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Part of the PwC network

EU recycling market

The EU recycling market – a viable and sustainable business

Joint study between Strategy& and
PEM of RWTH Aachen University

August 2023

PEM | RWTH AACHEN UNIVERSITY

Battery recycling gained huge momentum in the last year, with multiple stakeholders announcing various initiatives

Recent battery recycling press clippings

May 2022

Europe's largest electric vehicle battery recycling plant begins operations

Hydrovolt *(50:50 JV Hydro and Northvolt)*

March 2023

Mercedes-Benz celebrates its groundbreaking ceremony for a new battery recycling factory in Kuppenheim, Germany, cutting resource consumption and establishing closed-loop recycling of battery raw materials.

Mercedes-Benz Group

March 2023

Umicore Battery Recycling: Capturing profitable growth and enabling a circular and low-carbon battery value chain

Umicore

June 2022

Toyota joins Redwood Materials' EV battery recycling initiative

Toyota / Redwood Materials

February 2023

BASF and Tenova Advanced Technologies enter into a joint development agreement for efficient recycling of lithium-ion batteries

BASF / Tenova Advanced Technologies

August 2022

Volkswagen-led research team to recycle batteries multiple times for the first time

Volkswagen Group

The EU battery recycling market will evolve into a sustainable business, extending the EU value chain

Management summary

1 Battery market
High electrification rates and the ramp-up of EU cell production to ~900 GWh in 2030 will drive the EU recycling market up to ~6,000 kt end-of-life batteries in 2040

2 Regulatory drivers
Following Asian regulation, the EU revised its regulatory environment in 2023 – among other things, requiring a recycling efficiency of 70% from 2031 onwards

3 Recycling technology
With a clear technological pathway and established supply chains, costs are expected to scale down by up to 50% for hubs operating at 40 kt and spokes at 10 kt

4 2030 EU recycling market outlook
By 2030, we expect more than €2 bn in investments into the EU recycling market. Handling further market growth trough to 2035 requires additional investments of €7 bn

5 Implications and recommendations
Recycling will become a viable and sustainable business beyond regulatory pressure with projected ~€8 bn in revenue and potential reduction in battery cost (e.g., €2…4/kWh cathode active material)

High electrification rates and the ramp-up of EU cell production will drive the EU recycling market

Electrification increases significantly

By **2030**, around **40% of light vehicles globally** will be based on a BEV platform, and over **70% BEV share** is expected in **2040**. From 2030 to 2040, **global battery demand** will nearly double to **up to 6.5 TWh**.

Gigafactory ramp-up in Europe

Following the EU electrification market dynamics, **battery manufacturing ramps up significantly** all over Europe. By 2030, **nearly 1.0 TWh in EU gigafactory supply** is expected.

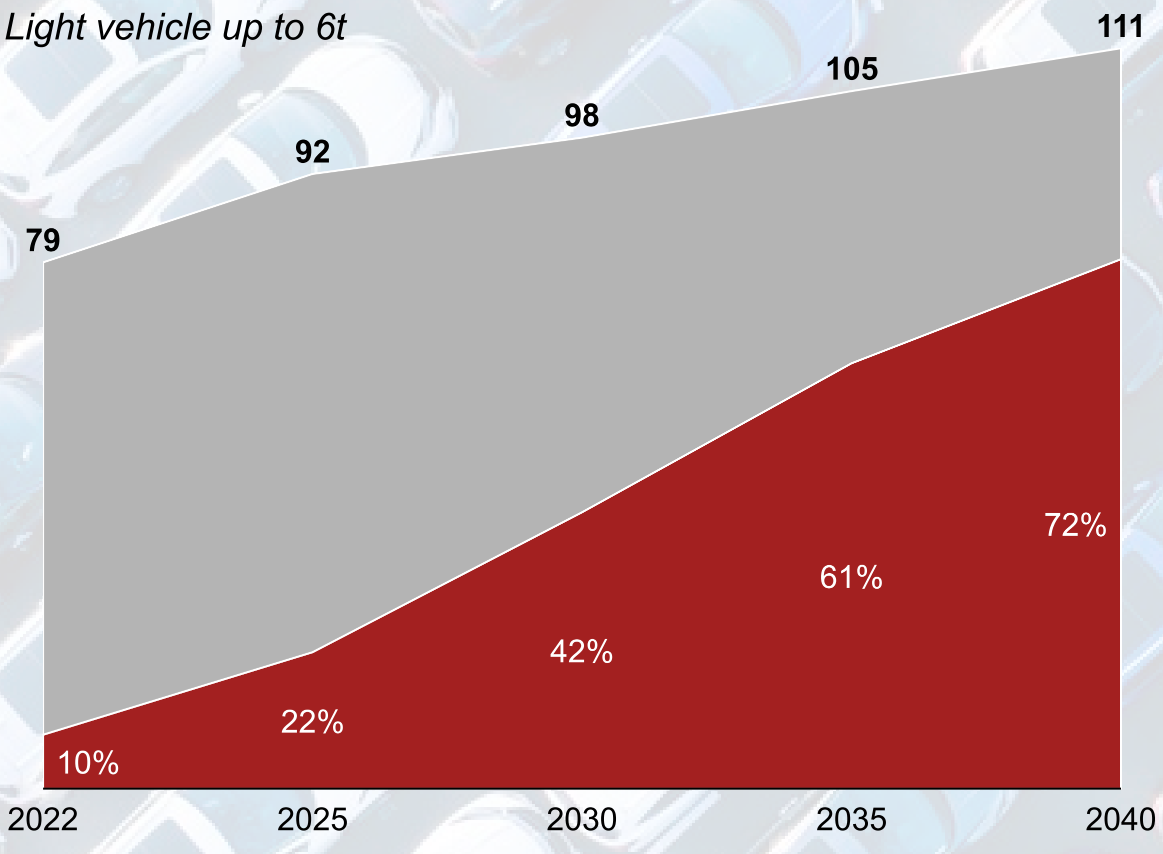
End-of-life batteries take major role in recycling

Driven initially by gigafactory scrap, the **market turns from 2030 onwards**, with vehicles from the **first wave of electrification reaching end-of-life**. By 2040, the EU battery recycling **market will ramp up towards 1.0 TWh**.

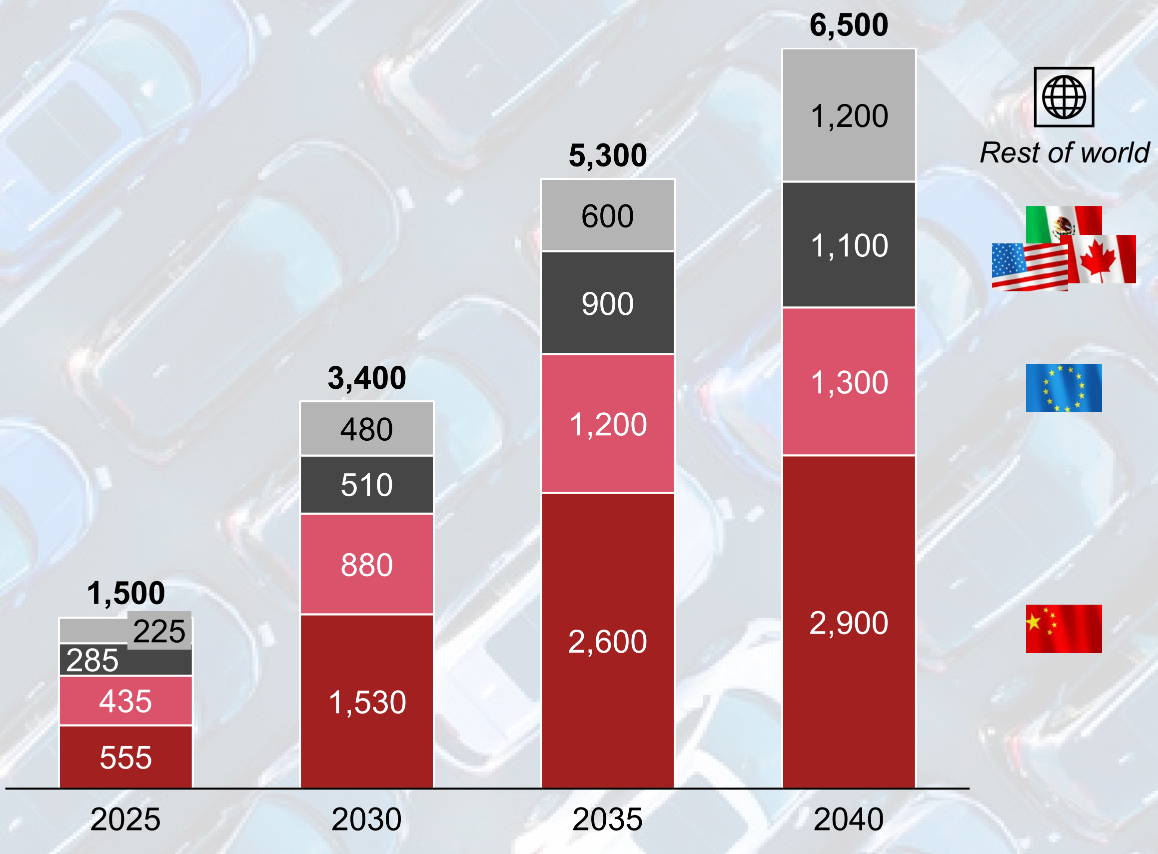
By 2030, ~40% of all light vehicles will be a BEV platform, fueled by EU and China, with over 3.4 TWh battery demand

BEV diffusion and battery demand (realistic scenario, as of 2023)

Global BEV diffusion (in m units)



Global battery[1] demand (in GWh)

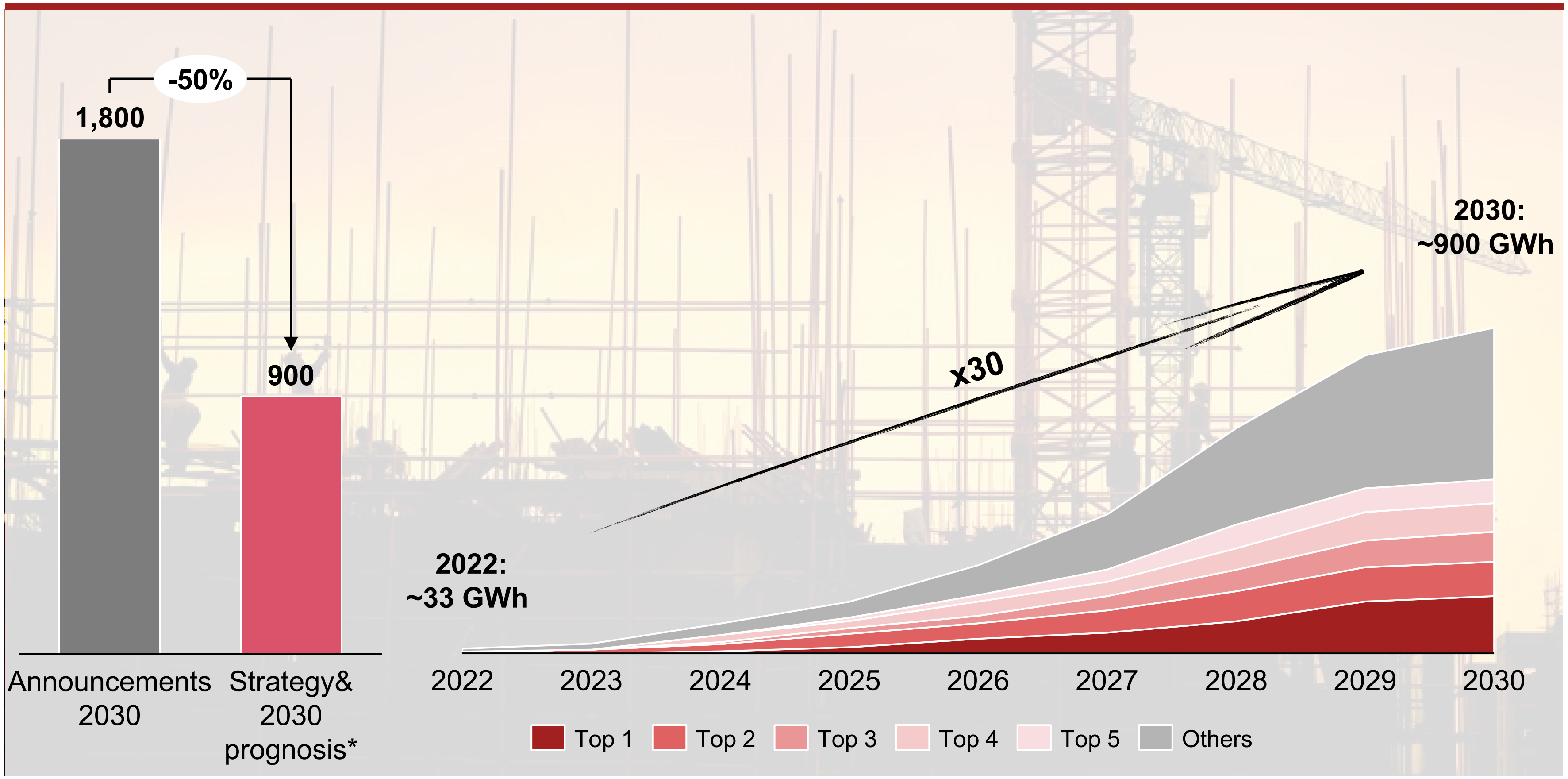


1) In the following, "battery" stands for high-voltage lithium-ion batteries in the automotive sector

Following the demand for electric vehicles, European battery cell production ramps up over the next decade

EU gigafactory ramp-up

Forecast for gigafactory ramp-up in Europe



Comments

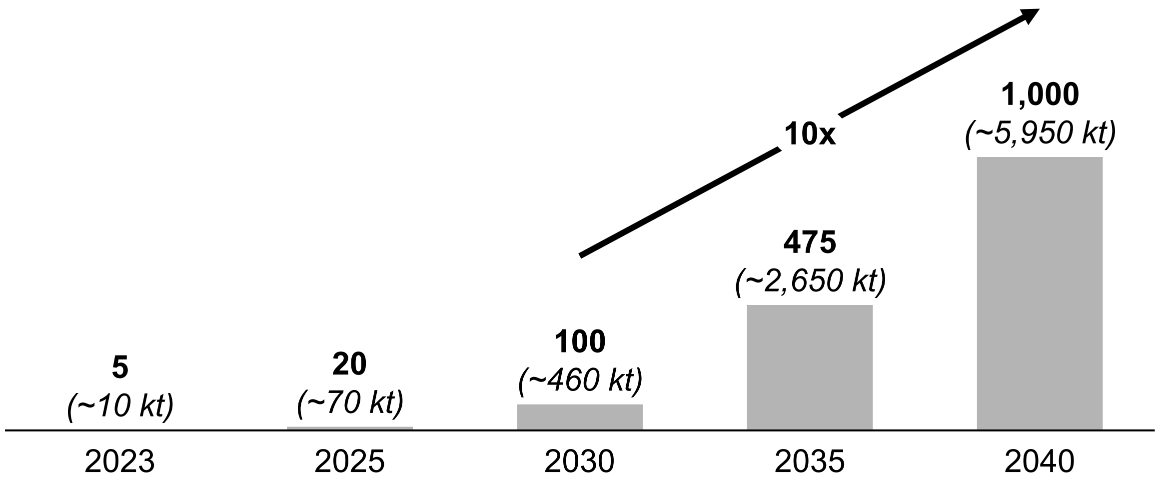
- **Difference between announced and expected** GWh ramp-up primarily **due to late start of construction and market consolidation**
- **Top 5 manufacturers** cover about **half of total capacity** in 2030
- Most **small manufacturers start ramp-up from 2027 onwards**

*) Adjusted forecast based on announced GWh capacity compared to current project start-up status, based on desktop research and expert estimates.

By 2040, battery recycling is up ten-fold vs. 2030 – driven by gigafactory scrap initially, EoL batteries ramp up from 2030+

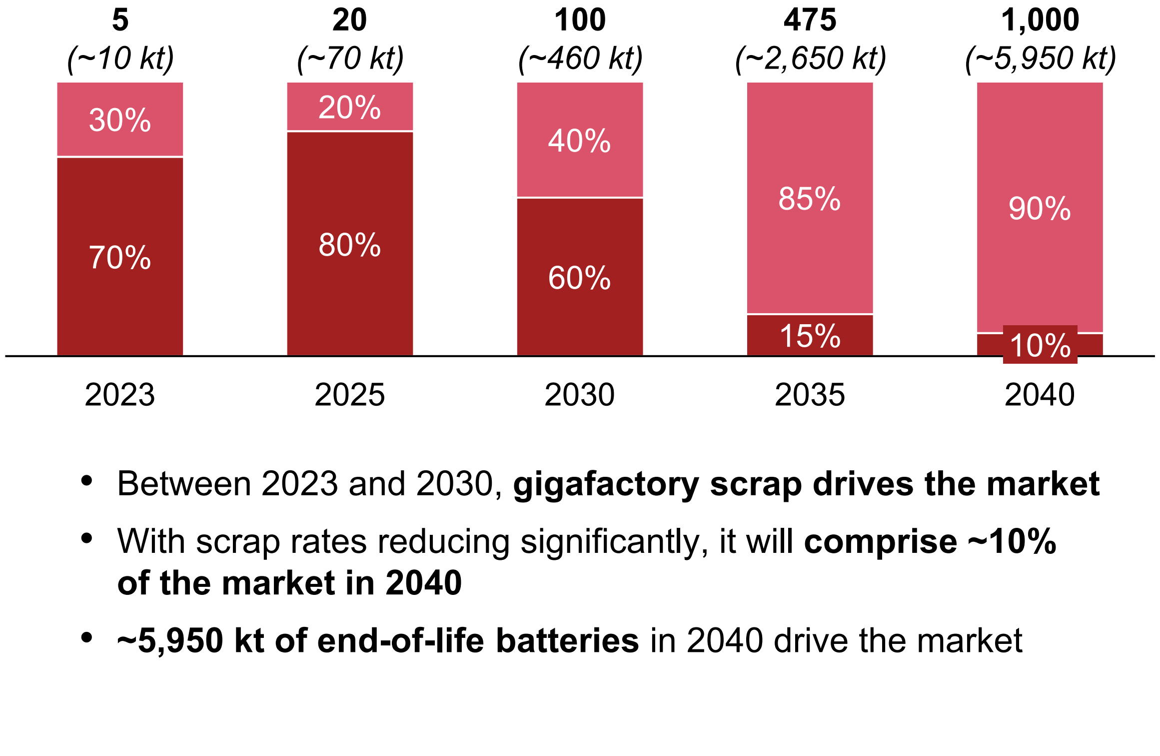
European recycling market (in GWh)

Development of recyclable material (in GWh, kt)



- Approx. **ten-fold increase** in share of recyclable material between 2030 and 2040
- Fast ramp-up from 2030 onwards because of **first wave of electrification reaching end-of-life**

Distribution of recyclable material (in GWh, kt)



- Between 2023 and 2030, **gigafactory scrap drives the market**
- With scrap rates reducing significantly, it will **comprise ~10% of the market in 2040**
- **~5,950 kt of end-of-life batteries** in 2040 drive the market

Following Asian regulation, the EU revised its legislation and set a regulatory environment from 2023 onwards

Asia leads way in regulation

With **initial regulations since 2013**, South Korea and China are leading the way in battery recycling. **Current battery recycling rates are ~90%**.

EU revised its legislation

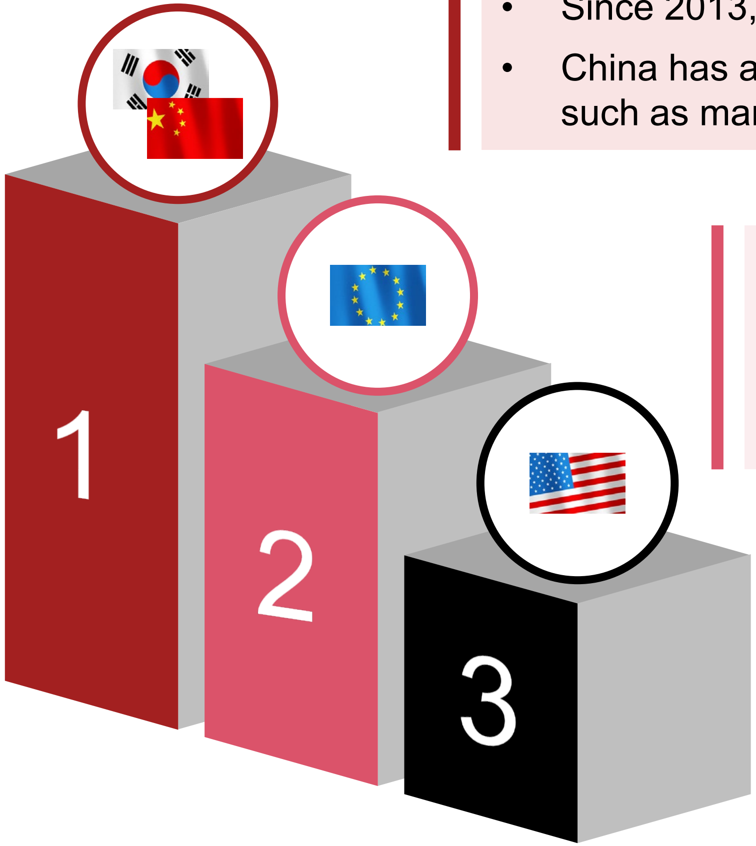
The EU Battery Directive, stipulating **recycling rates of 55% since 2006**, required a new framework. With the **Battery Regulation 2023**, the EU set a relevant **milestone for an EU closed-loop battery value chain**.

Clear targets enabling a closed loop

With the **EU legislation taking effect in 2023**, it sets recycling efficiencies and rates for each critical material and defines a minimum target for use of recycled material for cell production.

Following Asian regulations, the EU recently set its recycling agenda, effective from 2023 onwards

Regulatory environment



Advanced battery recycling regulation and efficiency

- Since 2013, South Korea has **established recycling rates of about 90%** for batteries
- China has a battery recycling rate of about 90% and **recycling rates for materials of lesser importance** such as manganese of above 85%, as well as regulations for **wastewater handling**

New regulatory environment for battery recycling adopted in August 2023

- Europe **revised its Battery Directive** from 2006 to **regulate the entire battery lifecycle**
- The updated regulatory framework **introduces end-of-life requirements** such as collection and recovery targets, as well as extended producer responsibility

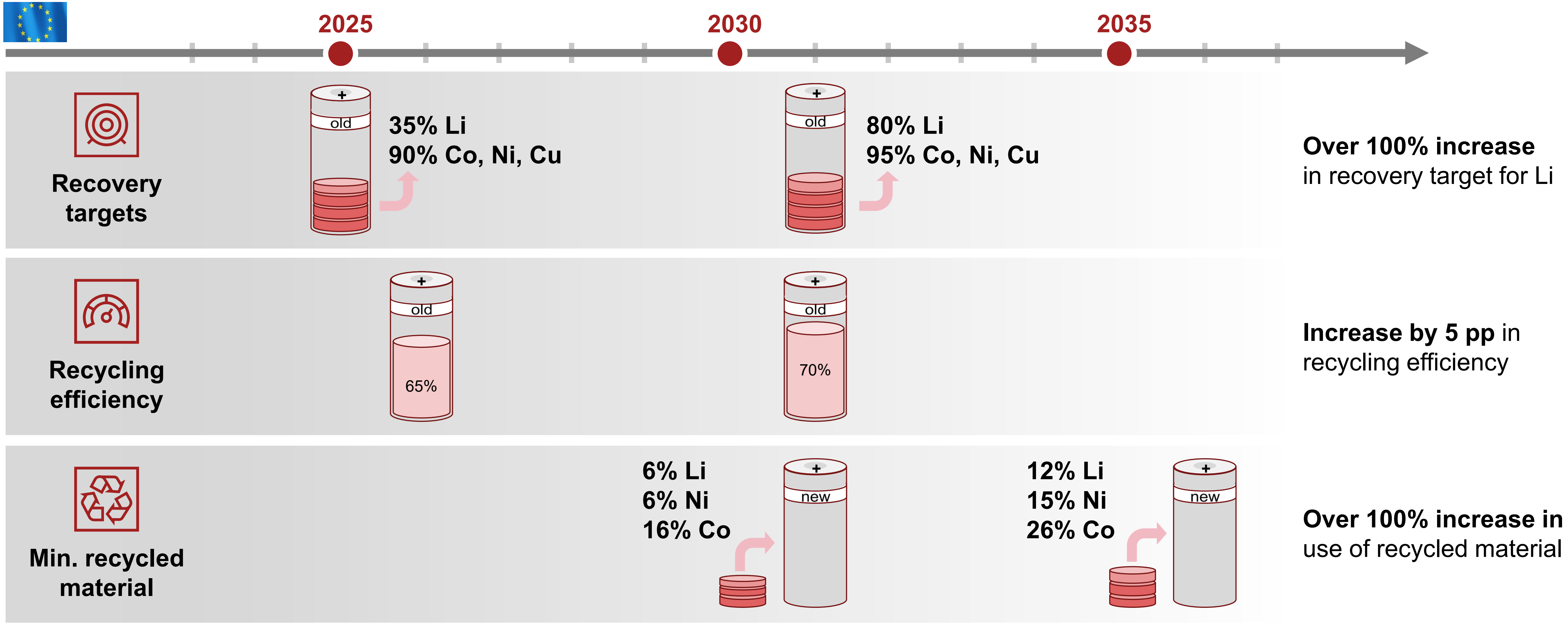
Deep dive on next slide

USA still has no general obligation in place for battery recycling

- There are **research projects and programs like "Call2Recycle"** which push for battery recycling regulation
- By **classifying materials for clean technology as critical**, the Critical Minerals and Materials Program indirectly impacts battery recycling

The revised EU Regulation sets increased recovery targets, recycling efficiencies and minimum level of recycled material use

Milestones of European battery regulation and implications



With a clear technological pathway, we see recycling preparation in decentralized spokes and the main recycling activities in central hubs

Technological pathway is clearly set

Over the coming years, the technological development will move **from pyrometallurgy towards hydrometallurgy, at higher recycling efficiencies**.

Value chain is being established

A **value chain consisting of preparation, pre-treatment and main treatment** is currently being built up. Further specialization and scaling along the value chain could **reduce investments by up to 50%**.

Hub-and-spoke footprint to be established

The high CAPEX for main treatment drives the value chain set-up towards **centralized hubs**, with preparation and pre-treatment placed in **decentralized spokes** close to customers.
A **1:10 hub-to-spoke ratio** is expected.

Recycling can be divided into three steps: decentralized preparation and pre-treatment and centralized main treatment

Overview of battery recycling processes

Decentralized activities across spokes
(lower capital requirements)

1 Preparation

Discharging

Discharging batteries to enable safe recycling process

Discharged pack

Disassembly

Disassembling battery pack, removing housing, frame, wiring, and cooling system

Modules/ cells

Thermal treatment

Pyrolysis or atmospheric thermal processing of the battery pack to prepare for comminution

Modules/ cells

2 Pre-treatment

Comminution

Crushing of cells by dry or wet shredding, impact mill or shockwaves

Shredded pack

Separation

Separating different materials by sieving, froth flotation, density, and magnetic-based processes

Black mass (BAMM[1])

3 Main treatment

Centralized activities in hubs
(high capital requirements)

Pyrometallurgy

Applying high-temperature processes to produce alloys (Cu, Co, Ni) and slag (Li)

Metal alloy/slag

Hydrometallurgy

Applying chemical processes of leaching, removal of impurities and separation. Steps might be followed by purification to produce battery-grade materials

Battery-grade materials

Direct recycling

Producing directly reusable cathode active material

Cathode active material

[1] Battery active material mixture

Driven by efficiency and maturity, main treatment processes evolve from pyro- to hydro-metallurgical processes

Main treatment: Process types and characteristics

3 Main treatment

	Pyrometallurgy	Hydrometallurgy	Direct recycling
Technology	• Producing concentrated alloy containing Co, Ni, and Cu, by smelting the batteries in a heat-based process at ~1,500°C • Li and Mn end up in slag, ready to be used in the construction industry or processed further to recover Li	• Hydrometallurgy is a chemical process involving leaching, removal of impurities, and separation • Followed by solvent extraction and/or chemical precipitation to recover and increase the purity of Li, Ni, Mn, and Co	• Material is recovered to be used directly in battery production • Any combination of thermal and chemical processes to specifically recover CAM[1] without breaking it down into individual elements • This process is still mostly in the R&D phase
Output	 **Metal ore/alloy**	 **Battery-grade materials**	 **Cathode active material**
KPIs *(as of today)*	TRL[2] ■■■■■ CAPEX ■■■□□ OPEX ■■■□□ Efficiency ■■□□□	TRL ■■■■□ CAPEX ■■■■■ OPEX ■■■□□ Efficiency ■■■■■	TRL ■■□□□ CAPEX ■■■□□ OPEX ■■□□□ Efficiency ■■■■□

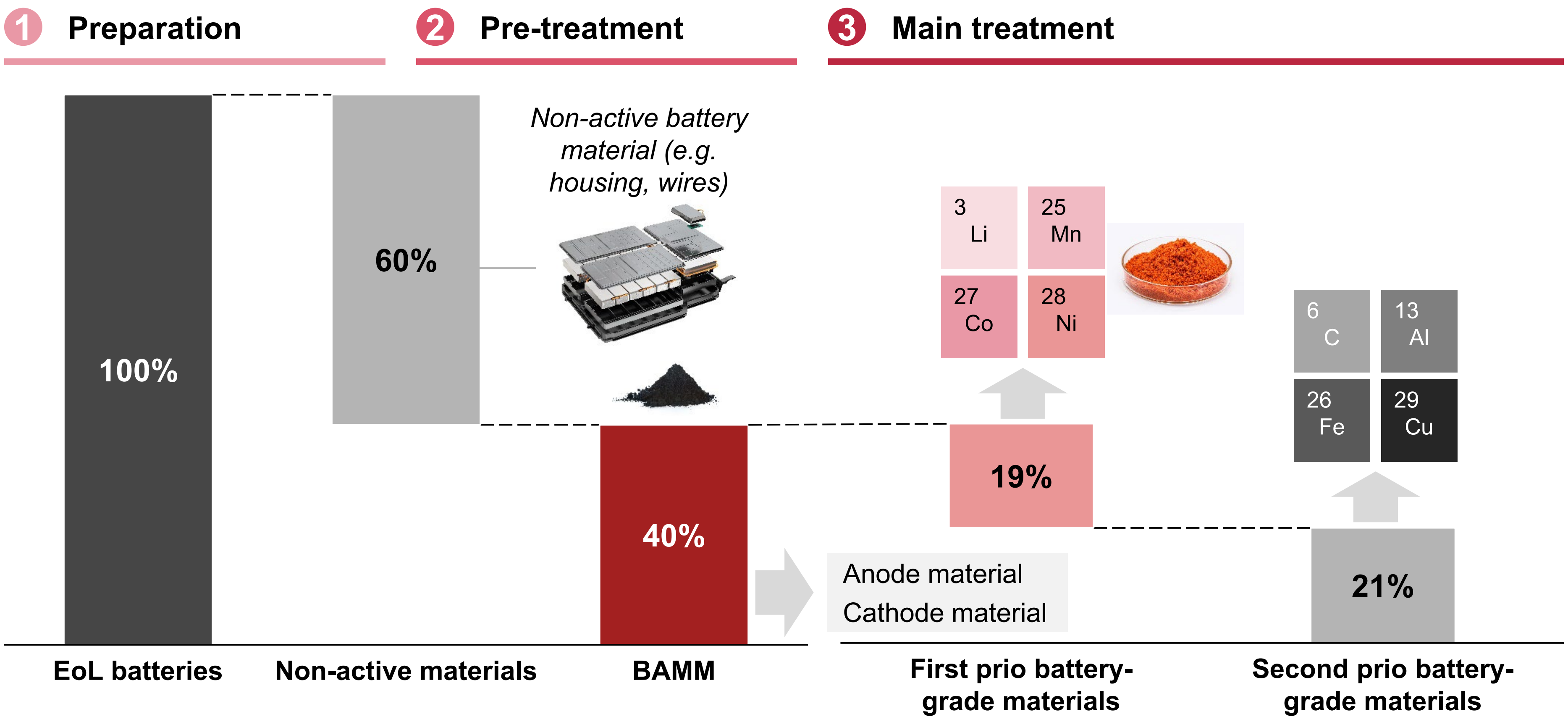
Low ■□□□□ High ■■■■■

1) CAM = Cathode active material; 2) TRL = Technology Readiness Level

With current hydrometallurgical processes, ~20% of the EoL battery mass can be recycled for active materials

Recycling efficiency: Battery material recovery *(illustrative for hydrometallurgy)*

Recovery efficiency



Comments

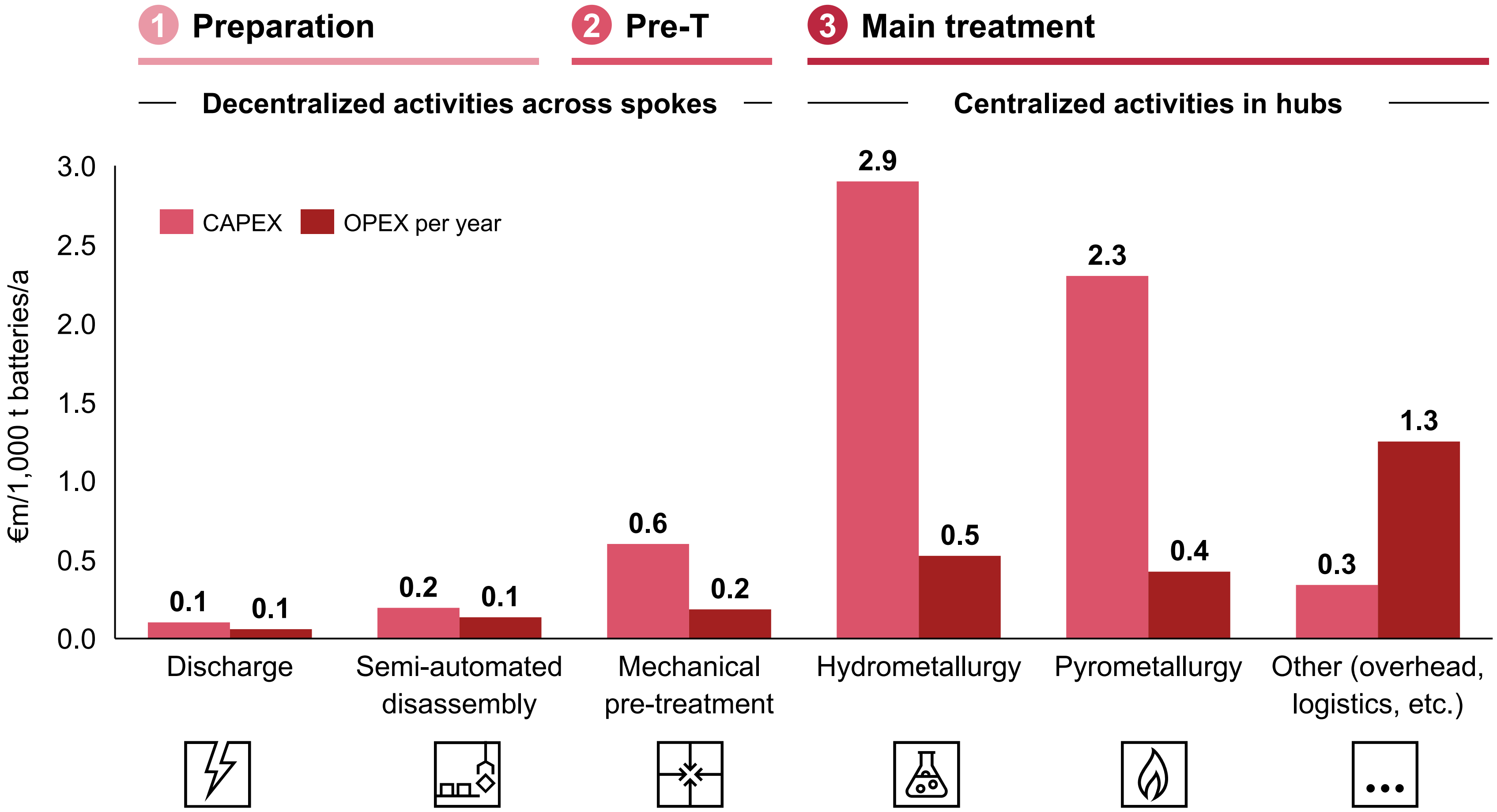
- Overall, **19% of EoL battery mass can be recovered** to first prio battery-grade materials
- With **90% efficiency over the whole recycle path**, first prio battery-grade materials are extracted from BAMM
- **Recovering second prio** battery-grade materials is still in the **development stage**

Assumption of 70:30 ratio between NMC and LFP batteries

Picture source: https://www.ilpeagalvarplast.com/ev-cooling-systems/

Main treatment accounts for the majority of capital demand – recycling hubs as potential opportunity for economies of scale

CAPEX/OPEX[1] for battery recycling process elements



Comments

- Spokes are **responsible for the less capital-intensive** preparation and pre-treatment phases
- Hubs focus on **main treatment with a major CAPEX and OPEX** share
- "Other" category **includes overhead for all parts of the recycling process** chain, logistics, etc.

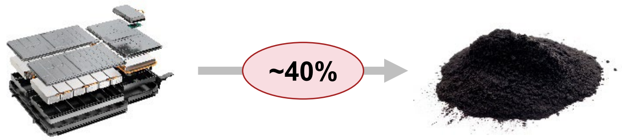
1) Operating and capital costs were calculated to a class 4 accuracy (± 25%) by the Association for the Advancement of Cost Engineering (AACE)
Source: VDMA/Fraunhofer ISI (Recycling of lithium-ion batteries: Opportunities and Challenges for Mechanical and Plant Engineering) 2021; Sattar et al. (Automotive Lithium ion Battery Recycling in the UK) 2020; Primobius (Recycling JV with Primobius – Operating and Investment Cost Estimates) 2021; Lima et al. (Economic Aspects for the Recycling of Used Lithium-Ion Batteries from EVs) 2022; PEM insights

For both hubs and spoke, exploiting economies of scale in process chain design can approximately halve CAPEX

Cost evaluation along the process chain

Recycling chain

Recycling spoke *(10,000 t/a)*
Mechanical preparation and pre-treatment

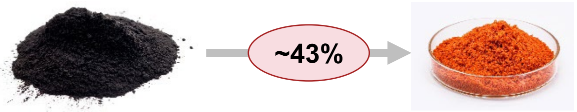


10,000 t
EoL batteries

~4,000 t
BAMM

Transport
With an expected ratio of 1:10, ten spokes serve one hub

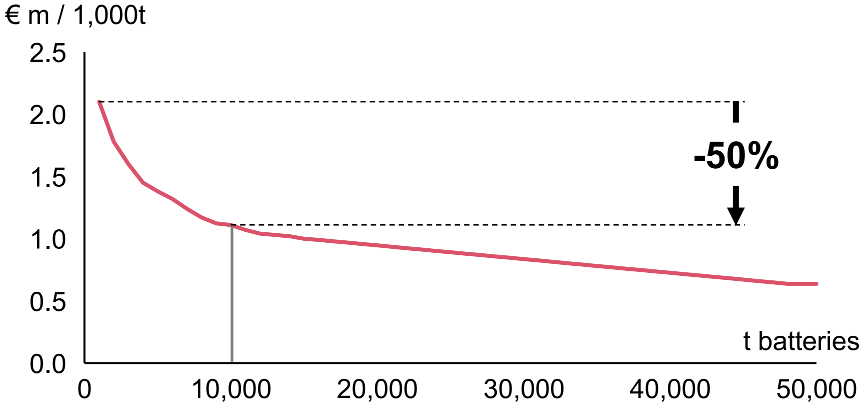
Recycling hub *(40,000 t/a)*
Main treatment (hydro)

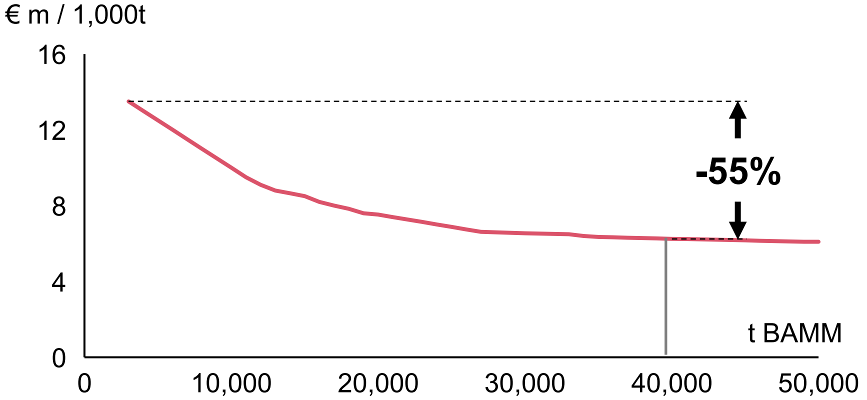


40,000 t
BAMM

~19,000 t
Battery-grade materials

Economy of scale (CAPEX in €/t)





Comments

- The **trade-off between economy of scale and distance to customer** determines the ideal facility size of hubs and spokes
- For spokes, the ideal size is **expected to process ~10 kt/a EoL batteries**
- **Larger spokes** with further exploitation of economies of scale are **contradicted by rising transport costs**
- For hubs, the ideal size is **expected to process ~40 kt/a BAMM**

By 2030, we expect investments of more than €2 bn in the EU recycling market

Announced ramp-up requires significant invests

After initial recycling overcapacities, the market is expected to be fully utilized from 2030 onwards, **requiring investments of more than €2.2 bn** for a **total recycling capacity of ~570 kt/a**.

Recycling capacity gap arises from 2030

With the first wave of electrification reaching end of life, the **recyclable material exceeds the announced capacity,** resulting in a recycling capacity gap by 2030.

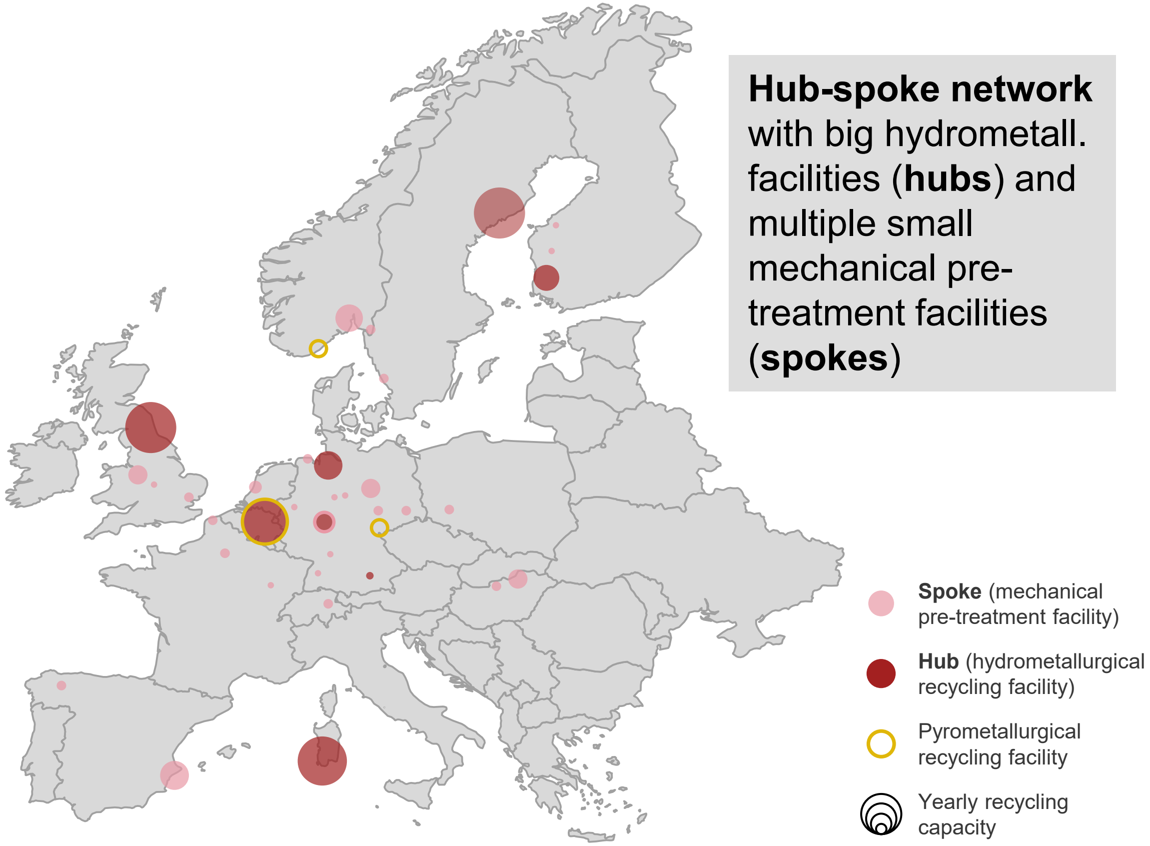
Additional investments required for 2035

To handle all recyclable material in 2035, **additional investments in recycling capacity of ~€7 bn** are required.

For the capacity ramp-up of hubs and spokes, investments of approximately €2.2 billion by 2030 have been announced

Announced recycling landscape and capacity development

European recycling landscape in 2030



Investments into recycling supply chain (CAPEX in €m)

∑CAPEX in € m

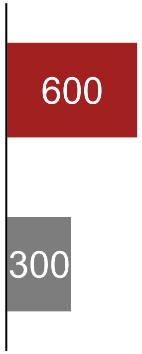
By 2025…

5 *hubs*

~15,000 *Ø BAMM capacity/hub*

33 *spokes*

~8,000 *Ø battery capacity/spoke*



~900 *Total CAPEX [€ m]*

~260 *kt battery recycling capacity*

~70 *kt BAMM recycling capacity*

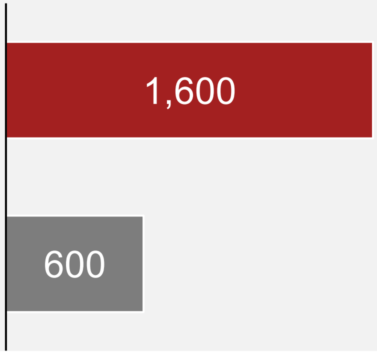
By 2030…

16 *hubs*

~40,000 *Ø BAMM capacity/hub*

57 *spokes*

~10,000 *Ø battery capacity/spoke*



~2,200 *Total CAPEX [€ m]*

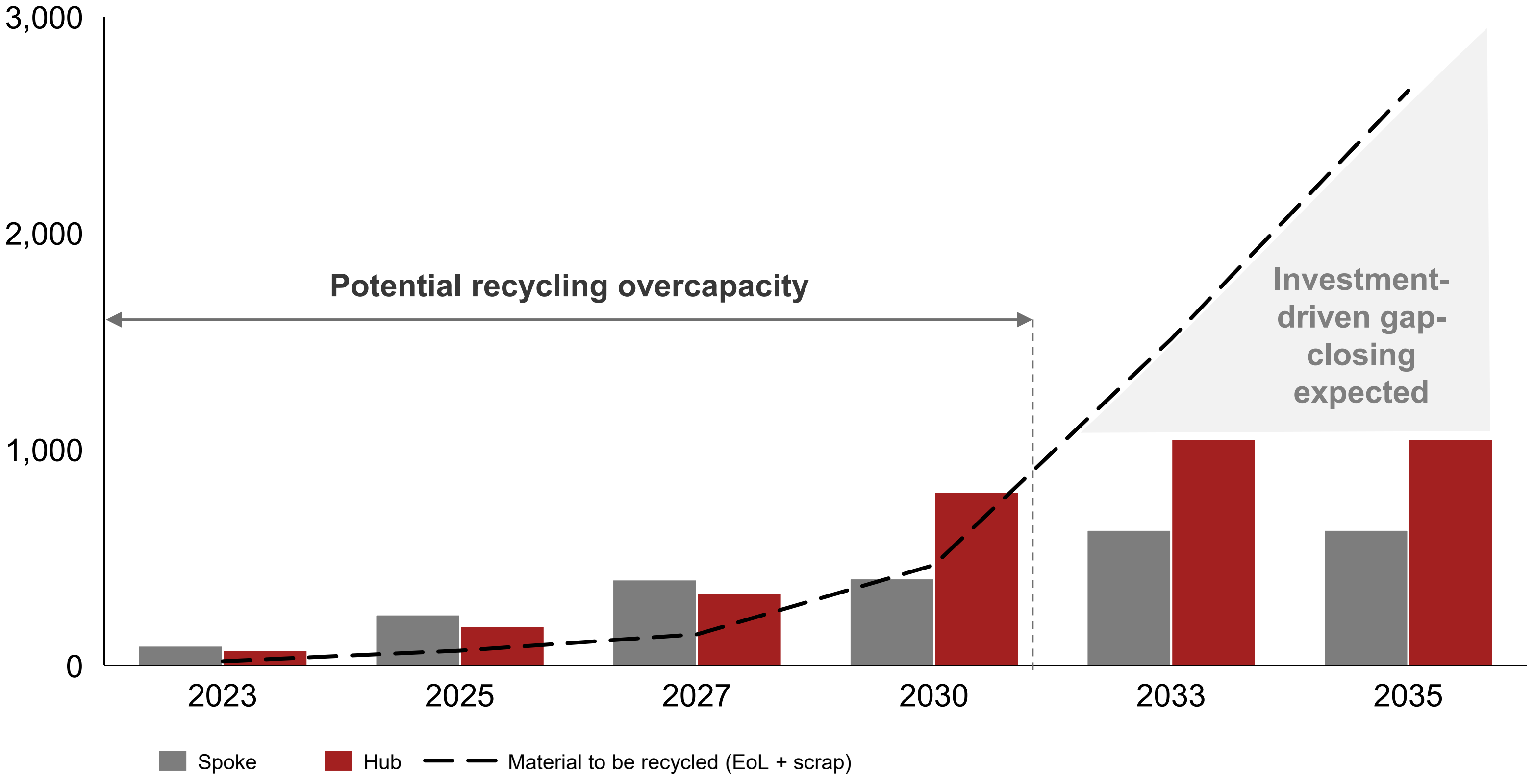
~570 *kt battery recycling capacity*

~254 *kt BAMM recycling capacity*

Putting the announced recycling capacity in context against available material, a capacity gap arises from 2030 onwards

Recycling capacity development from today to 2035

Recycling capacity development (in kt batteries)



Comments

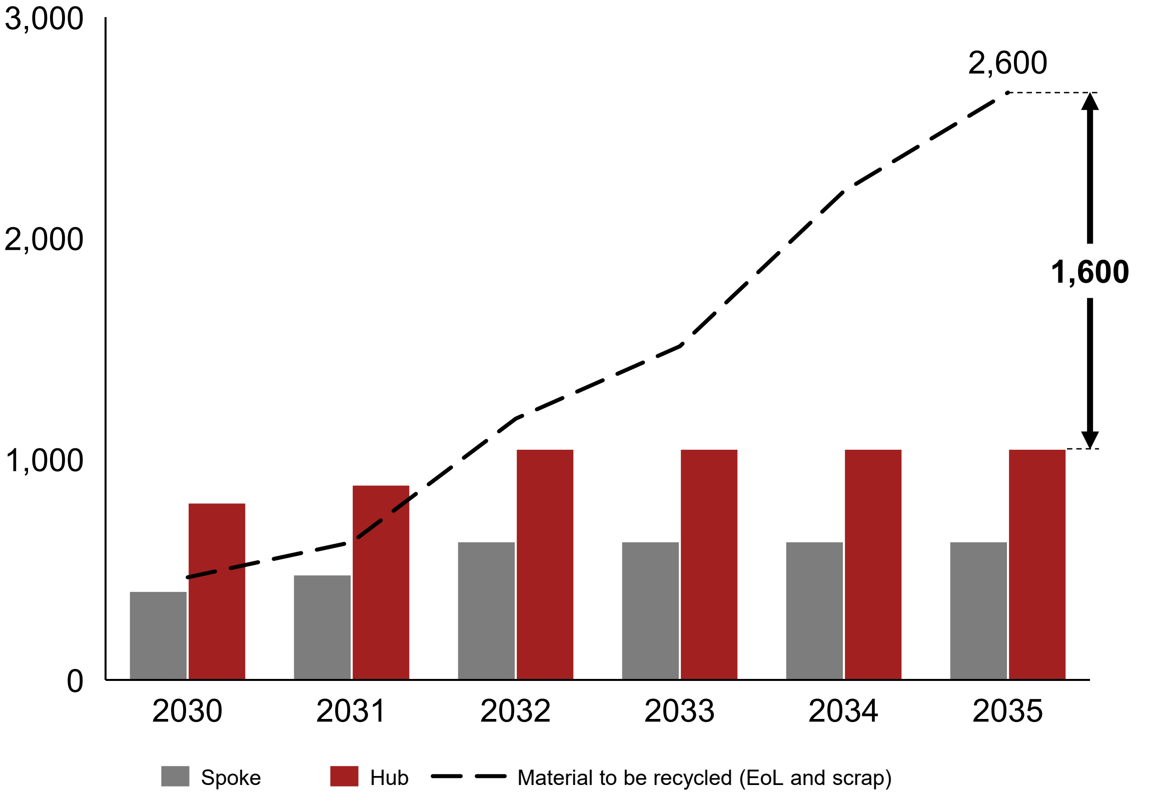
- **Significant overcapacities** in the European recycling market by 2030, **market expected to consolidate**
- **From 2030 onwards, a gap** between available material and recycling capacity arises
- The **spokes, in particular,** have a **large capacity gap**
- The **recycling capacity gap** is expected **to be closed by additional investments**

Note: Hub comprises capacity for hydrometallurgical and pyrometallurgical recycling

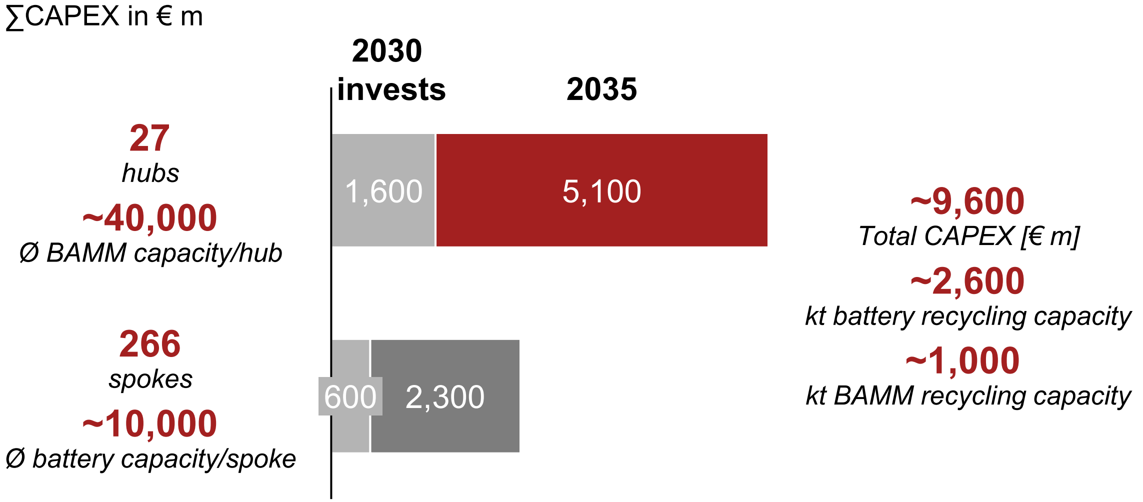
Additional investments of approximately €7 billion are expected to close the recycling capacity gap by 2035

Recycling capacity development beyond 2030

Recycling capacity development 2030-2035 (in kt batteries)



Investments into recycling supply chain (CAPEX in €m)



- To meet the demand for recycling capacity in **2035, a total CAPEX of €9.6 bn is required**
- Based on the announcements, **€1.6 bn will already be invested in hubs and €0.6 bn in spokes** by 2030
- To build up the capacity needed, a **further ~€7.4 bn** in total must be invested by 2035

Note: Hub comprises capacity for hydrometallurgical and pyrometallurgical recycling

Recycling will become a viable and sustainable business, beyond regulatory requirements

Recycled material contribute significantly

In 2035, **recycled material may account for up to 30%** of Li, Ni, and Co demand for battery cell production. The **EU recycling targets are expected to be met**, with only minor deviations.

Economic motivation drives ramp-up

With ramped-up operations and increasing battery disposal, the recycling business is capable of **building viable and sustainable profits** for all value chain stakeholders.

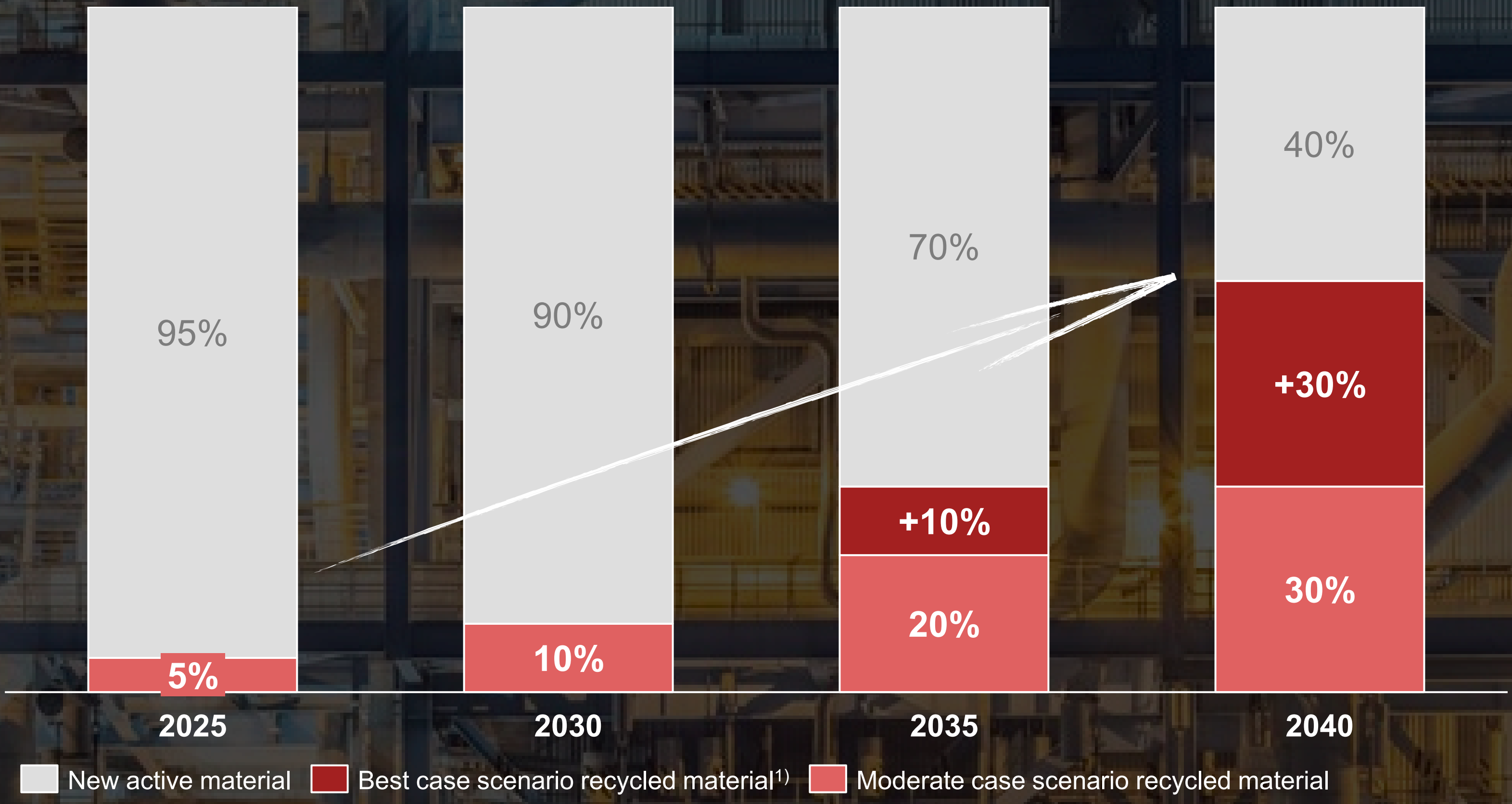
Recycling potentially reduces CAM price

With more recyclate available at competitive cost, a **positive impact on battery prices** can be expected through reducing CAM price by up to 20% (i.e. 2…4 €/kWh), further **spurring electrification and recycling market uptake**.

In 2040, recycled material can contribute up to 60%, although a completely closed loop not possible until well beyond 2040

Material demand for battery production

Development of recycled active material share (multiple case scenario)



Comments

- To create a **best-case scenario,** we have assumed the maximum possible recycling rate
- In the **moderate scenario**, we have assumed a slightly lower recycling rate
- In best-case scenario a ratio of about **40:60 newly mined to recycled material** for battery cell production is projected by 2040
- The recycled active material share will **gain momentum from 2030 onwards**, when the first wave of end-of-life batteries kicks in
- Nevertheless, an almost **completely closed loop** with recycled material will **not be possible until well beyond 2040**

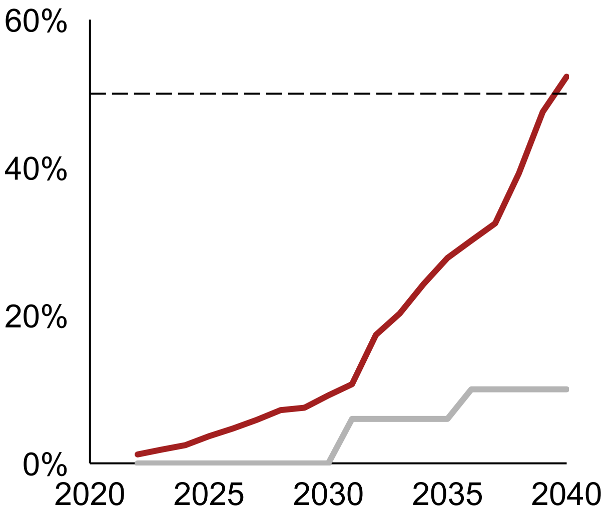
1) Best case scenario assumes nearly full recycling of all available EoL batteries and production scrap

The amount of recycled material available for cell production consistently exceeds the amount required by EU regulations

Trend in recycled material

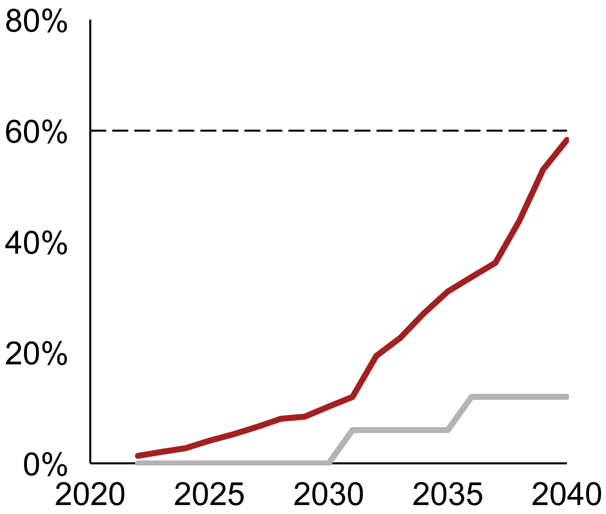
Min. % under EU regulations *vs.* max. possible %

Lithium



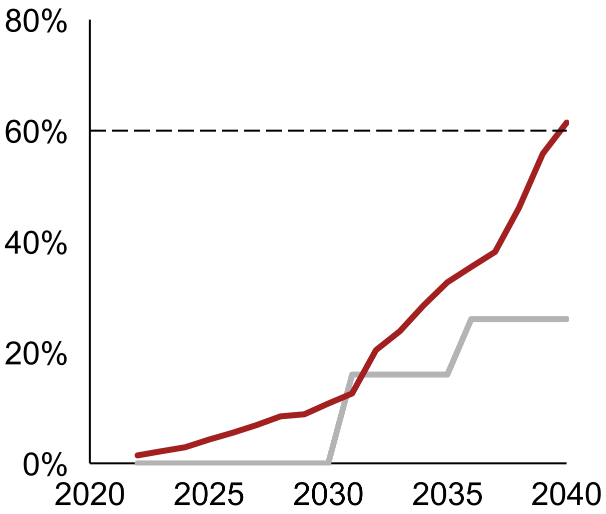
Enough recycled lithium available to **satisfy EU regulations**

Nickel



Enough recycled nickel available to **satisfy EU regulations**

Cobalt



Enough recycled cobalt available, apart form a **potential shortage in the early 2030s**

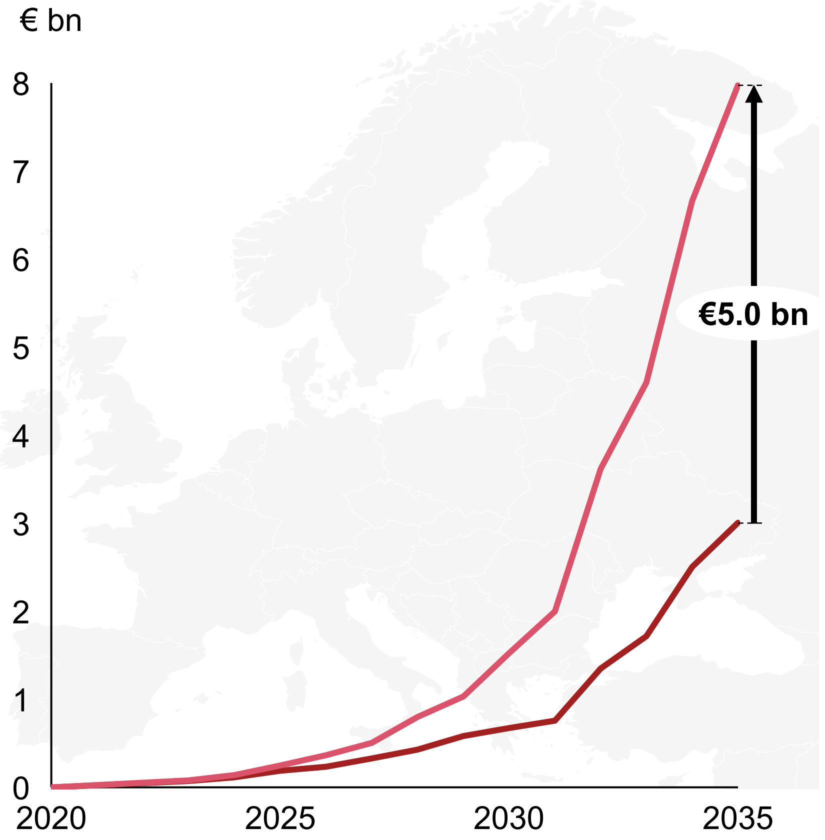
EU regulatory targets

Minimum percentage of recycylate in production based on EU regulations — Maximum percentage of recycylate in production based on available recycylate

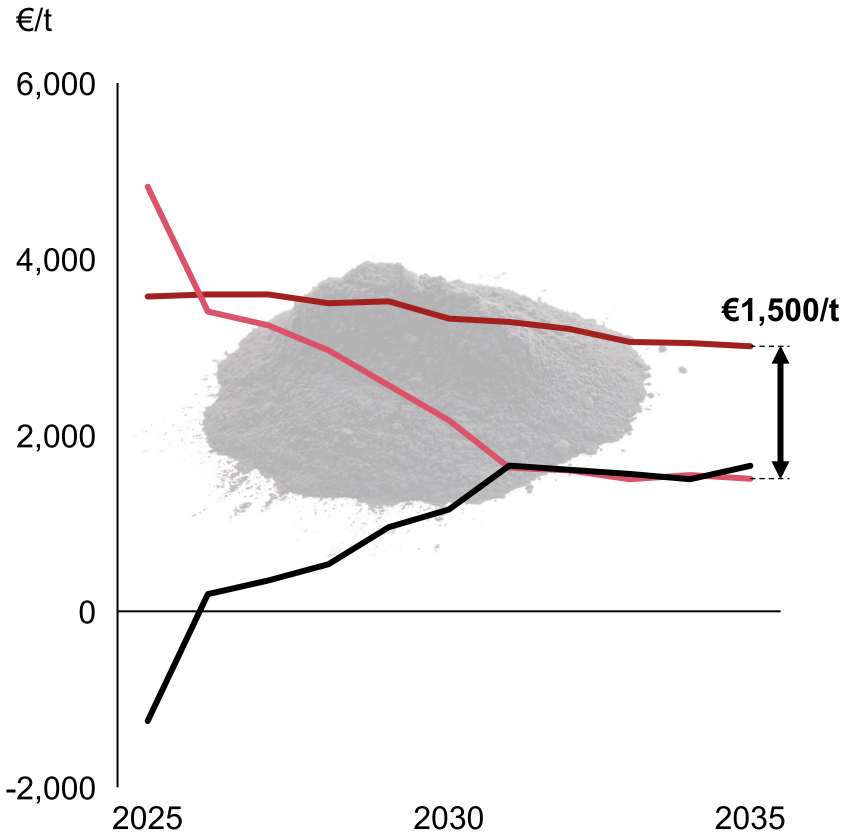
European recycling reaches break-even by 2025 and develops from then on with an increasing margin

Sales and cost projection

Sales and costs European market



Sales, costs, and profits



Comments

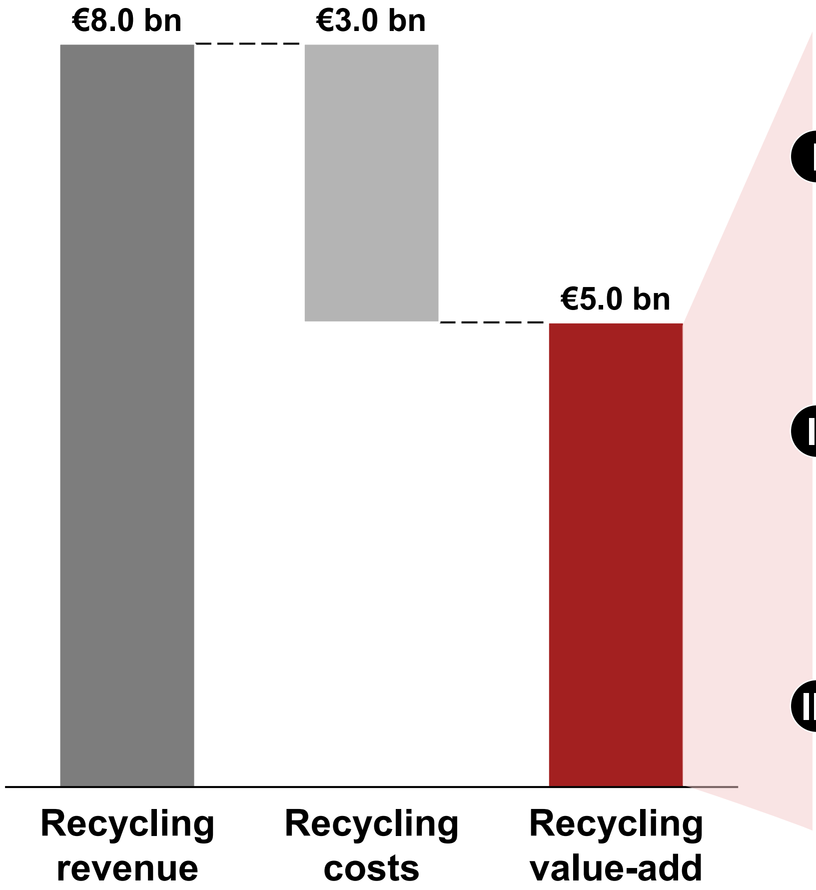
- Calculation of **sales volume** is **based** on the **trend in market prices** for the recycled materials
- European recycling **reaches profitability from 2025** onwards, with costs being scaled down and overcapacities reduced
- **Distribution of margins** across the recycling value chain (i.e. intensified competition) or the battery value chain (i.e. cell and battery manufacturers) has a high impact on future battery prices

Sales Cost Profit

Material price assumptions for calculation 2025+: Lithium € 13/kg (LCE), Nickel € 20/kg (ME) and Cobalt € 37/kg (ME)

Most stakeholders along the battery value chain benefit directly or indirectly from value-add of battery recycling

2035 value-add distribution and implications



Value chain	Today	Implications by 2035	Likely scenario
I Customer/ OEM	OEM/customer **must pay for disposal** of end-of-life batteries	Disposal of EoL batteries will be **free of charge** or even **generate value to the owner**	**No OEM accrual required** for battery disposal – customer will be **paid for EoL battery**
II Recycler (hub/ spoke)	Very **little to no margin** for recycler	Recycling value-add will lead to **sustainable margins**	**Margin** expected to meet automotive industry average (**8...10%)**
III Material prices	**No price reduction** for cathode active materials **through recycling**	Recycling value-add may enable **price reduction for cathode active materials**	**Up to 20% price reduction** for cathode active materials

Material price assumptions for calculation 2025+: Lithium € 13/kg (LCE), Nickel €20/kg (ME) and Cobalt €37/kg (ME)

Battery recycling industry scenario analysis reveals an ideal environment, with low cost combined with excess materials

Scenario analysis

Availability of recycled material	Low *(recycled > virgin)*	High *(recycled < virgin)*
	Limited recycling business	**Viable recycling business**
Excess	"**The availability of expensive recycled material** will lead to **oversupply**, as cell manufacturers will only **comply with regulatory conditions**."	***Expected situation*** "The **combination** of high material **supply at low recycling cost** will **realize an ideal market environment** for the battery industry."
Lack	"**A shortage of recycled material** combined with **high recycling costs** as well as **regulatory requirements** will lead to a **difficult market environment.**"	"**Low-cost recycled material** in **small quantities** leads to a **significant increase in demand** from of cell manufacturers, **causing material prices to rise again.**"
	Infeasible recycling business	**Potential recycling business**

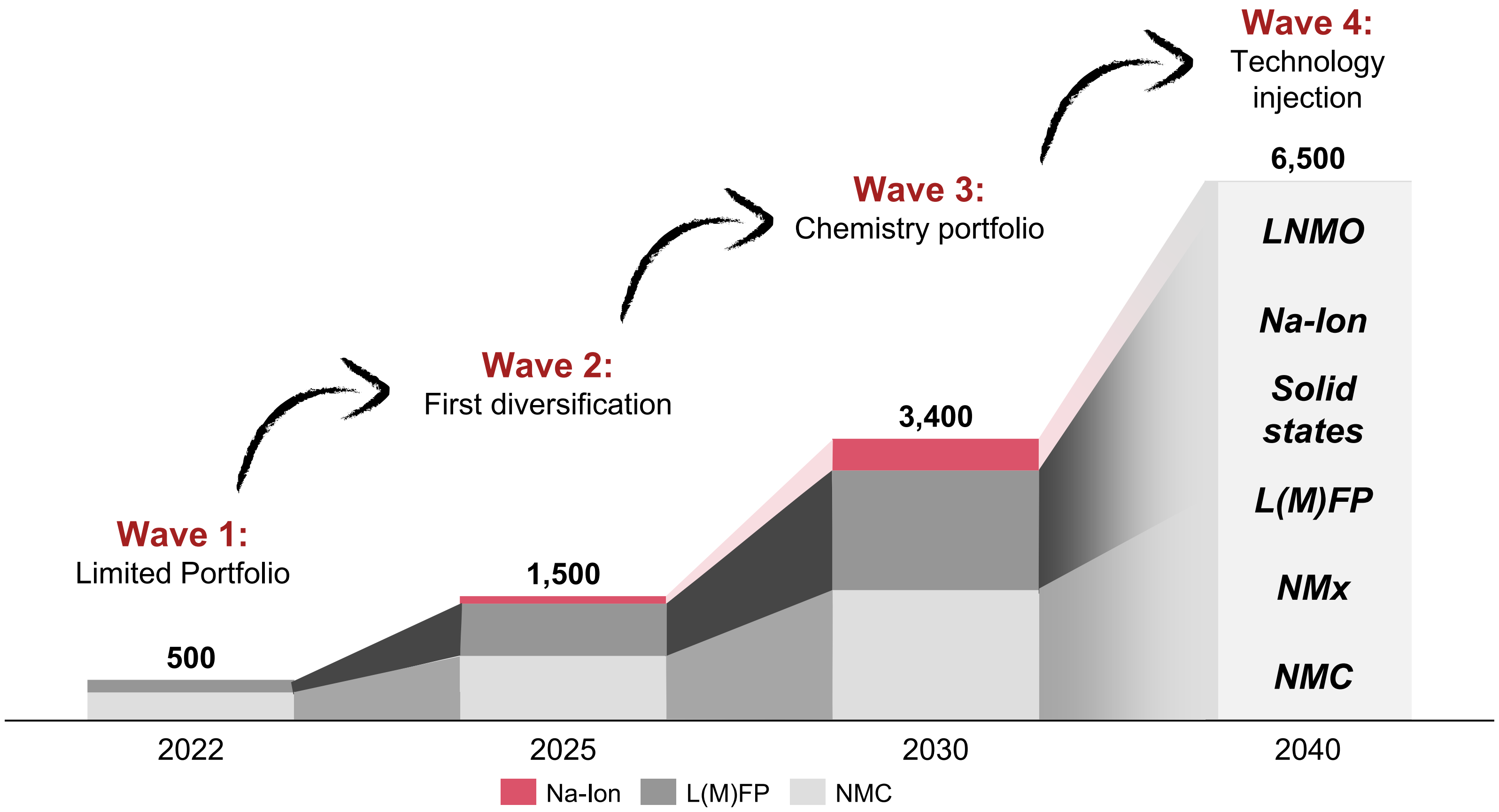
Costs virgin/recycled

Comments

- According to market analysis, there will be an **excess of recycled battery material**, ready to be **back-cycled into battery cell production**
- Low costs for recycled material in combination with **excess materials** realize an **ideal market environment** for the battery recycling industry
- Cell production also benefits through **cost reduction**
- **Battery closed-loop recycling** will thereby be enabled, potentially **improving availability of materials within Europe**

NMC chemistries continue to dominate the market – L(M)FP and Na-Ion chemistries entering via entry & volume segments

Global battery demand – cell chemistry split *(in GWh)*



Key takeaways

Wave 1:
Limited portfolio with NMC dominant cell chemistry, driven by the premium segment.

Wave 2:
Diversification driven by entry and volume segment.

Wave 3:
Platform diversification further drives cell chemistry portfolio.

Wave 4:
Future technology injection (e.g. solid-state batteries) results in more diversification of cell portfolio.

We would like to exchange our ideas with you!

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