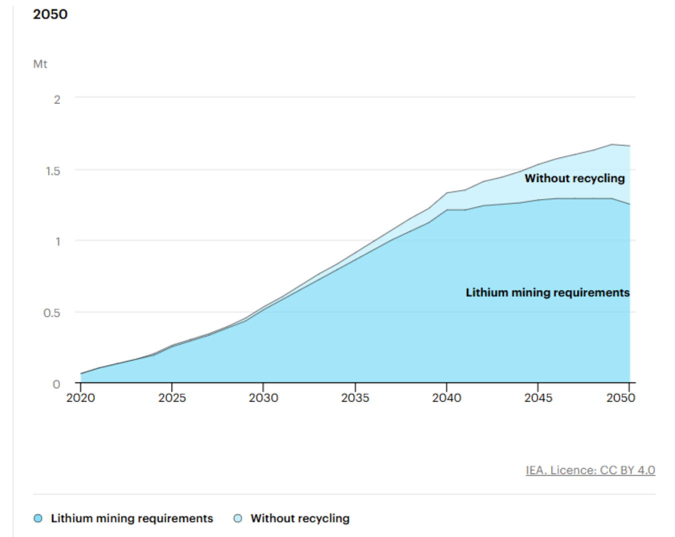
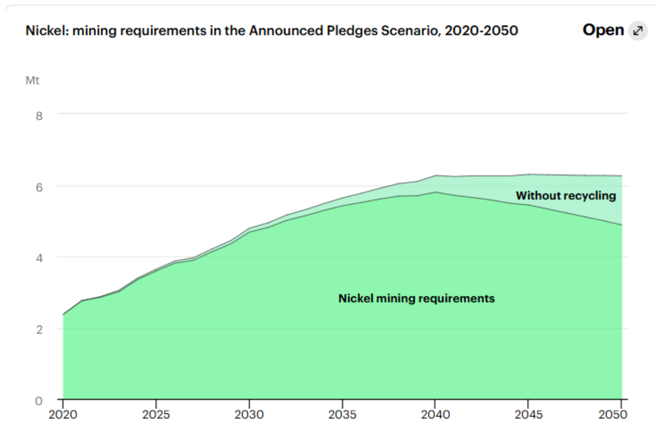
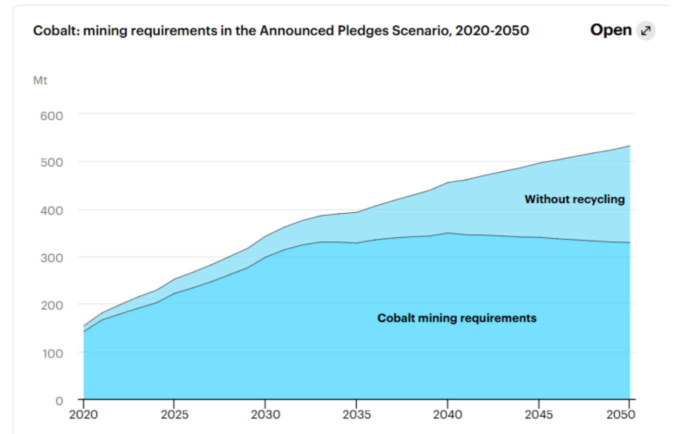
Recycling

Potential –









Source: Executive summary – Recycling of Critical Minerals – Analysis - IEA

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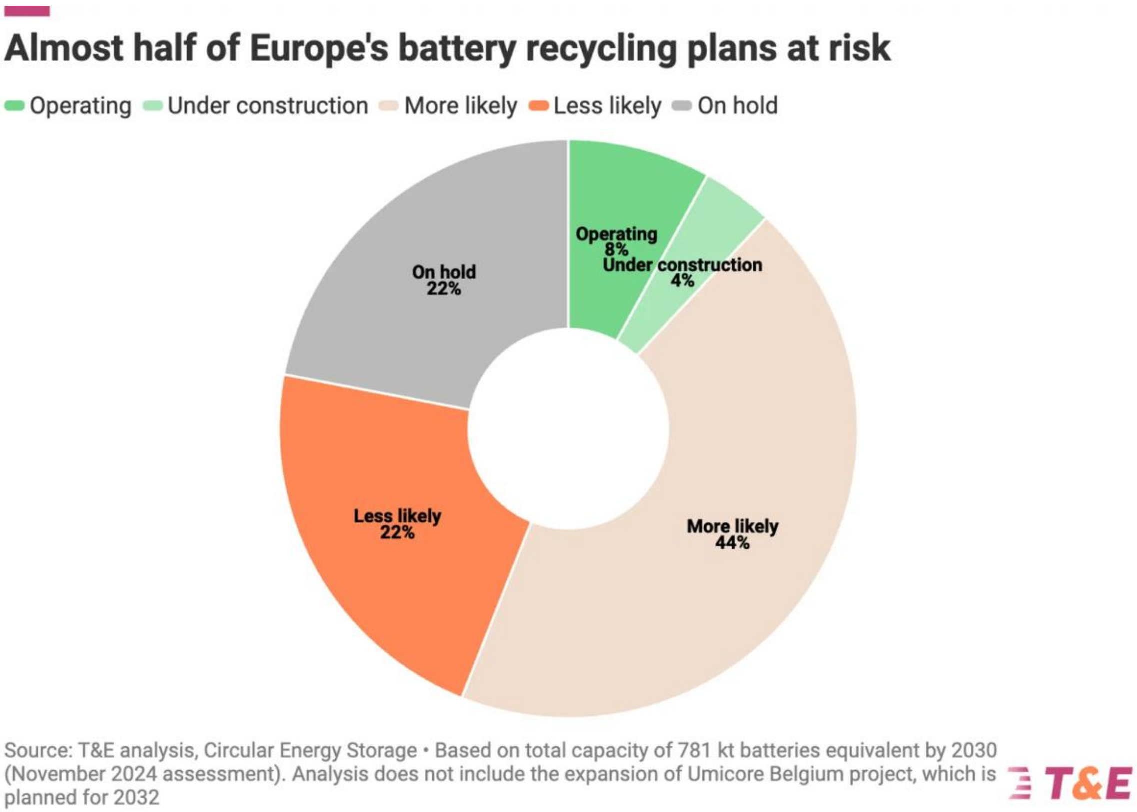
Recycling

Potential – Materials, processes and costs

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



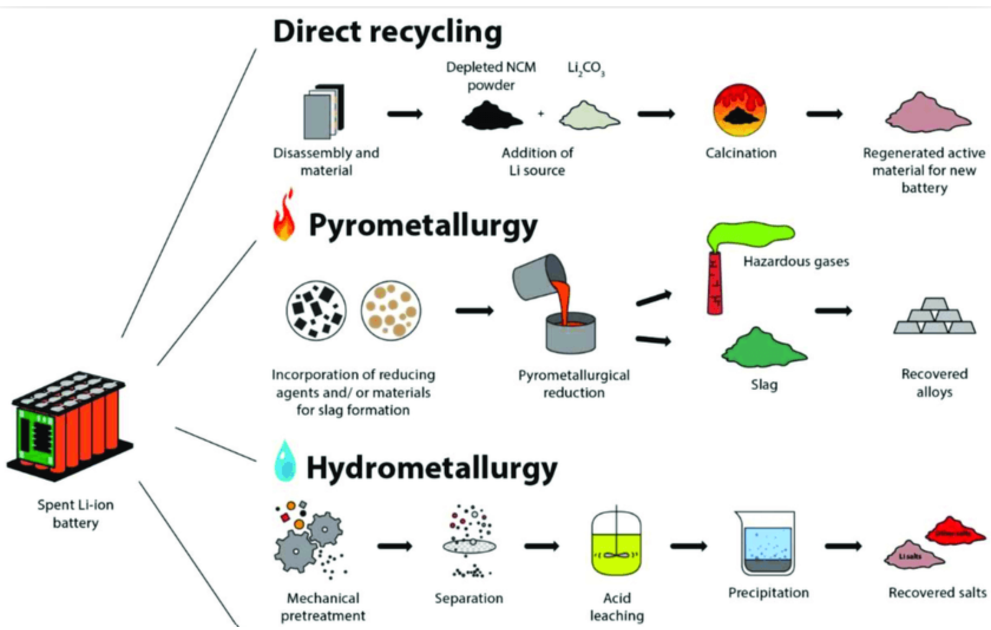
Source: From waste to value: the potential for battery recycling in… | T&E

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

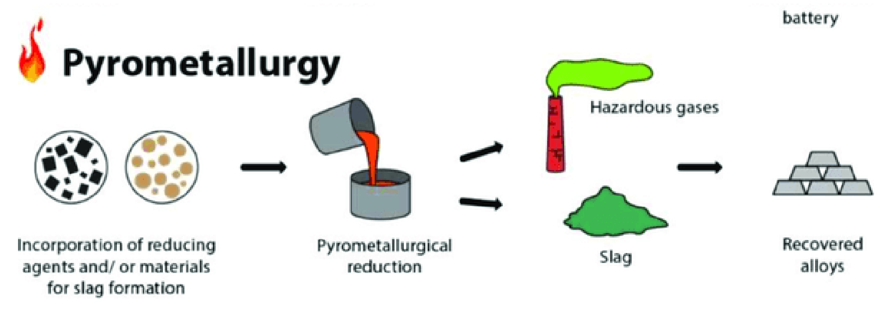
DOI: 10.1016/B978-0-12-803581-8.03609-2

Source: DOI: 10.1002/idm2.12041, Hydrometallurgical Battery Recycling Plant Quotation - Guanma Machinery

Recycling

Overview of main processes

Pyrometallurgy



Source: Hydrometallurgical Battery Recycling Plant Quotation - Guanma Machinery

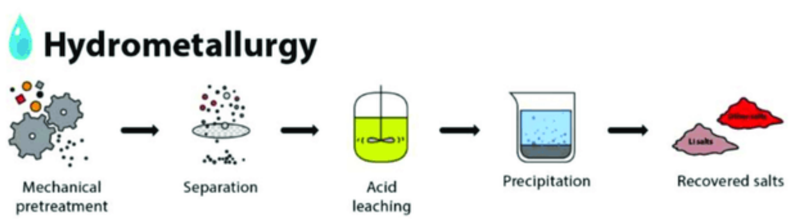
- Recovery rates for Ni, Co & Cu and copper can reach 95%.
- Li and Mn lost in the remaining slag → require additional processing through hydrometallurgy, where lithium recovery can exceed 70%.
- Graphite from anode is typically burned off

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

Recycling

Overview of main processes

Pyrometallurgy

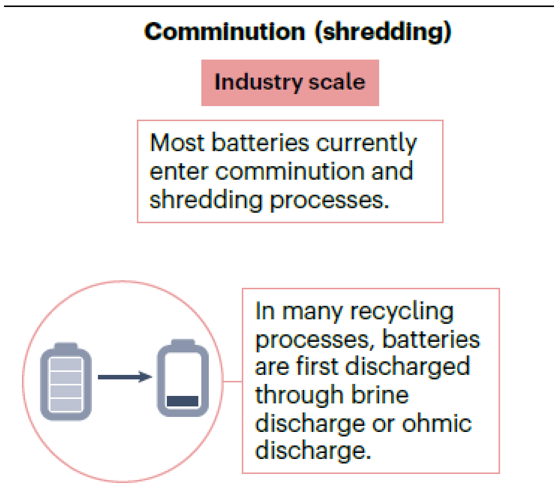


Source: Hydrometallurgical Battery Recycling Plant Quotation - Guanma Machinery

- 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

Recycling

Flexible recycling process design



Currently: shredding

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

- Applicable on all chemistries
- Standard general procedure

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

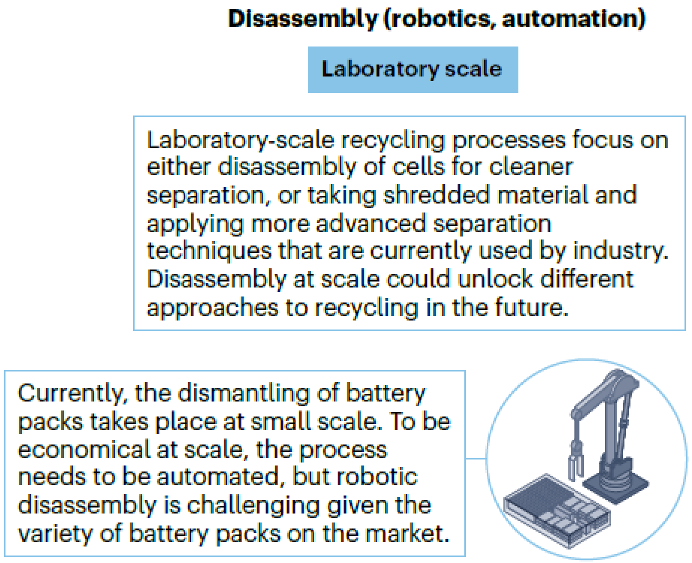
Recycling

Flexible recycling process design

Alternative: disassembly route

- Higher yield of material recovery
- Recovery at higher value state

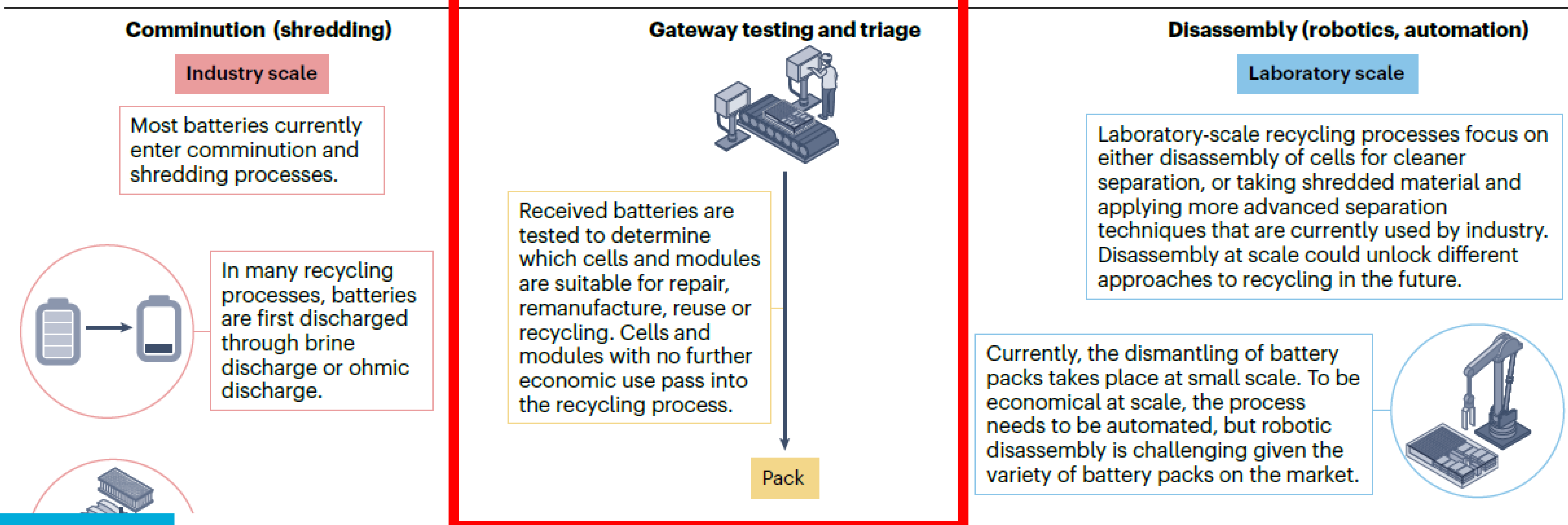
- Specific for battery composition
- Labour intensive
- Robotic disassembly in infancy state



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

Recycling

Flexible recycling process design



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

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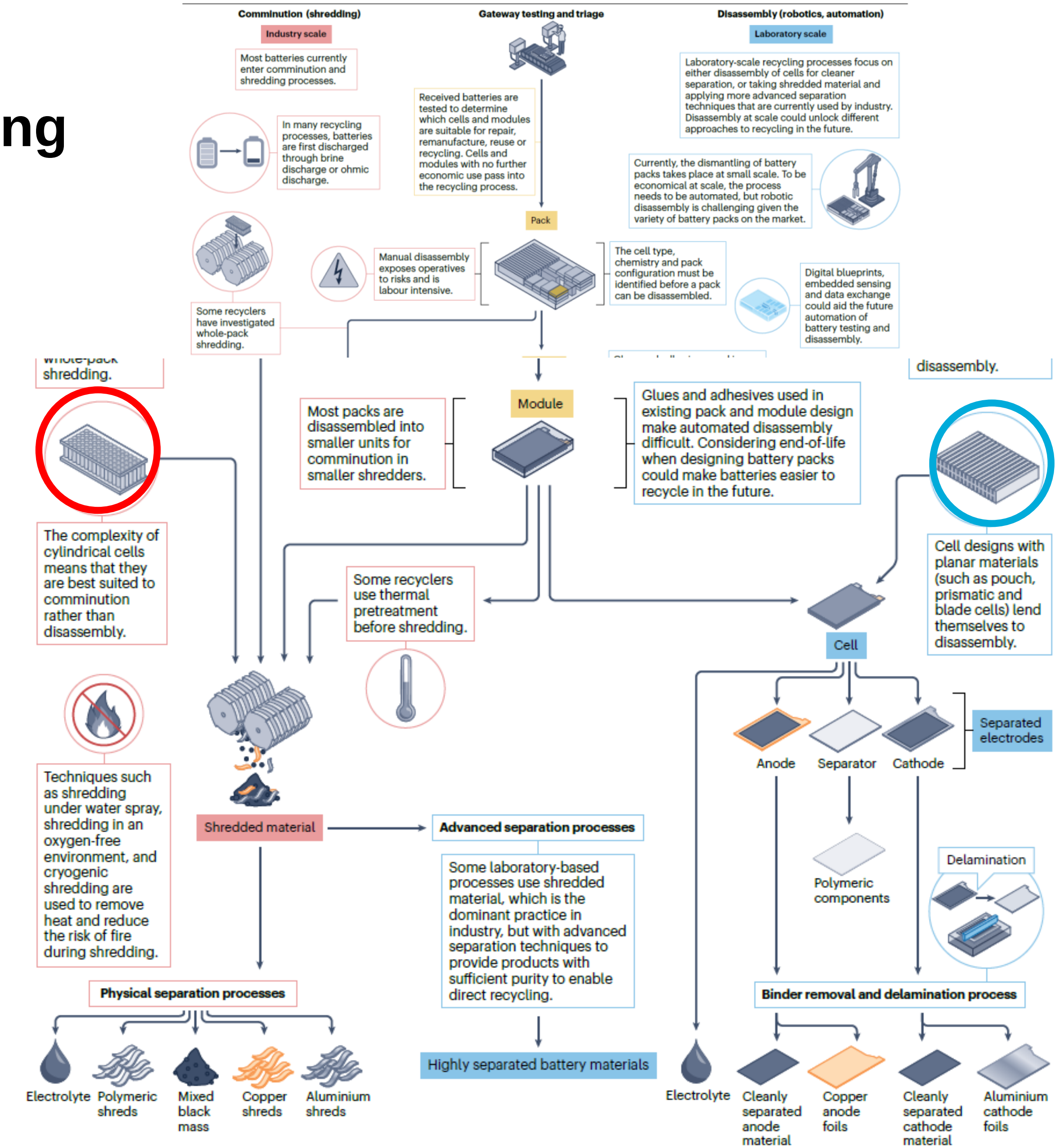
Recycling



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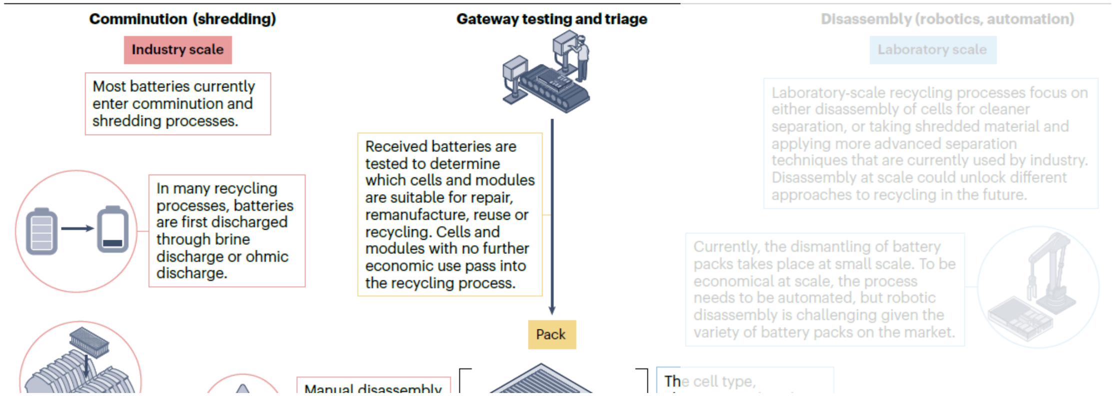
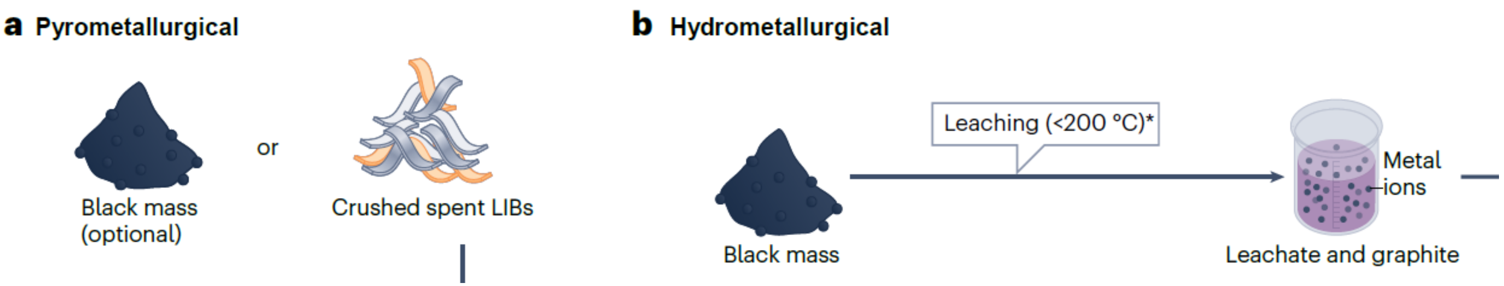
Recycling



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



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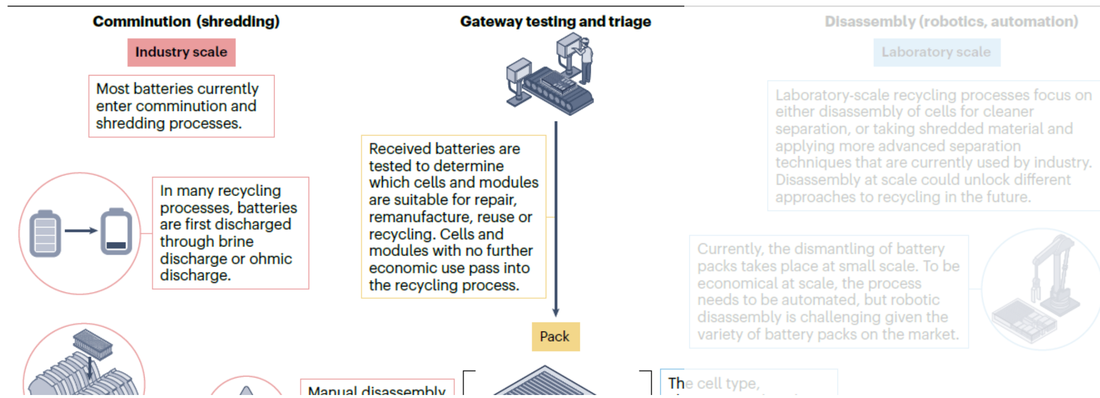
Recycling



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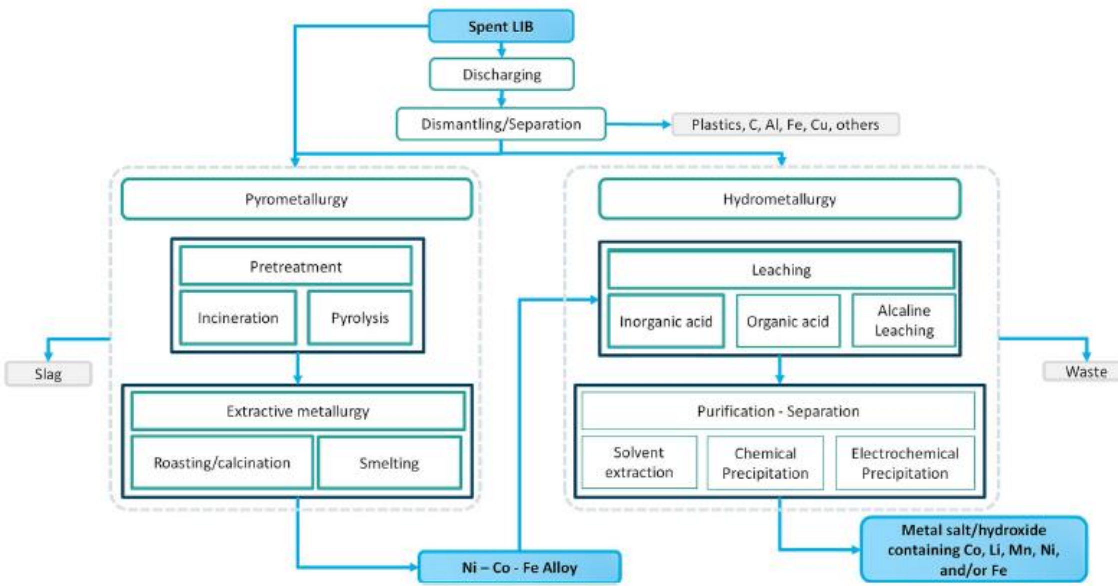

Source: Chacana-Olivares et al. 2025. Lithium-ion battery recycling: a perspective on key challenges and opportunities. Materials Sustainability. NPJ. https://doi.org/10.1038/s44296-025-00083-7

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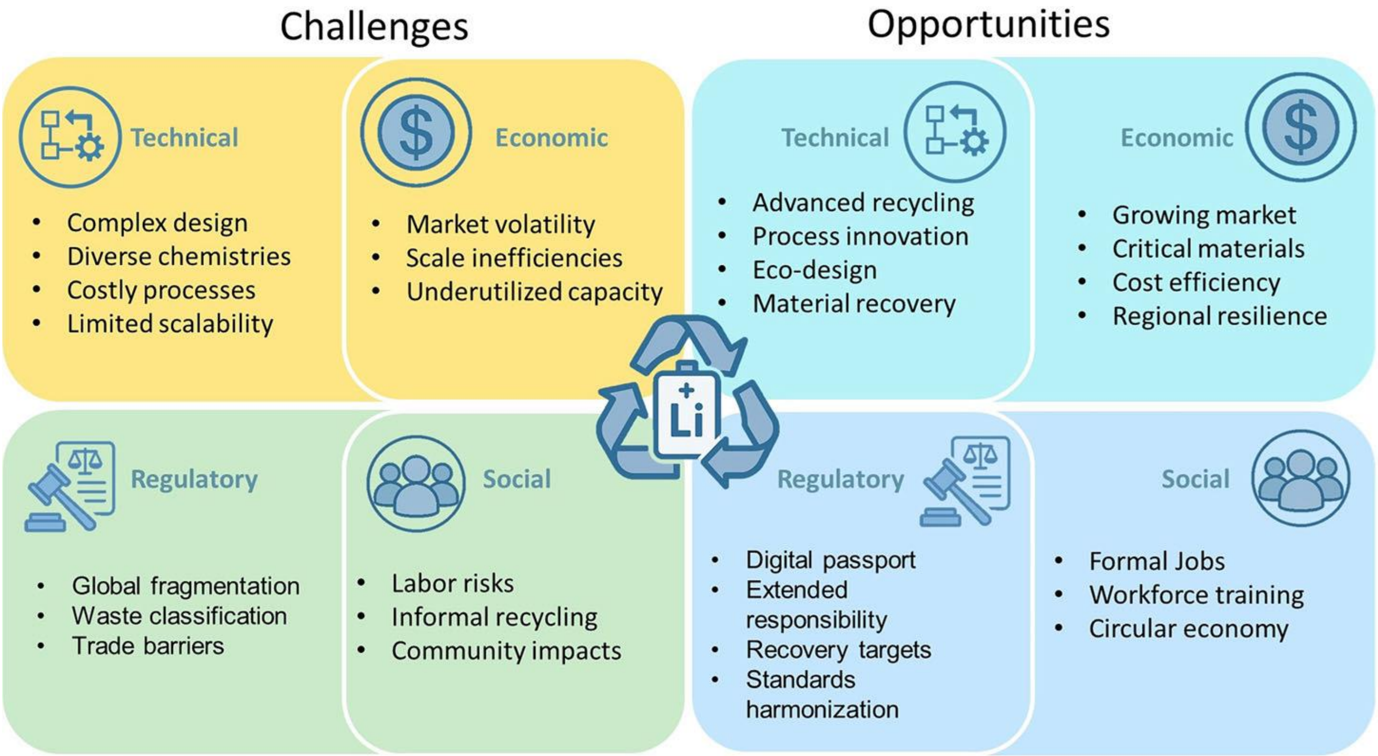
Closing the loop
Sustainability – Supply Chain Characterization

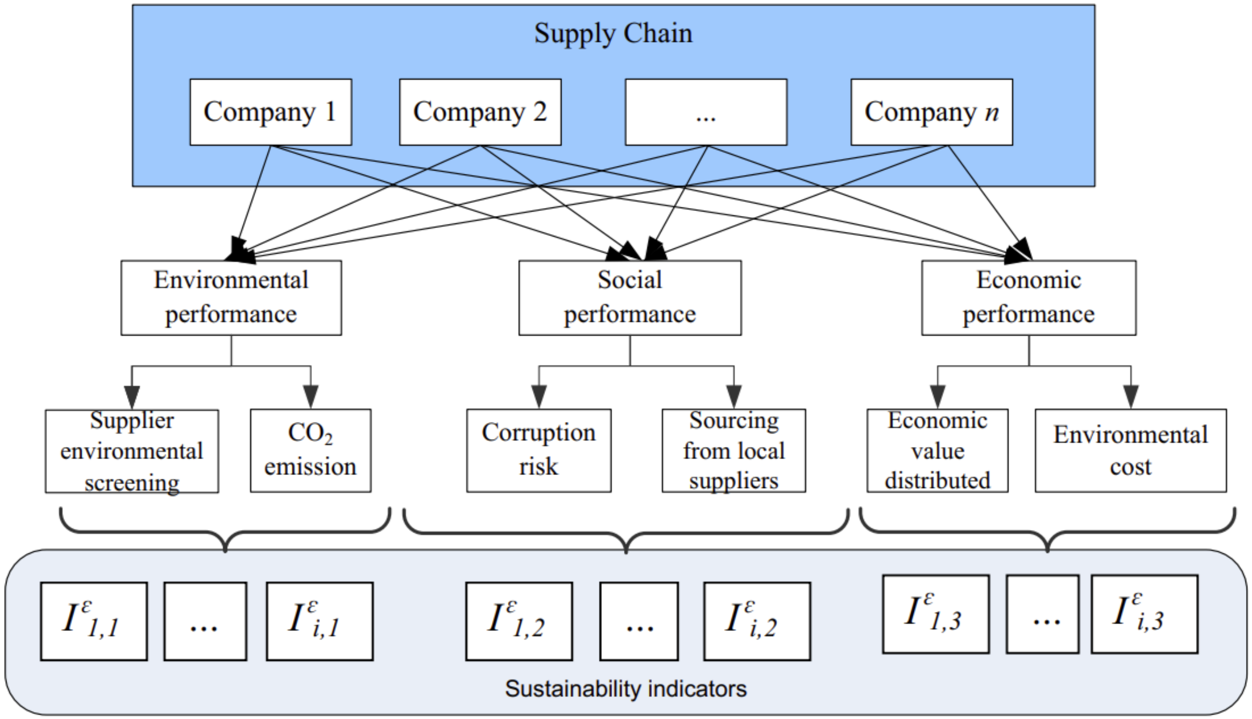
SWOT analysis (reloaded)



Source: Chacana-Olivares et al. 2025. Lithium-ion battery recycling: a perspective on key challenges and opportunities. Materials Sustainability. NPJ. https://doi.org/10.1038/s44296-025-00083-7

Closing the loop
Sustainability – Supply Chain Characterization

Hierarchical approach



--> Link to MCDM methods

Source: DOI 10.1007/s10668-016-9853-0