Agora Verkehrswende

STUDY

Material Cycles for Traction Batteries

Raw material potential of battery recycling in the automotive industry and options for meeting extended producer responsibility in Europe

Stiftung GRS Batterien

Öko-Institut Consult GmbH

Legal notice

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The conclusions and results presented in this publication do not necessarily reflect the views of the participants. Responsibility for the content rests solely with Agora Verkehrswende.

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Foreword

Dear readers,

The industrial transformation toward climate neutrality is well under way. New technologies and products rely on raw materials and value chains that differ fundamentally from those of the past. In the automotive industry, this primarily concerns raw materials and intermediate products used to manufacture traction batteries for electric vehicles – in particular lithium, cobalt, nickel, and graphite. Global competition for access to primary production of these materials has been intensifying for years. This makes it all the more important to recover secondary raw materials from the recycling of used traction batteries.

The EU has already launched key initiatives to close gaps in Europe's raw material supply. Of particular importance are efforts to build a European battery and recycling industry – for instance through recycling targets for batteries placed on the European market (Battery Regulation), supply targets for critical raw materials (Critical Raw Materials Act), and the industrial strategy for the automotive sector. Germany is now in the process of aligning its national battery legislation with these European developments, including provisions on the take-back of traction batteries from electric vehicles. Current legislation was never designed for e-mobility. It covers a wide range of product groups – from disposable e-cigarettes to the traction batteries of SUVs.

Yet battery recycling is about far more than waste or environmental policy. Above all, it concerns the strategic supply of raw materials to industry and the economy at large. After all, the traction battery is the core component of electric-mobility value creation. Recycling battery materials strengthens the competitiveness of Germany's automotive industry, reinforces Europe's market independence, and contributes directly to climate protection in road transport. Germany can build on decades of experience in recycling. With traction-battery recycling at industrial scale, there is now an opportunity to establish a new, globally leading high-tech sector for Europe.

Against this background, Agora Verkehrswende – together with the Oeko-Institute and with support from Stiftung GRS Batterien – has examined in this study how value chains and material cycles for lithium-ion batteries in the automotive sector are likely to evolve, and what business models for lithium-ion battery recycling in the EU could look like. Following the EU Battery Regulation adopted in 2023, vehicle manufacturers – as those placing traction batteries on the market – are legally obliged to take back their batteries and to meet recovery rates for lithium, cobalt, and nickel. From 2031, mandatory recycled content targets will also apply for the production of new batteries. To meet these obligations, manufacturers can either organise recycling themselves – potentially through their own recycling facilities – or appoint a producer responsibility organisation to manage it on their behalf.

The challenges are substantial. These investments require long-term planning horizons. If sufficient quantities of battery materials recycled within Europe are to be available by 2040, the groundwork must be laid now. At the same time, ongoing technological change – for example in the chemical composition of traction batteries – will continue to bring new requirements. To address these and other questions effectively, dialogue and cooperation among stakeholders must be further strengthened.

This study represents a first step. It is intended to help inform the decisions now facing policymakers and industry on traction-battery recycling, and to support an ongoing dialogue on the outstanding issues. We look forward to continuing the debate – and wish you an engaging read.

Christian Hochfeld
for the Agora Verkehrswende team
Berlin, im September 2025

Findings and recommendations

1. **Recycling traction batteries within the EU can make a substantial contribution to securing the automotive industry's strategic raw material supply.** Over the next decade, demand for traction batteries in the EU is expected to increase sixfold — reaching a steady level of around 1,200 gigawatt hours per year. The growing volume of used traction batteries will provide valuable feedstock for the production of new ones. With efficient circular management, up to 25 percent of lithium demand could be met from recycled materials by 2040, and up to 50 percent of nickel demand. For cobalt, the potential share of secondary raw material exceeds 60 percent. Battery recycling is therefore not merely an issue of environmental or circular-economy policy — it is also a matter of industrial and economic strategy.

2. **The gaps in the EU's raw material cycles for lithium-ion batteries remain substantial and must be closed without delay.** Action is needed at many points along the value chain: in raw material extraction, cathode and anode material production, cell manufacturing, and the recycling of black mass to recover battery materials — thereby securing battery-grade feedstock from European sources. Demand for key raw materials is set to rise significantly by 2035, while the chemical composition of traction batteries continues to evolve. A clear trend can already be seen toward lithium-ion batteries using lithium-iron-phosphate cathodes, which require no nickel or cobalt.

3. **Through the implementation of the Critical Raw Materials Act, the EU is continuously supporting the establishment of closed material cycles for traction batteries and adjusting its approach as needed.** This includes robust measures to strengthen the recycling industry across the entire value chain and to prevent the outflow of intermediate products — such as black mass or recovered raw materials — to non-EU countries. At the same time, market participants will find it difficult to meet their legal obligations if sufficient capacity for the recovery and processing of recycled materials is not available within the EU. Accordingly, the EU should maintain close monitoring of these material cycles and roll out its policy measures incrementally over time.

4. **The EU aims to further harmonise recycling systems for traction batteries across Member States in order to achieve economies of scale and improve cost efficiency.** Under the current Battery Regulation, various business models are possible. Vehicle manufacturers may organise take-back schemes independently or appoint a producer responsibility organisation to manage them. However, the legal frameworks differ from one Member State to another. All recycling-system models are capable of meeting ambitious environmental and social standards. Nonetheless, the greatest economies of scale can be achieved when large volumes of batteries from different manufacturers are processed under uniform conditions.

5. **The EU, Member States, vehicle manufacturers, and producer responsibility organisations are working together to address the remaining challenges.** Some of the pressing questions for traction-battery recycling in the EU include: How realistic is it to keep all vehicles produced in the EU within the Union until the end of their service life? What potential lies in cross-border cooperation — possibly extending to non-European markets? How can recycling systems for traction batteries be made future-proof, given that ongoing technological change, such as in battery chemistry, is fundamentally reshaping business models? Answering these questions will require close and sustained dialogue across the entire value chain.

Contents

List of abbreviations

AAM	Anode active material
Al	Aluminium
ATF	Authorised treatment facility
BESS	Battery energy storage system
BEV	Battery electric vehicle
CRMA	Critical Raw Materials Act (EU regulation establishing a framework for a secure and sustainable supply of critical raw materials)
Co	Cobalt
$CoSO_4$	Cobalt sulphate
Cu	Copper
EC	European Commission
EoL-LIB	End-of-Life lithium-ion battery (battery that has reached the end of its service life in its original application)
EPR	Extended producer responsibility (as defined under the EU Battery Regulation)
EU-BattVO	EU Battery Regulation
EV	Electric vehicle
Fe	Iron
$FePO_4$	Iron phosphate
HDV	Heavy duty vehicle (> 3.5 t)
HEV	Hybrid electric vehicle (without external charging capability)
LFP	Lithium iron phosphate
LCV	Light commercial vehicle (< 3.5 t)
LIB	Lithium-ion battery
Li_2CO_3	Lithium carbonate
$LiOH*H_2O$	Lithium hydroxide monohydrate
LMO	Lithium manganese oxide
LTO	Lithium titanium oxide
Mn	Manganese
NCA	Lithium nickel cobalt aluminium oxide
Ni	Nickel
$NiSO_4$	Nickel sulphate
NMC	Lithium nickel manganese cobalt oxide
OEM	Original equipment manufacturer (in this study: vehicle manufacturer)[1]
P	Phosphorus
PHEV	Plug-in hybrid electric vehicle (with external charging capability)
PRO	Producer responsibility organisation
SIB	Sodium-ion battery
SSB	Solid-state battery
SWOT	Strengths, weaknesses, opportunities, threats (analytical framework)
TWh	Terawatt hours

1 In European regulation (the EU Battery Regulation), the abbreviation OEM refers both to manufacturers of traction batteries and to vehicle manufacturers as entities placing traction batteries on the market. In the automotive industry, however, OEM is generally used as a synonym for vehicle manufacturer. Accordingly, this study focuses on the role of vehicle manufacturers, and the abbreviation OEM is used here exclusively in that sense.

1 | Background and project objectives

The rapid market expansion of electromobility in the European Union (EU) and worldwide is driving a continued surge in demand for raw materials and creating significant challenges for the globally integrated supply chains of lithium-ion batteries (LIBs) [SKN 2023, BMWK 2023]. For European manufacturers and entities placing traction batteries for vehicles on the market, a key question is how they can ensure sufficient access to the necessary quantities of critical raw materials and components in the future – while safeguarding their competitiveness and establishing efficient material cycles. The growing geopolitical and geo-economic tensions of recent years, and their consequences such as trade barriers, tariffs, and export restrictions, make it increasingly important for vehicle manufacturers – as entities placing traction batteries on the market – to take strategic action to make their value chains both durable and resilient. Equally relevant in this context is the new EU Battery Regulation adopted in 2023, which introduces mandatory recycled content targets in new batteries, specifically for key raw materials such as lithium, cobalt, and nickel [BatReg 2023].

Against this background, Stiftung GRS Batterien, in cooperation with Agora Verkehrswende, commissioned the Oeko-Institut in July 2024 to prepare a comprehensive study. The study addresses the following topics:

- An analysis of how value chains and material cycles for traction batteries in electric vehicles are developing – both globally and with a particular focus on the EU.
- The challenges facing European manufacturers and entities placing traction batteries on the market in closing material cycles under global competition and securing access to relevant battery raw-material value chains at competitive cost.
- An examination and assessment of potential business models and system structures for vehicle manufacturers (original equipment manufacturers, OEMs) and producer responsibility organisations (PROs) relating to the collection and recycling of traction batteries.
- The development of policy recommendations for affected manufacturers and industry associations, as well as for policymakers and regulatory authorities, based on the study's findings.

Chapter 2 provides a general overview of the current global battery market and the developments that can already be anticipated. Chapter 3 then presents a more detailed analysis focusing on the EU, examining the value chains for both primary and secondary raw materials.

To support its assessment of likely developments – particularly regarding the potential availability of secondary raw materials within the EU – the Oeko-Institut developed up-to-date scenarios for the expansion of electromobility in the EU and calculated the expected impacts on material flows. It should be noted that the value chains of lithium-ion batteries (LIBs) vary depending on the cathode material used. Batteries with lithium-iron-phosphate cathodes (LFP cathodes) contain only lithium and graphite among the raw materials relevant to this project. The extraction and processing of the other cathode components, iron and phosphorus, are therefore not considered within the scope of this study. By contrast, lithium-nickel-manganese-cobalt-oxide cathodes (NMC cathodes) also contain the critical raw materials cobalt and nickel, in addition to lithium and graphite. Consequently, the extraction and processing of these materials to battery-grade quality represent another key segment of the value chain examined in this study.

Building on this analytical foundation, Chapter 4 explores perspectives for an optimised lithium-ion battery (LIB) cycle within the EU. It examines in detail a range of potential business models for the take-back of traction batteries from the vehicle sector, including an analysis of strengths and weaknesses of the different approaches. Finally, Chapter 5 draws together all project findings to formulate strategic courses of action and recommendations for the relevant manufacturers and associations, as well as for policymakers and regulatory authorities.

The project, commissioned by GRS Batterien and carried out by the Oeko-Institut, was accompanied by Agora Verkehrswende in a scientific advisory role.

Among other contributions, Agora Verkehrswende hosted two in-person expert workshops in Berlin. This advisory group was composed of selected representatives from OEMs, recycling companies, non-governmental organisations, consultants, and public authorities. The main thematic focus of the advisory meetings included:

- scenarios for the passenger-car and commercial-vehicle sectors in the EU-27 up to 2040 (28 November 2024), and
- value chains for LIBs (primary and secondary), as well as system structures and business models for optimising the circular management of LIBs (15 April 2025).

The intensive exchange with the advisory group — before, during, and after the meetings — played a crucial role in discussing preliminary assessments and findings throughout the project period and significantly strengthened the validity of the results.

2 | Overview of the global lithium-ion battery market

Global demand for batteries[2] has been rising steadily in recent years. In 2020, around 0.3 terawatt hours (TWh) of batteries were placed on the market across all sectors; by 2024, the figure had already reached approximately 1.2 TWh. According to Benchmark Minerals, total demand across all sectors is projected to reach 3.8 TWh by 2030 – more than a tenfold increase [Benchmark Minerals 2025d]. Another source estimates a global battery production capacity of 6.3 TWh for 2030 [Renard 2024]. These figures are not necessarily contradictory, as many battery factories currently operate at relatively low capacity utilisation.

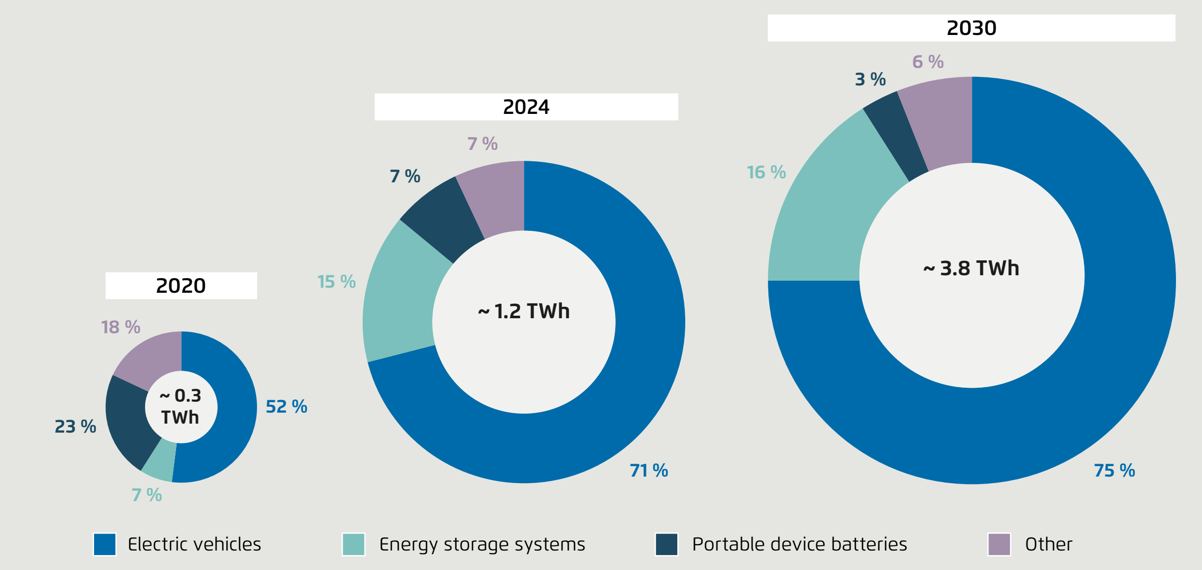
Measured in terms of energy content, the battery market is dominated by electric vehicles – and their share continues to grow. While vehicles accounted for just over half of total battery demand in 2020, their share rose to more than 70 percent by 2024. Stationary energy storage systems ranked second with around 15 percent, followed by portable devices such as mobile phones and laptops, which made up roughly 7 percent.

The People's Republic of China is both the largest producer and the largest consumer of batteries[3], dominating most stages of the value chain as of 2024. In just the first two months of 2025, a total of 1.4 million electric vehicles – both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEV) – were sold in China, accounting for 58 percent of the global market. Over the same period, Europe recorded sales of only around 0.5 million electric vehicles (21 percent), while North America reached approximately 0.3 million (13 percent) [Benchmark Minerals 2025e].

2 In the following chapters, the terms batteries and battery market refer primarily to lithium-ion batteries (LIBs). They also include sodium-ion batteries (SIBs) and lithium-based solid-state batteries (SSBs).

3 Throughout the remainder of this report, all references to China refer exclusively to the People's Republic of China.

Global battery demand in 2020, 2024 and 2030 — Figure 2-1



Agora Verkehrswende (2025) | Source: Benchmark Minerals (2025d).

2.1 Introduction to the global cathode market

The global trend toward nickel- and cobalt-free batteries – in particular the use of lithium-iron-phosphate (LFP) as cathode material – is considerably stronger than in the German or wider European battery market. While LFP cells accounted for only about 13 percent of the global battery market in 2020, their share had risen to an estimated 49 percent by 2024. This shift is largely driven by China's dominance, where LFP held a market share of around 70 percent in 2024, compared with just 28 percent in the rest of the world. Outside China, lithium-nickel-manganese-cobalt oxide (NMC) remained the prevailing cathode material [Benchmark Minerals 2025f]. According to another source, China is still expected to account for roughly 66 percent of global battery production capacity by 2030 [Renard 2024].

Traditionally, LFP has held a smaller share of the automotive market than NMC, due to the latter's higher energy density. However, LFP's share in this segment is now rising rapidly. Globally, LFP accounted for around 18 percent of the vehicle battery market in 2020; by 2024 its share had already risen to about 46 percent – bringing it broadly in line with its overall market share.

This development – alongside China's rising market share – is largely driven by technological innovation and the resulting lower cost of LFP compared with NMC. Most of these innovations have taken place at the battery-pack level. LFP enables the use of larger battery cells that require less cooling, thereby significantly improving the overall energy density of this cell chemistry at vehicle level and narrowing the gap with NMC. As a result, the share of LFP is expected to continue increasing, at least in the short and medium term [Benchmark Minerals 2025f]. The advantages of NMC technology lie primarily in its higher energy density and its good practical recyclability. In addition, there are new innovations involving NMC chemistries with moderate nickel content, which help offset NMC's cost disadvantage compared with LFP [Benchmark Minerals 2025a]. Combined with its existing technological maturity, this means NMC is unlikely to disappear from the market in the medium term.

In 2024, total demand for NMC cathode material in China, Europe, and North America was roughly comparable – each between about 133 and 152 megawatt hours (MWh). Although China dominates global demand for cathode materials overall, the smaller NMC share described above results in a similar absolute demand for NMC in all three regions [Benchmark Minerals 2025a].

With respect to the origin of cathode materials, China remains by far the largest producer across the entire value chain. While only around 17.5 percent of lithium was mined in China in 2023, the country accounted for an estimated 68 percent of global processing capacity for lithium chemicals in 2024. Current developments suggest that other market participants are gradually expanding their capacity, and China's share of lithium processing is expected to decline by 2030 – though it will still represent more than half of the global market [Benchmark Minerals 2025g].

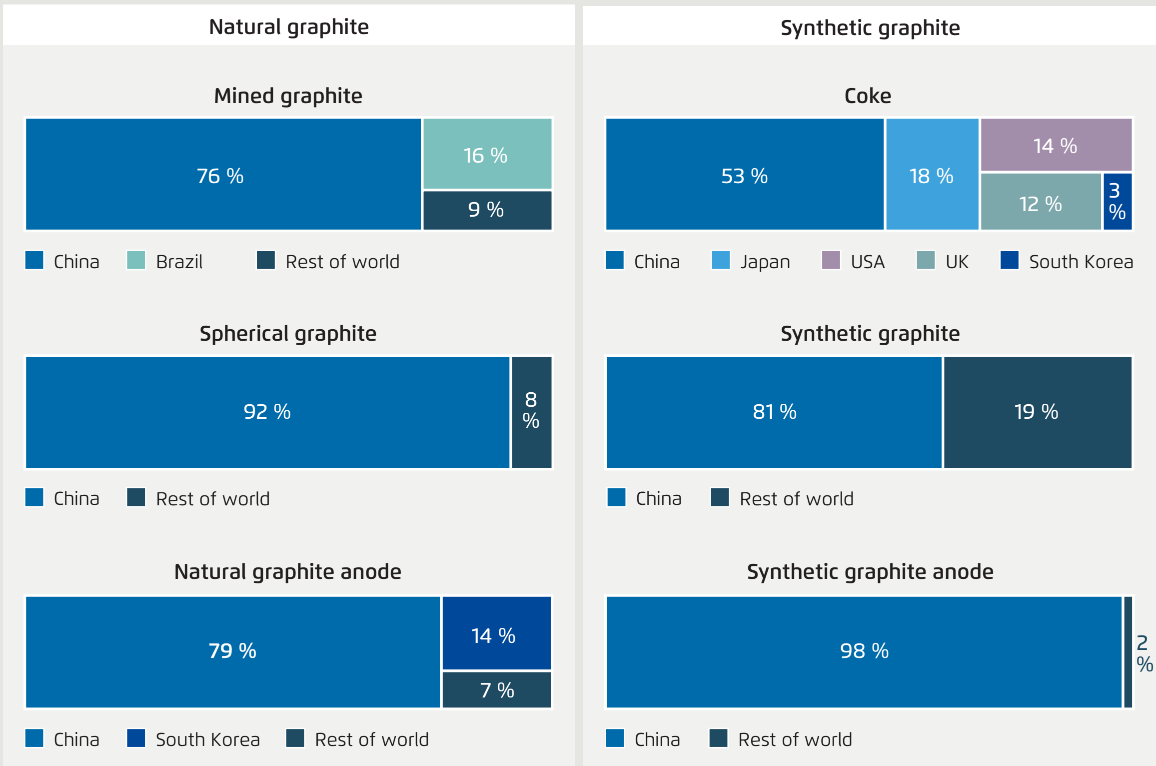
China's dominance is even greater in cathode material production itself. In 2024, China produced around 99 percent of the world's LFP active material. Forecasts indicate that this share may fall slightly in the coming years but will still stand at around 97 percent in 2030 [Benchmark Minerals 2025g]. For NMC cathode materials, around 75 percent of global production capacity is also located in China. Other Asian countries together account for roughly 23 percent, while the EU currently holds only about 1.5 percent of global NMC production capacity. Projections suggest that the EU's share could rise to around 10 percent by 2030, while China's share would remain just above 60 percent despite strong growth elsewhere. North America, too, is expected to see rapid expansion in NMC production, potentially increasing its global market share from under 1 percent today to around 10 percent by 2030 [Benchmark Minerals 2025a].

2.2 Introduction to the global anode market

The global anode market is dominated by graphite, which continues to offer the best combination of cost and electrochemical performance – particularly in terms of the durability of the cells it is used in. Alternatives to pure graphite anodes primarily include anodes that contain a proportion of silicon alongside graphite. These can be divided into two categories: simple graphite–silicon blends, and composite anodes in which the silicon is embedded within the graphite structure. The latter type is still under development. In general, silicon significantly increases the potential energy content of an anode but also reduces its lifetime. According to expert interviews, cells with silicon-containing anodes are currently more expensive than pure-graphite cells and are therefore mainly found in the premium segment – although this could change in the future. Other anode materials—lithium titanium oxide (LTO), pure silicon, and lithium metal—are currently confined to niche applications. LTO is already used to a limited extent, whereas pure silicon and lithium metal are still under development.

In China, roughly 95 percent of batteries are currently manufactured with pure graphite anodes. Globally, graphite accounts for around 85 percent of anodes in the vehicle sector, with the remainder consisting largely of graphite–silicon blends. LTO covers only about one percent of the vehicle battery market. Due to the strong projected growth of the vehicle market in China, the global share of graphite anodes containing silicon may decline in the short term. However, a gradual increase in the silicon content of graphite anodes is expected in the medium to long term [Benchmark Minerals 2025d].

Comparison of the value chains for anodes made from synthetic and natural graphite — Figure 2-2



Agora Verkehrswende (2025) | Source: Benchmark Minerals (2024d).

Graphite anode material is produced via two main routes: natural graphite, mined from ore, and synthetic graphite, typically produced from coal tar pitch or petroleum coke. Both types are used in batteries across all sectors and differ only slightly in performance characteristics. Natural graphite generally provides higher energy density, while synthetic graphite tends to offer greater purity and therefore longer service life [Giga Europe 2025]. In 2022, synthetic graphite accounted for about 58 percent of the global anode-material market, compared with around 32 percent for natural graphite (the remainder being mainly graphite–silicon blends) [Renard 2024]. Forecasts identify synthetic graphite as the fastest-growing material category and suggest that its market share is likely to continue expanding [Giga Europe 2025; Renard 2024].

China also dominates the production of graphite and graphite-based anodes. In 2024, the country accounted for roughly 76 percent of global supply of natural-graphite flakes — the precursor for battery-grade material. This share is expected to decline somewhat over the coming years due to rapid growth in African countries such as Mozambique and Tanzania. A similar pattern applies to uncoated spherical graphite (USPG), where China currently controls about 92 percent of the global market. This share is forecast to fall to around 86 percent in the coming years, although a significant portion of the production capacity outside China is owned or operated by Chinese companies [Giga Europe 2025]. Synthetic graphite production is likewise concentrated in China, which held over 80 percent of global capacity in 2024. The needle coke used as feedstock for synthetic graphite is only about 50 percent sourced domestically, but both shares are rising.

Anode-material production itself is almost entirely localised in China. South Korea retains a small share of just over 10 percent for anodes made from natural graphite, while China holds nearly 80 percent. In the case of synthetic-graphite anodes, China accounts for more than 95 percent of global production [Benchmark Minerals 2023]. Since 2022, anode-material prices have fallen sharply — in some cases more than halving by early 2025 — making it difficult for producers in other parts of the world to establish alternative production lines [Giga Europe 2025].

3 | Value chains for lithium-ion batteries on the EU market

3.1 Overview of the value chain for LIBs based on primary raw materials

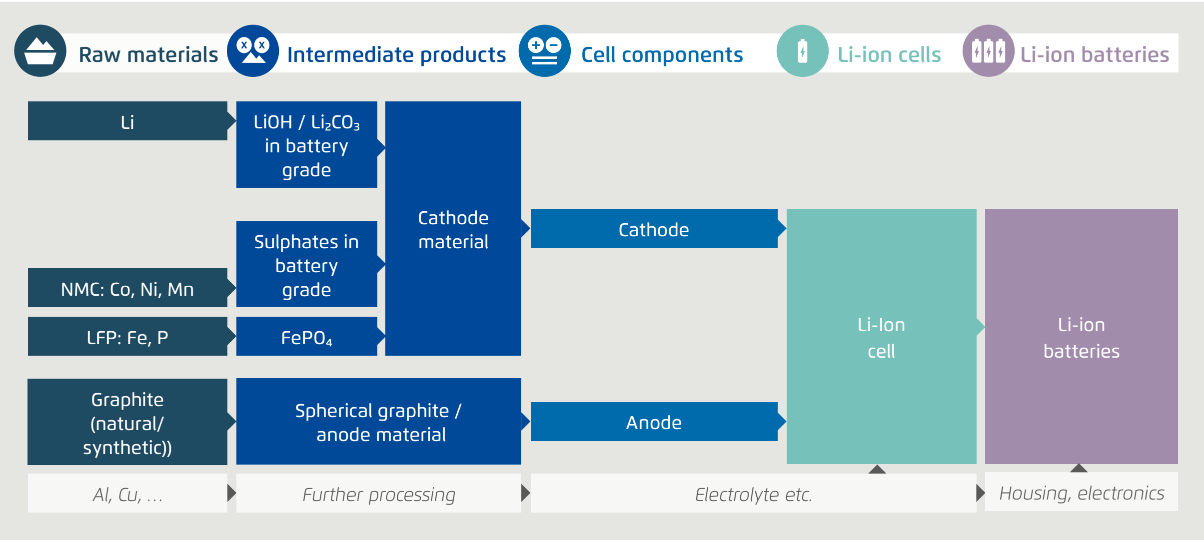
To counter the geopolitical dependence of the value chain on a small number of countries – particularly the People's Republic of China – as discussed in Chapter 2, a range of recent initiatives have emerged to localise more stages of the process within Europe and, specifically, within the EU. Under the EU Battery Regulation [BatReg 2023], vehicle manufacturers and other entities placing lithium-ion batteries (LIBs) on the market will face increasingly stringent obligations under the principle of extended producer responsibility (EPR). Ensuring a reliable and competitively priced supply of raw materials, intermediates, and components for European manufacturers is therefore of critical importance. At the same time, greater diversification of supplier countries for raw materials, intermediates, and components is intended to reduce risk exposure and strengthen resilience.

A key element of these efforts is the Critical Raw Materials Act (CRMA), adopted in 2024 [CRMA 2024], which aims to promote the reuse and recycling of strategic raw materials while also strengthening the establishment of primary raw-material value chains for traction batteries within the EU. For the designated strategic raw materials, the regulation sets the following explicit targets:

- 10 percent of annual EU demand for each raw material is to be extracted within the EU. 25 percent is to be produced through recycling within the EU. 40 percent of processing is to take place within the EU.
- No more than 65 percent of any strategic raw material may be sourced from a single non-EU country. These thresholds apply to all stages of the value chain.
- Strategically important projects are to be identified and supported.
- Permitting procedures for European projects along the value chains are to be made simpler and faster.

The following section examines current developments in the establishment of value chains within the EU, focusing on the most critical stages. Figure 3-1 provides a simplified overview of the various steps in the value chain for producing a lithium-ion battery (LIB) with either a lithium-nickel-manganese-cobalt oxide (NMC)

Value chain (highly simplified) for LIB (NMC and LFP) Figure 3-1



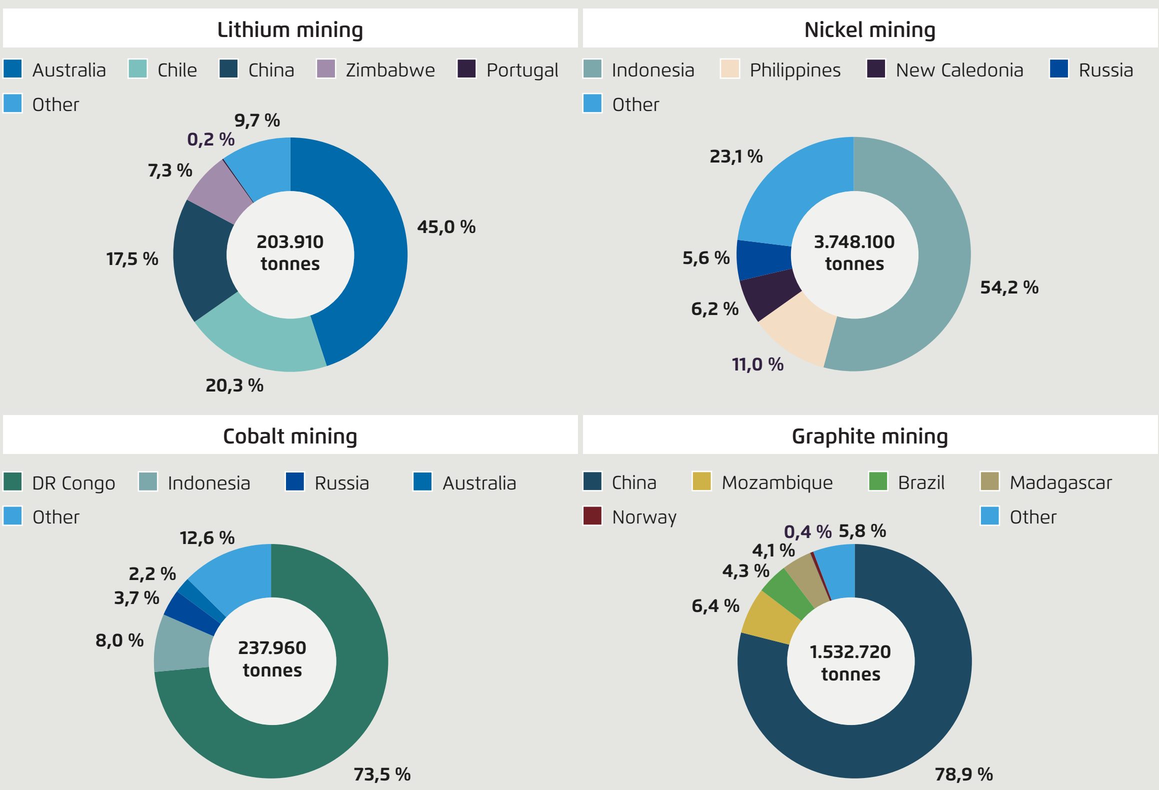
Agora Verkehrswende (2025) | Source: Oeko-Institut cathode or a lithium-iron-phosphate (LFP) cathode using primary materials.

After extraction of the relevant raw materials – lithium, graphite, nickel, and cobalt – each is processed into the required battery-grade compounds. The subsequent stages involve separate production of anodes and cathodes, followed by assembly of these components, together with other components, into lithium-ion cells. The final stage consists of assembling multiple lithium-ion cells into a complete battery pack, together with peripheral components such as housing and electronic systems. The process steps considered particularly critical are highlighted for discussion here, while the steps shown in italics are not part of the detailed analysis. Accordingly, the analysis is structured around the extraction and processing of the relevant raw materials into intermediate products, the production of anodes and cathodes, and cell manufacturing. Because lithium-ion battery production is an exceptionally agile and dynamic field – with new projects being announced, planned, and sometimes cancelled within short time-frames – the capacity figures presented in this chapter represent a snapshot that may change within just a few months. The following discussion is based on announcements and information available up to the end of April 2025.

3.1.1 Raw material extraction and processing

The geographic distribution of raw material extraction for lithium-ion batteries (LIBs) is shown in Figure 3-2. In every case, the data reveals varying degrees of dependence on a small number of countries – in some instances, even on a single producer nation. To counter this dependency, increasing efforts are being made to explore natural deposits within the EU in preparation

Production of lithium, cobalt, nickel and graphite by country worldwide (2023) — Figure 3-2



Agora Verkehrswende (2025) | Source: Oeko-Institut based on USGS (2023).

for potential future extraction. Although only limited quantities of raw materials are currently mined within Europe, a number of projects for extracting various strategic raw materials are already in the planning or development phase. The few European countries that currently produce small quantities of the relevant materials are highlighted separately in the figures.

Lithium extraction in the EU

According to data from the US Geological Survey, lithium extraction in the EU currently takes place only on a very small scale in Portugal – and the ore mined there is not yet processed into battery-grade material. The most advanced lithium-mining projects planned within the EU appear to be the Barroso Project in Portugal, operated by Savannah Resources (United Kingdom) [Savannah Resources 2024], and the Keliber Project in Finland, led by Sibanye-Stillwater/Keliber Oy [Keliber 2025], where production is scheduled to ramp up in summer 2025. Table 3-1 provides an overview of the more advanced projects for lithium extraction intended for battery applications, together with their projected capacities. When fully operational, these projects could jointly supply nearly 30 kilotonnes of lithium per year in Europe.

All four projects listed in the table have recently been designated as strategic projects under the Critical Raw Materials Act (CRMA) [CRMA 2025]. This designation ensures significantly faster permitting procedures and provides project developers with direct support from the European Commission and its competent institutions in preparing and finalising their financing plans.
In addition, the European Commission has granted strategic project status under the CRMA to five further lithium-extraction projects – in France, the Czech Republic, Spain (two projects), and Portugal. These initiatives appear to be at earlier stages of development. Under the CRMA, all designated projects are required to be operational at industrial scale by 2030, meaning that they must be actively extracting lithium from natural deposits.

Processing into lithium hydroxide monohydrate

As an intermediate step in cathode production, the extracted lithium is further processed along the value chain into battery-grade lithium hydroxide monohydrate ($LiOH{\cdot}H_2O$). This stage of production is also being actively developed in Europe. In Germany, AMG Lithium's plant in Bitterfeld, inaugurated in autumn 2024, is currently in its ramp-up phase [AMG Lithium 2025]. Initially, the facility is supplied with material mined outside Europe (in Brazil) and processed in the People's Republic of China into technical-grade lithium hydroxide monohydrate. The Bitterfeld site upgrades this material to battery-grade lithium hydroxide monohydrate ($LiOH{*}H_2O$), making it the first lithium refinery in Europe. In the medium term, the intermediate processing step in China is to be relocated directly to the Brazilian mining site.

Most advanced projects for lithium extraction in the EU — Table 3-1

Location	Company headquarters	Project	Company	Production potential forecast [t Li/a]*
PT	UK	Barroso Project [1]	Savannah Resources	4.700
FI	FI	Keliber Project [2]	Sibanye-Stillwater/ Keliber Oy	4.400
DE	DE	Zero Carbon Lithium Project [3]	Vulcan Energie Ressourcen GmbH	7.000
FR	FR[d]	EMILI Project[4]	Imerys	10.100

***** All quantities are expressed as tonnes of contained lithium. The lithium content of the various compounds arising in lithium production is set out in annex 7.1.

Sources: [1] [Savannah Resources 2024], [2] [Keliber 2025], [3] [Vulcan Energy 2025], [4] [Imerys 2025a].

Agora Verkehrswende (2025) | Source: Compiled by Oeko-Institut.

Additionally, the input for Bitterfeld is expected to be supplemented with suitable lithium compounds recovered from recycling.

Vulcan Energy is also operating a pilot plant in Frankfurt am Main, Germany, where lithium chloride obtained from deep geothermal brine in the Upper Rhine Graben is converted on a small scale into battery-grade lithium hydroxide monohydrate ($LiOH*H_2O$) [Vulcan Energy 2025]. The company plans, within the next two to three years, to implement both lithium extraction and conversion to the final product – battery-grade lithium hydroxide monohydrate ($LiOH*H_2O$) – at industrial scale in Germany, with a projected production capacity of 24,000 tonnes of $LiOH*H_2O$. At the Keliber project and within the EMILI initiative, the operators likewise plan to include integrated refinery facilities [Imerys 2025a; Keliber 2025]. Beyond these already concrete projects, numerous additional plans have been announced – for example, a joint venture between RockTech Lithium and Arcore (NewCo) for a new facility in Guben, Germany. Taken together, the capacities announced to date could enable the EU to process, within Europe, the lithium quantities expected to be mined there in the coming years.

Cobalt, nickel, and graphite extraction and processing in the EU

Although this is not visible in Figure 3-2 due to the small volumes involved, nickel is currently mined in Finland and Norway [Boliden 2025a; Terrafame 2025; Glencore 2025a]. According to the European Joint Research Centre (JRC), EU production in 2022 accounted for about 1.5 percent of global output [JRC 2022]. This figure includes production from the Greek company Larco, which has faced serious financial difficulties in recent years [Labournet 2024]. It remains unclear whether the company's operations are still active. A few additional nickel-mining projects have been announced, but all are still at an early stage of development. It is worth noting that, unlike lithium, cobalt, and graphite – where demand for electric-vehicle batteries accounts for around 30 to 40 percent of the total market – only about 10 percent of global nickel production is currently used for traction batteries [NOW 2024]. According to estimates by Benchmark Minerals, this share is expected to rise sharply in the coming years as electromobility expands, reaching nearly 40 percent by 2040 [Benchmark Minerals 2025a].

In Europe, additional nickel-processing capacity is being developed, including by Umicore and the Russian company Nornickel in Finland. However, these projects have not yet reached production levels of any significance [Umicore 2025a; Nornickel 2025]. Moreover, it is unlikely that a Russian enterprise will be regarded as contributing to the EU's objective of strengthening raw-material resilience.

Cobalt is currently mined in Europe primarily as a by-product of copper or nickel extraction [Boliden 2025b; Glencore 2025b]. The UK-based company Anglo American is also planning a mine in Sakatti, Finland, that will produce a range of metals including nickel and cobalt [Anglo American 2025]. The only large-scale cobalt refinery in Europe is operated by Umicore in Kokkola, Finland [Umicore 2025b].

Graphite is also mined in small quantities at several sites across Europe. The only project explicitly focused on graphite extraction for anode active material is the recently commissioned Skaland Graphite Operation operated by Mineral Commodities in Skaland, Norway [Mineral Commodities 2025]. Announcements for future graphite projects remain limited and are concentrated mainly in Scandinavia. The most advanced of these is Talga Resources' project in Vittangi, Sweden [Talga Resources 2024].

At present, the European Commission has designated a total of five strategic projects for the extraction of cobalt, nickel, and graphite: two projects (in Sweden and Romania) target graphite, while three focus on nickel and cobalt [CRMA 2025]. In the field of processing, the Commission has also classified four graphite projects and two additional projects for cobalt and nickel as strategic. Despite these initiatives, there remain significant gaps in both raw-material extraction and processing capacities for cobalt, nickel, and graphite within the EU – gaps that must be closed if the targets set under the Critical Raw Materials Act are to be achieved by 2030.

3.1.2 Cathode and anode material production

The processing of natural graphite into anode active material (AAM) is, for now, largely linked to mining operations at the extraction sites themselves. At the facilities operated by Mineral Commodities in Norway and Talga Resources in Sweden, anode active material is to be produced directly on site [BFZ 2024]. Production of anode active material from synthetic graphite is somewhat more advanced within the EU, with several facilities already in operation. The German company SGL Carbon has produced anode active material at two sites in Poland [SGL Carbon 2025], although it withdrew from battery development during 2024, leaving the continuation of this production uncertain. In France, the Japanese company Tokai COBEX [Tokai COBEX 2024] manufactures anode material, while additional production facilities are operated by Vianode in Norway [Vianode 2025] and Imerys in Switzerland [Imerys 2025b]. Further announcements of planned capacity for anode-material production are concentrated primarily in Scandinavia [BFZ 2024].

In recent years, China has continued to expand its dominant position in cathode-material manufacturing. Around 75 percent of global production of NMC (lithium-nickel-manganese-cobalt oxide) cathode active material and as much as 99 percent of LFP (lithium-iron-phosphate) material originates from China [Benchmark Minerals 2025g]. Although plans to establish EU-based cathode-material capacity began as early as the early 2020s—somewhat earlier than for other parts of the value chain—only a few plants have so far entered operation. BASF currently produces NMC cathodes in Schwarzheide, Germany [BASF 2023], and Umicore operates another facility in Nysa, Poland [Umicore 2022a]. Both plants are still ramping up to full capacity and will jointly provide around 60 GWh per year once fully operational. Umicore is also planning, through its joint venture Ionway with Volkswagen's PowerCo, to construct a second plant in Nysa, expected to add a further 160 GWh per year of capacity once completed [BZF 2024b]. Three additional cathode plants are currently under construction: South Korea's EcoPro is building a facility in Debrecen, Hungary [EcoPro 2025], while the Chinese company Huayou Cobalt and the Franco-Chinese joint venture Orano XTC are developing projects in Acs, Hungary, and Dunkirk, France, respectively [BZF 2024b]. Together, these projects would add more than 200 GWh per year of production capacity within the EU, though all are owned by Asian companies. In March 2025, Finnish Minerals announced the start of construction of a cathode-material plant in partnership with the Chinese firm Beijing Easpring, with a planned capacity of around 10 GWh [electrive 2025].

Beyond these, only a few additional projects have been announced, and many are viewed cautiously, as several previously announced NMC-cathode projects were cancelled or suspended to realign planning with changing market demand resulting from the shift toward LFP batteries. Despite this, LFP cathode production in Europe remains limited. At present, only IBU-tec in Weimar, Germany, produces small volumes—around 2 GWh per year [BZF 2024b]. The most significant planned projects are those of Phi4Tech in Badajoz, Spain [Phi4Tech 2025] and Freyr in Vaasa, Finland. Chinese players remain active as well, including Hunan Yuneng, which plans to build an LFP factory in Spain with a capacity of 50,000 tonnes per year of fourth-generation LFP material, scheduled to begin production in 2027 [Hunan Yuneng 2024]. However, this project could be jeopardised by new Chinese export restrictions [Benchmark Minerals 2025c].

3.1.3 Cell manufacturing

Although the shift toward LFP cathodes has also led to the cancellation or postponement of several planned cell-manufacturing projects, the EU already hosts significantly more operational cell plants than in earlier stages of the value chain. However, non-European ownership remains predominant. Table 3-2 summarises the main EU-based projects, including their status and planned production capacities. In addition to a number of small firms serving niche markets and pilot lines (not listed in the table due to their limited output), the key European-owned facilities are those operated by Northvolt in Skellefteå, Sweden, and by ACC, a joint venture of Stellantis, Mercedes-Benz, and TotalEnergies [Northvolt 2025a; ACC 2025a]. As of March 2025, however, Northvolt is undergoing insolvency proceedings in Sweden [Northvolt 2025b], leaving the company's future uncertain. In August 2025, US-based Lyten announced plans to acquire Northvolt's facilities in Sweden and Germany (the latter still under construction). It remains unclear whether Lyten intends to produce lithium–sulphur cells instead of NMC cells in Europe [Lyten 2025].

All other gigafactories already in operation within the EU are owned by Chinese or South Korean manufacturers [BZF 2024a].

Projections nevertheless suggest a more favourable outlook for cell production in the EU than for earlier stages of the value chain. Although an exact forecast is difficult due to the constantly changing stream of project announcements, it is currently assumed that production capacity within the EU could increase by a factor of eighty by 2030 compared with 2020 [Battery Atlas 2024]. Figure 3-3 shows the shares of the companies behind these projects, broken down by continent.

In contrast to the facilities already in operation – where European companies accounted for only about 15 percent of total capacity in 2024 [BZF 2024] – the share of announced capacity attributable to European firms is significantly higher. However, such projections regarding planned capacities and European participation must be treated with caution – as demonstrated most recently by the Northvolt insolvency.

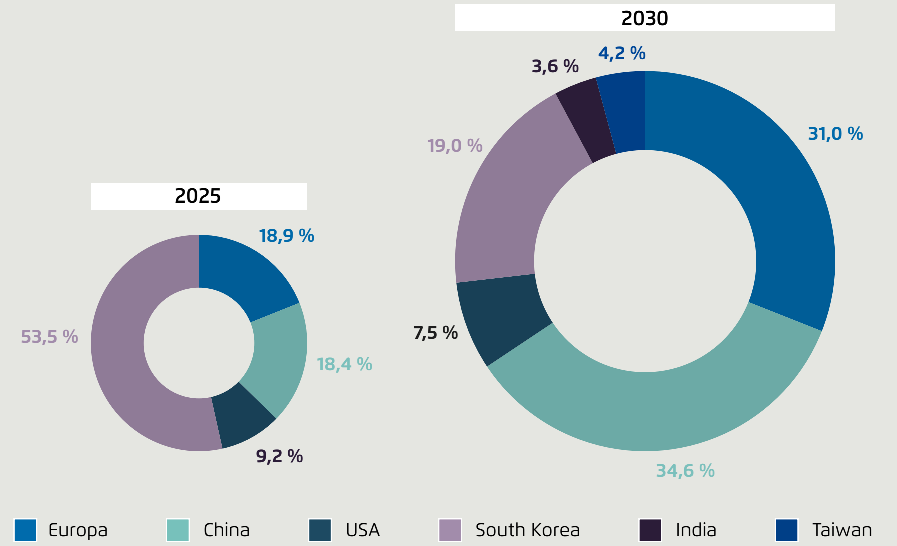
Key projects for the construction of cell factories in the EU — Table 3-2

Location	Company headquarters	Project	Company	Status	Production potential forecast/a
FR	FR	Billy Berclau/ Douvrin	ACC	In operation	[1]3 GWh, planned expansion to 40 GWh by 2030[1]
DE	CN	Arnstadt	CATL	In operation	2024 14 GWh[2]
PL	KR	Wroclaw	LG ES	In operation	Currently 86 GWh[3]
HU	KR	Göd	Samsung SDI	In operation	40 GWh[4]
HU	KR	Komarom	SK Innova-tion	In operation	Currently approx. 17 GWh, increasing to approx. 30 GWh[5]
HU	KR	Iváncsa	SK Innova-tion	Ramp-up	30 GWh[5]
DE	DE	Salzgitter	PowerCo	Under construction	20 GWh[6]
DE	SE	Heide	Northvolt	Under construction (uncertain)	60 GWh[7]
ES	DE	Valencia	PowerCo	Under construction	40–60 GWh[8]
FR	FR	Dunkerque	Verkor	Under construction	20 GWh[9]
HU	CN	Debrecen	EVE Energy	Under construction	28 GWh[10]
ES	CN	Navalmoral de la Mata	AESC	Under construction	50 GWh[11]
ES	NL/CN	Saragossa	Stellantis/ CATL	Under construction	Up to 50 GWh[12]
HU	CN	Debrecen	CATL	Under construction	100 GWh[5]
SE	SE	Skelleftea	Northvolt	Uncertain	Currently 16 GWh, expansion plans to up to 60 GWh on hold[13]
SE	SE	Gothenburg	Northvolt/ Volvo	Uncertain	Up to 50 GWh[14]
FR	JP	Duoai	AESC	In planning	24–30 GWh[15]

Sources: [1] [ACC 2025a], [2] [TÜV NORD GROUP 2023], [3] [LG Energy Solution 2025], [4] [Samsung E&A 2025], [5] [Sustainable Bus 2024], [6] [PowerCo 2023] [7] [Northvolt 2024] [8] [Volkswagen AG 2023], [9] [Werwitzke 2023], [10] [EVE Germany GmbH 2023], [11] [AESC 2024], [12] [Werwitzke 2024a], [13] [Northvolt 2025a], [14] [NOVO Energy AB 2024], [15] [Randall 2023a].

Agora Verkehrswende (2025) | Source: Compiled by Oeko-Institut.

Origin of the companies planning cell production facilities for LIB in Europe — Figure 3-3



Agora Verkehrswende (2025) | Source: Benchmark Minerals (2025h), as of 03/2025.

By the first quarter of 2025, it had already become clear that the weak European sales figures for electric vehicles in 2024 were posing major challenges for many cell manufacturers. Northvolt's insolvency, and the resulting uncertainty surrounding its cell plants, have upended earlier forecasts such as those in the Battery Atlas (2024), which predicted that European companies could hold a larger market share than Asian competitors by 2030.

It now appears increasingly likely that the largest share of the market will continue to belong to Asian companies – primarily from South Korea and China – until 2030. In addition to Northvolt, ACC has likewise stated that it will face financial difficulties without EU support [ACC 2025b]. Taken together with various project delays and cancellations, these developments raise serious doubts as to whether the ambitious 2024 projections will ultimately materialise. Nevertheless, construction continues on the two PowerCo gigafactories in Germany and Spain as well as the Verkor plant in France – all of which represent significant production capacity once operational.

3.1.4 Interim conclusion: Value chains for LIBs from primary raw materials for the EU market

The localisation of the various stages of the lithium-ion battery (LIB) value chain is regarded by the EU and its member states as both necessary and strategically important – a view reflected in measures such as the Critical Raw Materials Act (CRMA). Of the 47 projects recently designated by the European Commission as strategic projects under the CRMA [CRMA 2025], a large proportion directly support the development of the LIB value chain – from raw-material extraction and processing to the production of battery-grade intermediates. From the perspective of strengthening European resilience, these initiatives are both significant and welcome. However, whether they will be sufficient to meet the CRMA's ambitious targets remains open to question. In particular, given the current state of primary raw-material supply and the difficult economic situation of several cell manufacturers, it is already evident that Europe's medium-term demand cannot be fully met through EU-based resources and value chains alone. The EU will therefore remain heavily dependent on imports for at least the next five years.

In addition to European companies expanding capacity at various stages of the value chain, the growing presence of Asian firms establishing operations within Europe must also be taken into account – a development viewed differently by different stakeholders. On the one hand, it can be argued that capacities owned by Asian companies do not, in the strict sense, contribute to Europe's resilience. On the other hand, it remains unclear whether genuine resilience – or even meeting Europe's own demand – can realistically be achieved without drawing on the expertise and structures already established within these companies.

Another factor that will play a key role in future raw-material supply is the recovery of secondary raw-materials from end-of-life batteries, which is discussed in the following section.

3.2 Overview of the value chain for LIBs based on secondary raw materials

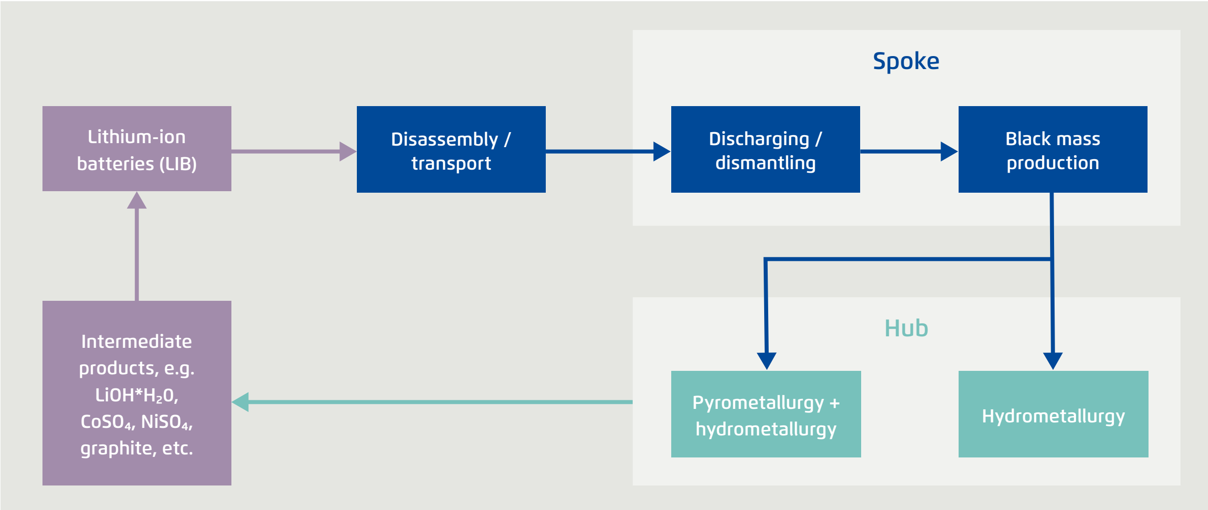
3.2.1 Introduction to LIB recycling

The following figure presents the main steps involved in the recycling of lithium-ion batteries (LIBs) in a highly simplified schematic form. Plants for the initial processing stages – such as collection, sorting, subsequent discharge and dismantling (removal of peripheral battery components like housings, cables, and battery management systems), and finally mechanical treatment – are referred to in the industry as 'spokes'. In these plants, battery modules or cells stripped of their peripheral components are processed through mechanical steps (shredding, magnetic separation, sieving, etc.), and often also a pyrolysis stage. These processes separate, as far as possible, organic solvents (from the electrolyte), binders, plastic components, ferrous materials, and aluminium and copper (from casings and cathode or anode foils).

The principal output is the so-called 'black mass', a valuable intermediate product containing mainly the active materials – primarily graphite (from the anode material) and, in the case of NMC batteries, the valuable metals lithium, nickel, cobalt, and manganese from the cathode material.

Black mass represents a marketable product that is traded between companies. To minimise long transport distances for whole batteries, black-mass production facilities are generally designed on a decentralised basis,

Schematic overview (highly simplified) of Li-ion battery recycling — Figure 3-4



Agora Verkehrswende (2025) | Source: Oeko-Institut.

with annual processing capacities ranging from a few thousand to several tens of thousands of tonnes of batteries. Across the EU, numerous recycling facilities for the mechanical processing of batteries into black mass are already in operation or in the planning stage. Several such plants also exist in non-EU European countries such as Switzerland, Norway, and the United Kingdom.

The further processing of black mass can follow different technological pathways. Despite variations in detail, these processes are typically either directly hydro-metallurgical – that is, leaching and processing in an acidic medium – or a combination of pyrometallurgical (high-temperature smelting) and subsequent hydro-metallurgical refining steps to produce battery-grade metal compounds such as lithium hydroxide hydrate or nickel sulphate. While not all process stages necessarily have to take place within the same facility, there is consensus that a larger, centralised plant is required for the core hydrometallurgical or pyrometallurgical treatment of black mass. In professional circles, such plants are referred to as 'hubs'. Compared with black-mass plants, hubs are designed for much larger capacities and therefore entail significantly higher investment costs.

However, the number of hubs required to cover Europe is expected to remain considerably lower than the number of spokes – despite the anticipated growth of electromobility and the resulting sharp increase in end-of-life battery volumes over the next 20 years. In essence, Europe is expected to develop a network of spokes and hubs: several dozen spokes for black-mass production, complemented by a smaller number of large hubs that process black mass into battery-grade intermediates. Some projects even combine both main modules of LIB recycling – spoke and hub – at a single site. These integrated plants enable the entire recycling process from mechanical treatment to raw-material recovery to take place in one location, eliminating the need to transport black mass between sites.

3.2.2 Black-mass production plants in the EU (spokes)

In recent years, numerous recycling plants for the production of black mass have been announced across the EU, and many have already been realised. A large number of these plants are already in commercial operation, with some planning further expansions.

These black-mass production plants are relatively easy to scale, since their core processes are mainly mechanical. When higher capacities are required, additional processing lines can simply be built in parallel – allowing, for example, a plant's annual capacity to be doubled from 5,000 to 10,000 tonnes within just a few years.

Most of these projects are located in Central and Northern Europe, with Germany hosting the largest number of such recycling plants among EU member states. Existing plants include those operated by BASF, Primobius, Li-Cycle[4], Fortum, and Redwood Materials [Schramm 2024b; Li-Cycle 2024a; Neometals 2022; Redwood 2025]. In addition, a new plant in Wernigerode with an annual capacity of 25 kilotonnes (kt/a) is currently in planning [Schramm 2024a].

Other black-mass production plants, which process end-of-life LIBs or production scrap from cell manufacturing, are distributed across various EU countries. Active mechanical-treatment plants with capacities exceeding 10 kt/a are located in Poland and Hungary, operated by AE Elemental and POSCO/ SungEel HiTech [Ascend Elements 2024; SungEel HiTech 2025; POSCO 2022]. Among the plants currently in operation with a capacity of around 10 kt/a are those run by SNAM and Li-Cycle in France, Stena Recycling in Sweden, and SK TES in the Netherlands.

Further black-mass production plants are currently in the planning stage across the EU. In Poland, for example, the company Attero is planning one of the largest black-mass production plants, with a capacity of 100 kt/a [Argus Media 2024].

The following overview provides a list of key existing and planned black-mass production plants in the EU. This list does not claim to be exhaustive, as new projects are being announced – and others withdrawn – on a regular basis in this highly dynamic market environment. The table illustrates the strong momentum behind the expansion of black-mass production capacity in the EU. It should be noted, however, that most existing plants are currently operating well below their nominal

4 The financial situation and future outlook of Li-Cycle remain uncertain as of May 2025, and this uncertainty extends to its corresponding plant.

capacity. Experts assume that, at least for the next five years, sufficient processing capacity will be available in the EU for the treatment of LIBs up to the intermediate product stage of black mass [T&E 2024].

3.2.3 Plants for further processing of black mass in the EU (hubs)

The EU Battery Regulation, which entered into force in 2023, establishes a wide range of requirements – including ambitious targets for both the metal-specific recovery rates achieved in the recycling of LIBs and the share of secondary metals to be used in new LIBs [BatReg 2023].

Black-mass production plants in the EU (spokes) Table 3-3

Location	Company headquarters	Project/location	Company	Status	Handling capacity forecast/a
HU	SK	Szigetszentmiklós, Bátonyterenye	SungEel HiTech	In operation	35 kt[1]
DE	DE	Schwarzheide	BASF	In operation	15 kt[2]
PL	PL (ESM) & US (Ascend Elements)	Zawiercie	AE Elemental	In operation	12 kt[3]
FR	CAN	Harnes	Li-Cycle	In operation	10 kt[4]
DE	USA	Bremerhaven	Redwood Materials	In operation	10 kt[5]
FR	FR	Saint Quentin	SNAM (Société Nouvelle d'Affinage des Métaux)	In operation	10 kt[6]
SE	SE	Halmstad	Stena Recycling	In operation	10 kt[7]
NL	SG	Rotterdam	SK Tes	In operation	10 kt[8]
PL	SK	Brzeg Dolny	POSCO/SungEel HiTech	In operation	7 kt[9]
PL	PL	Legnica	Royal Bees	In operation	3,6 kt[10]
DE	AT	Zwickau	Erlos	In operation	3,5 kt[11]
DE	FI	Kirchardt	Fortum Battery Solutions	In operation	3 kt[12]
DE	AUS	Hilchenbach	Primobius	In operation	10 t per day[13]; i.e. approx. 3 kt/a
PL	IN		Attero	In planning	100 kt[14]
DE	PL (ESM) & US (Ascend Elements)	Wernigerode	AE Elemental	In planning	25 kt[15]
ES	SK	Navarra	BeeCycle	In planning	10 kt[16]

Sources: [1] [SungEel HiTech 2025], [2] [Schramm 2024b], [3] [Ascend Elements 2024], [4] [Li-Cycle 2024a], [5] [Redwood 2025], [6] [SNAM 2025], [7] [Randall 2023b], [8] [Wilfer 2024], [9] [POSCO 2022], [10] [Bockey 2024], [11] [Schramm 2024c], [12] [Fortum 2023], [13] [Neometals 2022], [14] [Argus Media 2024], [15] [Schramm 2024a], [16] [Gobierno de Navarra 2024].

Agora Verkehrswende (2025) | Source: Compiled by Oeko-Institut.

For the target metals relevant to this study – lithium, cobalt, and nickel – the regulation sets the following target values:

- **Specific recovery rates** (by weight percentage) from the recycling of LIBs and the corresponding target years:
  Lithium: from 2027 50 percent, from 2031 80 percent
  Cobalt: from 2027 90 percent, from 2031 95 percent
  Nickel: from 2027 90 percent, from 2031 95 percent

- **Share of secondary metals** (by weight percentage) in LIBs[5] and the corresponding target years:
  Lithium: from 2031 6 percent, from 2036 12 percent
  Cobalt: from 2031 16 percent, from 2036 26 percent
  Nickel: from 2031 6 percent, from 2036 15 percent

The higher recovery rates for cobalt and nickel compared with lithium reflect the fact that the recovery of cobalt and nickel from LIBs has a longer history and is therefore technologically more mature. The recovery of lithium from LIBs, by contrast, has only been pursued by companies for a few years and remains considerably more challenging due to the chemical properties of lithium itself [BMWK 2023; SKN 2023]. The differing recycled content targets for these three metals are partly due to the expected variations in specific recovery rates, and partly a consequence of developments in battery chemistry – notably the trend towards nickel-rich and cobalt-reduced LIBs.

The complex task of recovering lithium, cobalt, and nickel compounds – ideally to battery grade – has long been the subject of intensive research in Germany and other EU countries. Numerous projects have been undertaken in collaboration between industry, universities, and non-university research institutes [LiBRi 2011; LithoRec I 2011; LithoRec II 2016; EcoBat-Rec 2016; MERCATOR 2023]. These efforts have led to the development of recovery processes at least at the pilot- and demonstration-plant level. However, unlike in Asia – especially in China and South Korea – Europe still lacks industrial-scale capacity for the further processing of black mass. This section presents notable examples of promising initiatives currently under way in Europe. The following section then outlines industrial projects involving integrated LIB recycling processes, combining spoke and hub operations at a single plant.

At present, the EU has only a small number of plants capable of processing black mass on the order of a few thousand tonnes per year. One of the key reasons is the still limited return flow of end-of-life LIBs. However, a significant increase in volumes is expected over the next five to ten years (see also point 3.3). Existing plants include Fortum and Akkuser Oy in Finland, Nickelhütte Aue and Düsenfeld in Germany, and Veolia in France (see Table 3-4). Other projects, given their smaller capacities, are presumed to be pilot-scale plants that are not yet ready for commercial operation. For example, Aurubis is currently operating a pilot plant in Hamburg for the hydrometallurgical processing of black mass [Aurubis 2022].

The following table lists plants for the further processing of black mass in the EU that are either operational, under construction, in planning, or at least announced. Given the rapid pace of developments in this field, the table does not claim to be exhaustive.

Recently, two companies in Germany have announced concrete plans to build large-scale facilities for the further processing of black mass. The company cylib plans to begin operations in 2027 at a site in the Dormagen Industrial Park, building on experience from its existing pilot plant in Aachen. The facility will be able to hydrometallurgically process up to 10,000 tonnes of black mass per year and recover lithium and other valuable materials [cylib 2024]. A second major project has been announced for Goslar by the established company H.C. Starck Tungsten, which was acquired in 2024 by the Mitsubishi Materials Corporation of Japan. The company intends to use a new, patented process, with construction of the plant – representing an investment of approximately €340 million – scheduled to begin in 2027, and operations expected to start two years later. The facility is designed to process 20,000 tonnes of black mass per year [H.C. Starck Tungsten 2025]. In addition, Altillium Metals is building a plant in Bulgaria for the recovery of raw materials from used LIBs, including lithium [Allen 2024].

5 Applies to industrial batteries (> 2 kWh), traction batteries for electric vehicles, and – from 2036 onwards – also to batteries for light means of transport.

Many other announced projects for black-mass processing have been temporarily suspended or put on hold, due to the uncertain market outlook and the substantial investment volumes involved (as illustrated by the H.C. Starck Tungsten example). The chemical company BASF had originally planned to build a hydrometallurgical plant in Spain, but – partly due to forecasts indicating low volumes of end-of-life EV batteries in the near term – has put the project on hold [Osusky 2025]. Another example is the previously mentioned Portovesme project, which has faced delays in the permitting process since its initial announcement in 2023 [Allen 2023]. Planning has since resumed [Li-Cycle 2024b], though currently only at the pre-feasibility stage.

Other projects – some involving very high projected capacities – have been publicly announced in the past, but their implementation remains uncertain. This includes, for instance, the Tozero project in Munich, which aims to process up to 90 kt/a of black mass and is currently operating at pilot scale [Wilfer 2023]. In several EU countries, plants are currently in planning or have at least been announced – yet for all these projects, the market environment remains highly dynamic and volatile, and the realisation of such plants is often subject to uncertainty.

Strategic partnerships between recycling companies have also been announced. For example, the black mass produced at Hydrovolt's mechanical treatment plant

Plants for further processing of black mass in the EU (hubs) — Table 3-4

Location	Company headquarters	Project/location	Company	Status	Handling capacity forecast/a
FI	FI	Project Fortum Hydromet/ Harjavalta	Fortum Battery Solutions	In operation	10 kt[1]
FR	FR	Moselle	Veolia	In operation	7 kt[2]
FI	FI	Nivala	Akkuser Oy	In operation	4 kt[3]
DE	DE	Aue	Nickelhütte Aue	In operation	4 kt[4]
DE	DE	Wendeburg	Duesenfeld	In operation	3 kt[5]
DE	DE	Salzgitter	VW	In operation	1,5 kt[6]
DE	DE	Hamburg	Aurubis	Pilot operation	Pilot scale[7]
BE	BE	Hoboken	Umicore	Completed	7 kt[8]
BG	UK	Medet	Altilium Metals	Under expansion	24.000 EV[9]
DE	DE	Dormagen	Cylib GmbH	In planning	30 kt[10]
DE	DE	München	Tozero	Announced	90 kt[11]
IT	CAN/USA	Portovesme	Li-Cycle/ Glencore	Announced	50–70 kt[12]
ES	ES	Cubillos del Sil	Endesa/ Urbaser	Announced	25 kt[13]
HU	SI	Alsózsolca	Andrada Group	Announced	10 kt[14]
FR	FR/FR/BE	Amneville	Renault/Veolia/ Solvay	Announced	4 kt[15]

Sources: [1] [Stephan 2024], [2] [ISWA 2024], [3] [Velázquez-Martínez et al. 2019], [4] [Hartmann 2022], [5] [Donner 2022], [6] [Volkswagen AG 2024], [7] [Aurubis 2022], [8] [Umicore 2022b], [9] [Mendoza 2024], [10] [Cylib 2024], [11] [Wilfer 2023], [12 [Allen 2023], [13] [Allen 2024], [14] [Randall 2023c], [15] [Innovation Origins 2023].

Agora Verkehrswende (2025) | Source: Compiled by Oeko-Institut.

in Norway is processed at the hydrometallurgical facility of Fortum Battery Solutions in Finland [Fortum 2024]. In addition to its collaboration with the car manufacturer Hyundai, Stena Recycling has announced another strategic partnership with BASF as its recycling partner [BASF 2024b].

3.2.4 LIB recycling plants with integrated processes in the EU (spokes and hubs)

Further recycling projects for end-of-life LIBs in the EU include fully integrated plants that cover the entire treatment process – from mechanical processing (spokes) to the recovery of recycled battery materials (hubs). Such plants play a key role in ensuring the comprehensive treatment of end-of-life LIBs and thereby in securing secondary raw materials within the EU. Their operation helps to ensure that spent batteries collected in the EU – and the secondary raw materials recovered from them – remain within the European market.

In the EU, the first integrated mechanical–hydrometallurgical recycling plant was opened in Germany by the Mercedes-Benz Group. This is a pilot plant with a capacity of 2.5 kt/a, designed primarily for research purposes [Mercedes-Benz 2024]. Another such project was originally planned by Suez and Eramet in France, but – like several others – has since been postponed or suspended [Werwitzke 2024b].

Despite the importance of such plants for securing secondary raw materials within the EU, their overall processing capacity remains very limited. Compared with facilities that only produce black mass (spokes), there are far fewer integrated treatment projects. In addition, there are several black-mass production plants where hydrometallurgical or pyrometallurgical processes are operated on the same site at pilot scale, for example to support the planning of future large-scale operations. Examples include the plants operated by SNAM in France, AE Elemental in Poland, and BASF in Germany [SNAM 2025; BASF 2024a; Ascend Elements 2024]. It remains uncertain whether and to what extent these existing pilot plants will eventually evolve into fully integrated, industrial-scale facilities.

Particular mention should also be made of the activities of Accurec GmbH in Krefeld, Germany. The company currently processes around 4,000 tonnes of end-of-life LIBs per year into black mass using a pyrolysis and mechanical-treatment process. Accurec has recently applied for a permit amendment under the Federal Immission Control Act to increase its capacity to 20,000 tonnes of end-of-life LIBs per year and to begin hydrometallurgical processing of the black mass. The company's stated targets are the annual production of 3,000 tonnes of lithium carbonate and 7,500 tonnes of cobalt-nickel products [Accurec 2025]. A distinctive feature of this project is that Accurec primarily focuses on LIBs from devices (such as portable batteries and power tools) and only secondarily on end-of-life traction batteries from electromobility [Accurec 2025].

3.2.5 Cooperation with partners outside the EU

The recent slowdown in projections for electromobility growth in the EU and the correspondingly slower increase in the return of end-of-life LIBs to the circular economy in the near term, raises the question of whether EU black-mass production plants will be sufficiently utilised – and thus profitable – in the coming years. If all currently announced black-mass production projects were realised with their planned capacities, the EU could face overcapacity in this area in the medium term. According to Benchmark Recycling, most material available for recycling in the EU up to 2031 will initially come from cell-manufacturing plants (production scrap) [Benchmark Minerals 2025b]. In the longer term, however, this picture is likely to change considerably as the LIBs currently in use reach the end of their service life.

Despite the number of ongoing recycling projects, it remains uncertain whether all end-of-life LIBs generated in the EU will actually be processed within the EU, or whether some will be exported for treatment outside the EU. This question mainly concerns black mass produced within the EU. Even though plans exist for new secondary-material recovery plants in Europe, it cannot be assumed that all black mass will be processed domestically, especially since EU black-mass production capacity already exceeds that for further processing. Moreover, several companies that produce black mass in the EU also operate pyrometallurgical or hydrometallurgical plants outside the EU, giving them a commercial interest in exporting black mass to those countries.

Plants with integrated processes in the EU (spokes and hubs) — Table 3-5

Location	Company headquarters	Project/location	Company	Status	Handling capacity forecast/a
DE	DE	Kuppenheim	Mercedes-Benz Group	In operation	2,5 kt (pilot operation)[1]
DE	DE	Krefeld	Accurec	In operation	4 kt, expansion to 20 kt requested[2]

Sources: [1] [Mercedes-Benz 2024], [2] [Accurec 2025].

Agora Verkehrswende (2025) | Source: Compiled by Oeko-Institut.

Since March 2025, black mass has been classified as hazardous waste in the EU, following the European Commission's decision – as part of its latest industrial strategy for the automotive sector – to update the Waste Catalogue [EC 2025]. The revised catalogue differentiates between hazardous and non-hazardous battery waste, but now classifies all intermediate products of battery recycling, including black mass, as hazardous, regardless of their actual composition. Under EU law, which follows the Basel Convention, hazardous waste may only be exported to OECD countries. In addition, any shipment within the EU or to OECD countries outside the EU (for example South Korea) must be formally notified. This change harmonises the handling of black mass, which was previously inconsistently classified as either a product or a waste material depending on the country, seller, or material quality. The update is intended to make exports more difficult – as classification as a product, and therefore export without notification, is no longer possible – while also allowing better monitoring of shipments. However, how these new rules will work in practice remains to be seen.

Currently, over 50 percent of black mass from the EU is exported to Asia, particularly to South Korea and various Southeast Asian countries, where numerous secondary-material recovery plants are already in operation – especially in South Korea and China [Gherasim/Michel 2024]. Following the update of the Waste Catalogue, this distribution may change, since no Southeast Asian country is an OECD member, making exports to those countries prohibited. South Korea, however, is an OECD member and home to several companies with recycling operations in the EU.

A good example is the South Korean company SungEel HiTech, which operates two black-mass production plants in Hungary but processes the resulting black mass at its hydrometallurgical plant in South Korea [SungEel HiTech 2025].

In this context, it is also worth noting the emergence of strategic partnerships between vehicle manufacturers (OEMs) and recycling companies. From the OEM perspective, it is clearly in their interest to develop such partnerships strategically, ensuring access to secondary raw materials recovered from their battery waste. Several such collaborations have recently been announced in the EU. For example, BMW has announced a long-term partnership with the recycler SK TES for the treatment of its battery waste. Under the arrangement, BMW will supply its spent batteries to SK TES, whose mechanical treatment plant in Rotterdam will produce black mass from them [Schaidnagel 2025]. It is assumed that this black mass has so far been exported outside the EU for recovery, since SK TES currently operates or plans no hydrometallurgical facilities in the EU, but does have one in Singapore [SK TES 2023]. In addition, Stena Recycling has announced a partnership with the car manufacturer Nissan [Nissan 2025].

3.2.6 Interim conclusion: Value chains for LIBs from secondary raw materials for the EU market

The growing demand for battery raw materials – and the potential to meet that demand increasingly through secondary raw materials – has encouraged both European and non-European actors to commit to long-term investments in battery recycling projects within the EU. Most of the facilities mentioned are joint ventures or projects involving European and Asian companies, with the majority of Asian players based in South Korea. In Asia, these companies already operate large-scale recycling plants and are now using their operational experience to expand investments into the European market. In Eastern Europe, particularly Poland and Hungary, investments are predominantly driven by Asian companies, whereas in Central Europe and in the Nordic countries – Finland and Sweden – the projects are mainly led by domestic enterprises. In addition, several North American firms are also active in the EU market.

Despite the global trend toward electromobility and the favourable outlook for securing secondary raw materials within the EU, recent years have shown a tendency for planned recycling projects not to materialise as expected. A number of projects announced in previous years have since been abandoned or significantly delayed. This can be attributed to several factors – most notably economic challenges, such as the high investment costs (especially for hub or integrated plants) and uncertainty over whether such large-scale capacities will be fully utilised. Some companies have also reconsidered their EU investment plans in light of forecasts predicting slower growth in end-of-life LIB volumes in the near future – as illustrated by the postponed large-scale recycling plant planned by Umicore [Benchmark Minerals 2024a]. Similarly, SungEel HiTech has halted its project in Gera as part of a global strategic realignment [MDR 2025].

In addition to economic factors, delays in permitting procedures have also led to cancellations or long-term postponements of projects. Some of these delays have been driven by citizens' initiatives opposing the construction or operation of recycling plants, primarily due to concerns over potential environmental pollution and declines in local property values. Projects affected include the planned Fortum Battery Solutions facility and the previously mentioned SungEel HiTech plant – both originally intended to be located in Thuringia [MDR 2024; MDR 2025; Randall 2024].

Despite these setbacks and delays in establishing a European value chain for LIBs based on secondary raw materials, recent developments – including concrete plans by companies such as cylib [cylib 2024], H.C. Starck Tungsten [H.C. Starck Tungsten 2025], and Accurec [Accurec 2025] – demonstrate that investment in LIB recycling infrastructure is continuing in earnest. These activities are receiving growing support from the EU, which has created key policy frameworks for further investment in the European LIB value chain – notably through the EU Battery Regulation [EU 2023], the Critical Raw Materials Act [CRMA 2024, 2025] and the recent Industrial Strategy for the Automotive Sector [EC 2025].

3.3 Definition of scenarios for traction batteries in the EU-27

In addition to mapping the relevant LIB market actors within the EU, an analysis of the potential market growth is an essential foundation for developing battery take-back systems. For this purpose, the Oeko-Institut has developed three current scenarios for the EU-27, analysing raw-material and recyclate flows under different boundary conditions of market development. The time horizon was set to 2040 in order to take account of the key development dynamics, but not so far ahead that assumptions would become increasingly speculative and uncertain. The analysis covers passenger cars as well as several categories of commercial vehicles. Within each defined category, an average representative vehicle was modelled, resulting in the vehicle classes and corresponding battery capacities shown in Table 3-6. In the heavy-duty vehicle segment, driving performance, service life, and battery capacity vary significantly by vehicle class [BMWK 2023]. Accordingly, this group was subdivided into four weight classes. An overview of the vehicle types considered and the assumed battery parameters is presented in Table 3-6.

Because the composition of batteries – and particularly the share of critical raw materials – has a far greater impact on raw-material demand than overall EV sales volumes, the registration numbers were kept identical across all scenarios. This approach isolates the effects of different market-penetration trajectories for various cell chemistries, resulting in three distinct future-development scenarios. The baseline parameters applied in all three scenarios were defined in consultation with several sources [SKN 2023; BMWK 2023; IEA 2023]. All scenario assumptions were additionally discussed and validated in consultation with experts.

To assess both future raw-material demand and the corresponding return flows and potential recyclate streams, assumptions were required for vehicle registrations in past and future years. Up to and including 2024, registration data published by the European Automobile Manufacturers' Association (ACEA) for the EU-27 was used [ACEA 2024]. From 2025 onwards, the projections from the accompanying study to the EU End-of-Life Vehicles Directive [ELV IA 2023] were adopted. Although the EU fleet-emissions targets – which amount to a de facto ban on new internal-combustion passenger cars – have recently faced strong criticism from some stakeholders, they are still expected to remain in force [EU 2023]. Accordingly, it is assumed that from 2035 onwards only fully electric passenger cars may be newly registered in the EU. Since none of the available sources differentiates adequately between weight classes for heavy duty vehicles, the (time-invariant) share of each class in the total number of heavy-duty vehicle registrations (HDV > 3.5 t) was extrapolated from German data [BMWK 2023].

The resulting registration figures for battery-electric vehicles (BEV) and hybrids (PHEV and HEV) across the various vehicle categories are shown in Figure 3-5. For light commercial vehicles (LCV < 3.5 t), heavy duty vehicles (HDV > 3.5 t), and buses, only fully electric powertrains (BEV) were included. As vehicles with diesel or petrol engines have no effect on the quantities of the battery raw materials prioritised in this study, they were considered only for calculating total vehicle numbers and are not listed further. From a purely numerical standpoint, passenger cars account for by far the largest market share in the EU compared with commercial vehicles. However, due to the significant differences in battery capacity, their impact on raw-material demand varies accordingly.

The number of vehicles deregistered in any given year was derived from the cumulative registrations in previous years combined with the assumed lifetime distribution for each vehicle category. Given the rapid advances in battery technology, it was assumed – as confirmed by expert inter-views – that the service life of traction batteries generally corresponds to vehicle lifetime. The material composition of a lithium-ion battery (LIB) with a given cell chemistry and capacity was taken from the BatPac model of the Argonne National Laboratory [BatPac 2022]. For the alternative solid-state battery (SSB) case, the average composition was estimated from other literature sources [Betz et al. 2019; Benchmark Minerals 2024c] and expert interviews. Sodium-ion batteries (SIBs), according to the assumptions used here, contain none of the priority raw materials – lithium, nickel, cobalt or graphite – and therefore affect the model only indirectly through the savings of these materials.

3.3.1 Scenario: Lithium-Nickel-Manganese-Cobalt Oxide (NMC)

In this scenario, nickel- and cobalt-free LIBs (particularly Lithium iron phosphate, LFP) continue to gain market share in the passenger-car segment, in line with current trends. However, nickel- and cobalt-containing LIBs – comprising various lithium nickel manganese cobalt chemistries and lithium nickel cobalt aluminium oxide (NCA) – retain a substantial share, especially among mid-range and premium vehicles. In this scenario, the market is expected to be dominated

Overview of the vehicle classes considered and the assumed battery parameters — Table 3-6a

Class	Car			Bus	
Powertrain	BEV	HEV	PHEV	BEV	BEV
Battery capacity [kWh]	70	2	15	80	480
Battery cell chemistry	NMC811, NMC622, NMC111[1], LFP, NCA, LMO[1]	NMC811, NMC622, NMC111[1]	NMC811, NMC622, NMC111[1]	NMC811, NMC622, NMC111[1], LFP	NMC622, LFP

Agora Verkehrswende (2025) | Note: [1] being phased out; Source: Compiled by Oeko-Institut.

Overview of the vehicle classes considered and the assumed battery parameters — Table 3-6b

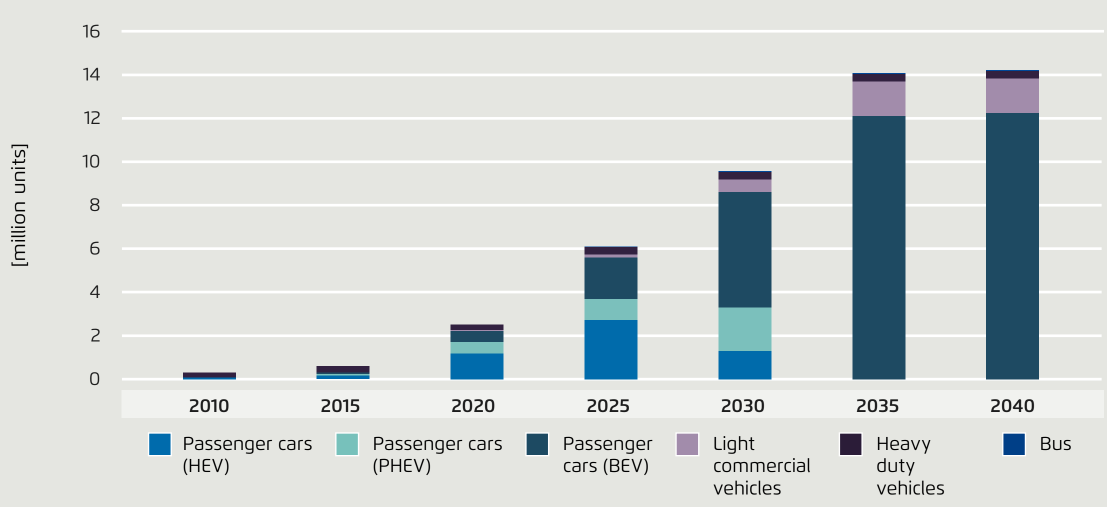
Class	HDV 1 (3.5-7.5 t)	HDV 2 (7.5-12 t)	HDV 3 (> 12 t)	HDV 4 (heavy-duty trucks / articulated lorries)
Powertrain	BEV	BEV	BEV	BEV
Battery capacity [kWh]	250	420	580	860
Battery cell chemistry	LFP	NMC622, LFP	NMC811, NMC622, LFP	NMC811, NMC622, LFP

Agora Verkehrswende (2025) | Source: Compiled by Oeko-Institut.

primarily by nickel-rich cell chemistries (NMC622[6] and NMC811). Battery types such as NMC111 and lithium manganese oxide (LMO), which already hold only negligible market shares today, are likely to be phased out within a few years (see Figure 3-6). For light commercial vehicles (LCV), the market shares are broadly aligned with the passenger-car scenario, though only NMC and LFP cathode materials are considered here. As the commercial-vehicle sector is generally more price-sensitive than the passenger-car market, the share of LFP batteries is assumed to be somewhat higher. In the heavy-duty-vehicle segment, LFP cathodes are likewise expected to dominate—again reflecting strong price sensitivity—although the higher-performance NMC cathodes will increasingly be required for the heavier vehicle classes due to their weight and power demands. Given the high degree of uncertainty, the shares of the different cell chemistries for commercial vehicles were assumed to remain constant throughout the scenario period. Detailed assumptions regarding the distribution of cell chemistries across the various commercial-vehicle classes are provided in Annex 7.2.

6 For NMC cathodes, the three digits (e.g. 622 or 811) denote the relative proportions of nickel, manganese and cobalt in the cathode material.

Registrations of BEVs and hybrids in the different vehicle classes in the model, 2020–2040 — Figure 3-5



Agora Verkehrswende (2025) | Source: ACEA 2024, ELV IA 2023, BMWK 2023.

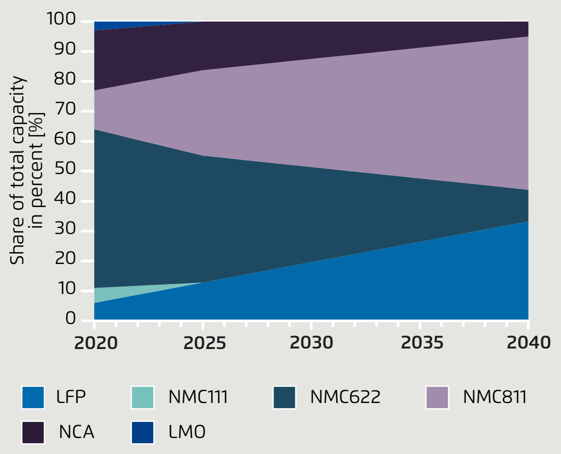
3.3.2 Scenario: Lithium Iron Phosphate (LFP)

In this scenario, nickel- and cobalt-free LIBs using LFP cathode materials gain market share year after year and become clearly dominant by 2035. This growth comes largely at the expense of all other battery chemistries. Only in the upper luxury segment, where performance demands outweigh price sensitivity, do nickel-rich NMC cathodes maintain a modest share (see Figure 3-7). For the commercial-vehicle scenarios, the temporal trend is assumed to remain constant, though with a higher overall share of LFP batteries.

Scenario: Alternative Batteries (AB)

In this scenario, the passenger-car sector sees a gradual increase in alternative battery technologies. Solid-state batteries (SSBs) increasingly replace conventional NMC cathodes, while sodium-ion batteries (SIBs) – which are currently at a lower technological maturity – begin to capture market share from LFP cells with a certain time lag. It is not assumed that LIBs will disappear entirely from new-vehicle markets by 2040; however, their market share is expected to decline steadily and significantly (see Figure 3-8). For the commercial-vehicle sector, no meaningful market penetration of these alternative technologies is expected by 2040. Here, a midpoint between the NMC and LFP scenarios is assumed.

Temporal development of cell-chemistry composition for passenger cars (EU-27) in the NMC scenario, 2020–2040 — Figure 3-6



Agora Verkehrswende (2025) | Source: own assumptions, Oeko-Institut.

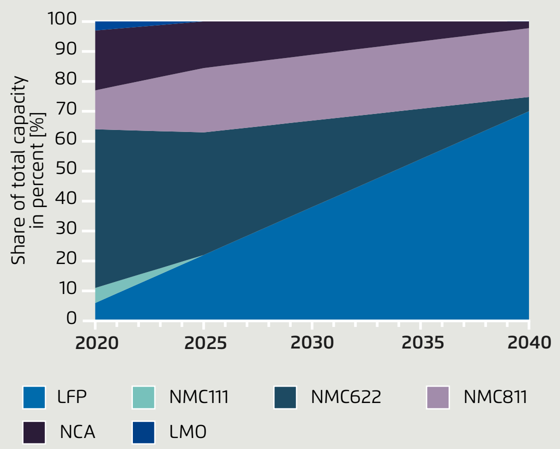
3.4 Results of the scenarios for traction batteries in the EU-27

From the assumptions on vehicle registrations and battery sizes, the annual battery demand within the EU and the return flow of batteries into the circular economy were calculated in gigawatt-hours (GWh) per year. With the complete electrification of new passenger-car registrations, total battery demand is projected to stabilise at around 1,200 GWh per year from 2035 onwards, roughly six times higher than today (see Figure 3-9). The data shows that, despite their comparatively low numbers (see Figure 3-4), heavy-duty vehicles represent a substantial share of total required battery capacity as fleet electrification progresses. Altogether, they account for roughly one quarter of the total capacity demand, with heavy-duty vehicles alone making up around 16 percent. By 2040, a significant volume of traction batteries is already expected to re-enter the circular economy, meaning that part of the raw material demand could be met through secondary materials.

When the projected demand is compared with the future cell-production capacities outlined in section 3.1, it becomes clear that progress along the different steps of the value chain remains uneven. For cell production, it appears plausible that by 2030 the required 600 GWh of annual capacity could be produced almost entirely within the EU. For anode and cathode materials, however, current announcements indicate that only about one third of the necessary capacity will be available (see section 2.1). The return flow shown in Figure 3-9, around 350 GWh per year, corresponds to a weight of just over two million tonnes of batteries that could potentially be recycled within the EU by 2040. Particularly in the final five years of the 2020–2040 study period, this return volume is expected to double again. Given the recycling capacity expansions discussed in section 3.2, it appears feasible that by this point the EU could handle such volumes and recover raw materials domestically. However, due to the long timeframe and today's highly volatile market conditions, a definitive assessment remains premature.

Temporal development of cell-chemistry composition for passenger cars (EU-27) in the LFP scenario, 2020–2040

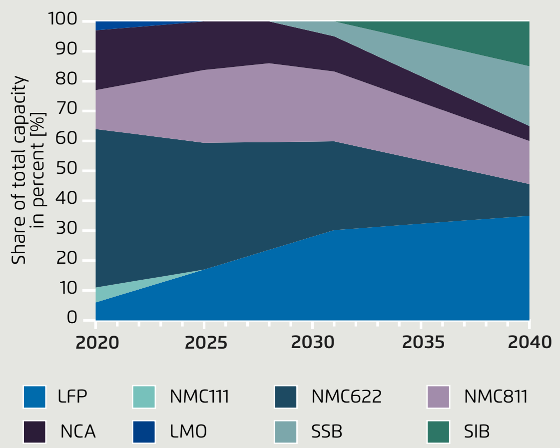
Figure 3-7



Agora Verkehrswende (2025) | Source: own assumptions, Oeko-Institut.

Temporal development of cell-chemistry composition for passenger cars (EU-27) in the AB scenario, 2020–2040

Figure 3-8



Agora Verkehrswende (2025) | Source: own assumptions, Oeko-Institut.

For the AB scenario, Figure 3-10 shows the shares of different battery types by total weight of all required batteries. While the market will still be dominated by conventional LIBs in 2040, alternative batteries already account for a non-negligible 25 percent share by weight, and thus of total raw material demand. Because of their much lower energy density (around 60 percent of LIBs for the cases considered here), the sodium-ion batteries (SIBs) represent a significantly higher share by weight compared with solid-state batteries (SSBs), even though their sales numbers are similar. However, it is important to note that although sodium-ion batteries (SIBs) have a higher overall raw-material intensity, they dispense entirely with the critical materials found in LIB cells. In contrast to the demand side, the return flows show no discernible effect of the introduction of alternative cell chemistries over the time horizon considered here. Owing to the now comparatively long service lives of traction batteries (see point 3.3), such effects will only emerge much later.

The following analysis examines how the three scenarios affect raw-material demand and the secondary-resource potential for the four key materials: lithium, nickel, cobalt, and graphite. Figures 3-11 to 3-14 follow a consistent structure: The temporal progression of raw-material demand and return flows (per year) is shown for 2020–2035 in five-year increments, based on the NMC scenario results. For the target year 2040, the outcomes for all three scenarios are displayed side by side as bars – since only at that point do significant differences between scenarios emerge. For raw-material returns, it is important to note that these represent the total quantities of materials contained in the batteries of vehicles deregistered in a given year, without accounting for recycling efficiency – in other words, the maximum theoretical secondary-resource potential per year.

Figure 3-11 illustrates the annual lithium demand across the three scenarios. As with the near-stagnant number of new registrations after 2035, total lithium demand in the NMC scenario also remains almost constant at roughly 110 kilotonnes per year for all vehicle classes combined.[7]

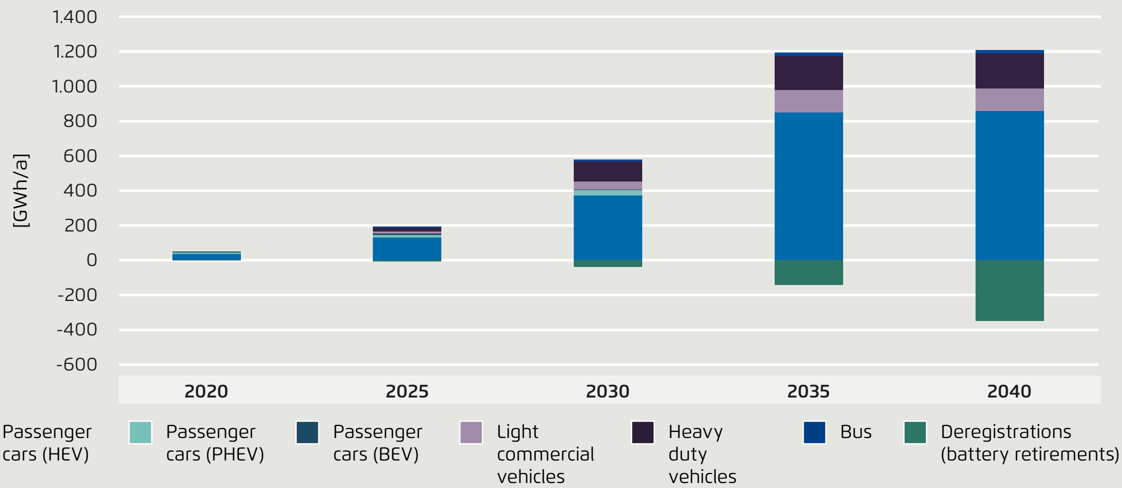
7 All quantity figures for lithium, nickel and cobalt refer to the intrinsic amounts of these metals contained in the batteries themselves – not to lithium-carbonate equivalents (LCE) or similar units frequently used in statistical reporting.

Although commercial vehicles contribute more noticeably due to their large battery sizes, passenger cars remain the main driver of lithium demand, accounting for nearly 70 percent of the total traction-battery requirement. A comparison of the 2040 results across scenarios shows only minor differences. Since LIBs with NMC and LFP cathodes contain similar lithium proportions, this outcome is consistent with expectations. In the alternative-battery scenario, two opposing effects can be observed: Sodium-ion batteries (SIBs) use no lithium at all, while solid-state batteries (SSBs) require roughly twice as much lithium as conventional liquid-electrolyte LIBs due to their solid-electrolyte composition. Given the comparable market penetration assumed here, these effects largely cancel each other out. It should be noted, however, that differing degrees of adoption of these technologies couldlead to a marked increase or decrease in total lithium demand.

If one assumes—quite plausibly—that all EU-based lithium-mining projects listed in point 3.1 reach their fully announced build-out by 2040, amounting to roughly 30 kt/a of lithium output, then just under 30 percent of annual demand could in principle be met from European primary sources. In addition, it remains possible that several of the projects currently at earlier stages of development, or merely announced, will also reach meaningful production volumes by 2040, further increasing this share. The planned capacities for processing the extracted lithium currently exceed the mining projects slightly, indicating that this stage of the value chain should also be able to cover the stated share of overall demand. While the secondary-raw-material potential remains very low up to 2030, by 2040 enough vehicles will have been de-registered and recycled for there to be – at least in principle – a meaningful opportunity to meet a relevant share of lithium demand through battery recycling. The traction batteries from vehicles deregistered in 2040 will contain just over 30 kilotonnes of lithium that could, in principle, be recovered and reprocessed. Given that the EU Battery Regulation [BatReg 2023] requires 80 percent of the lithium in a battery to be recycled by 2031, and assuming primarily closed-loop recycling, more than half of the lithium demand in 2040 could be met from European primary and secondary sources (secondary potential roughly 25 percent).

The nickel demand for the three scenarios is shown in Figure 3-12. In the NMC scenario, nickel demand declines slightly after 2035 and reaches just over 400 kilotonnes per year by 2040. his is because LFP batteries

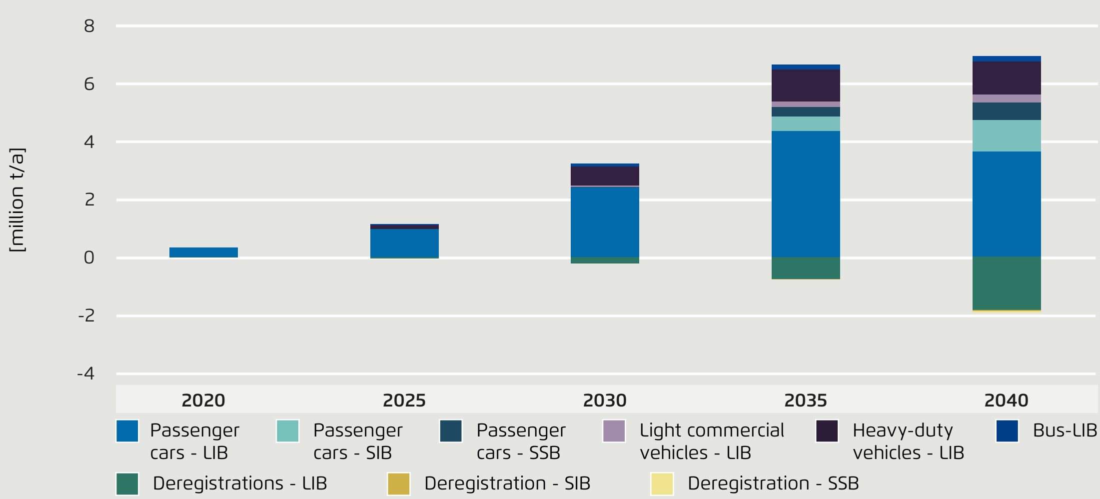
Required traction battery capacities by vehicle class and their returns in the EU-27 in GWh/a 2020–2040 — Figure 3-9



Agora Verkehrswende (2025) | Source: modelling, Oeko-Institut.

Share of different battery types in the total mass of required traction batteries in the AB scenario in the EU-27 in million t/a 2020–2040

Figure 3-10



Agora Verkehrswende (2025) | Source: modelling by Oeko-Institut.

continue to gain market share in this scenario as well, albeit somewhat more moderately. With registrations remaining roughly constant between 2035 and 2040, this has a slightly dampening effect on nickel demand. In the LFP scenario, annual nickel demand in 2040 is reduced by almost half compared with the NMC scenario, while the alternative batteries scenario again falls between the two. Across all scenarios, the announced capacities of the few nickel-mining and nickel-processing projects explicitly underway in the EU cover only a fraction of the demand expected by 2040. Moreover, given the current market shift toward LFP cells, investments in value-chain stages that do not involve this cell chemistry are assumed to be delayed for the time being, as investors wait to see how this trend develops.

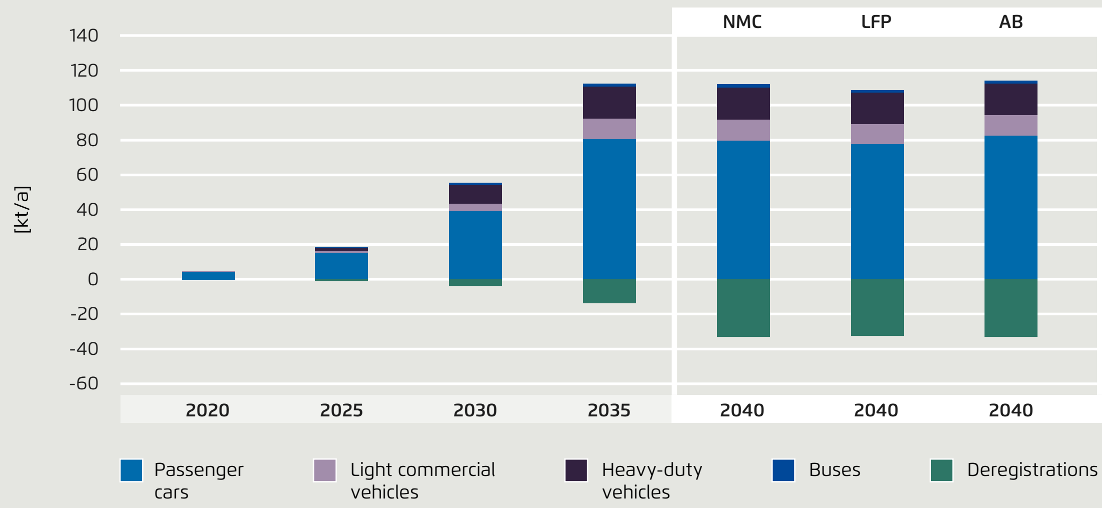
The reduced market share of NMC cathodes in the LFP scenario is already reflected in the return flows of nickel. In the NMC scenario, end-of-life batteries generate around 110 kt/a of nickel by 2040, whereas the corresponding return flows in the LFP scenario fall to below 100 kt/a. However, as the return flows in this period are still dominated by today's installed LIBs – of which a very large proportion use nickel-bearing cathodes – demand decreases much more sharply than returns over the run-up to 2040. In the NMC scenario, the maximum theoretical secondary-raw-material potential for nickel in 2040 is a little over 25 percent; in the LFP scenario it increases to around 50 percent. The alternative batteries scenario once again lies in between. Recycling nickel from end-of-life LIBs can therefore make a clearly significant contribution to future nickel supply for the European value chain.

For cobalt, shown in Figure 3-13, the trends broadly mirror those for nickel. The reduction in annual cobalt demand between 2035 and 2040 is even more pronounced in the NMC scenario, owing to the continued shift toward nickel-rich (and therefore cobalt-lean) NMC cathodes, compounded by the moderate rise in LFP uptake. Consequently, an even larger share of cobalt remains in circulation up to 2040 – material that could, in principle, be recovered and reintroduced into battery production.

In the LFP scenario, the combination of a high market share for LFP batteries and the wider move toward nickel-rich NMC cathodes significantly suppresses cobalt demand. By 2040, up to two thirds of cobalt requirements could, in principle, be supplied by end-of-life batteries. A notable point here is that the proportional reduction for heavy-duty vehicles is even greater

Comparison of primary raw material demand and secondary raw material potential for lithium in the three scenarios considered in the EU-27 in kt/a 2020–2040

Figure 3-11



Agora Verkehrswende (2025) | Source: modelling by Oeko-Institut.

than for passenger cars, reflecting the assumption that, by the end of the assessment period, only LFP and the lower-cobalt NMC811 chemistry retain market share in these vehicle classes.

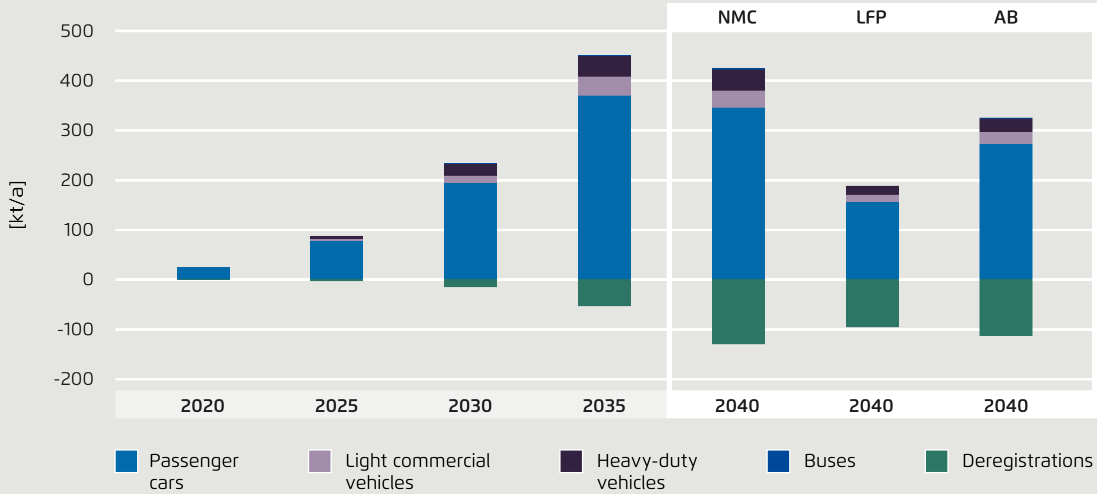
In the NMC scenario, the maximum secondary-material potential for cobalt still reaches around 40 percent in 2040. In the Alternative Batteries scenario, annual cobalt demand declines to roughly 70 percent of the value calculated for NMC, while return flows remain broadly similar up to 2040. It should be noted, however, that return flows will also gradually fall once demand begins to decline, albeit with a time lag. Even so, the scenario results indicate that cobalt recovered from end-of-life LIBs could cover a very substantial share of EU cobalt demand – drawn largely from the NMC batteries already in circulation or soon to be placed on the market.

The final key raw material considered is graphite. Figure 3-14 sets out the evolution of annual demand and the potential return flows from deregistered vehicles. Between the two scenarios based on established LIB technologies – LFP and NMC – there is essentially no difference in graphite demand or in return flows. Demand in both cases is slightly above 1,000 kilotonnes in 2035 and again in 2040, with a very similar distribution across vehicle classes. In the alternative batteries scenario, however, the effect of the two alternative chemistries becomes immediately apparent: neither technology requires graphite. As a result, graphite demand falls markedly, to around 800 kilotonnes in 2040. Given the assumption that alternative cell chemistries will, over the considered time horizon, gain a foothold only in the passenger-car segment and not in the commercial-vehicle sector, the share of commercial vehicles in total graphite demand rises significantly.

Another factor shaping future graphite requirements is the trend—visible for several years now—toward substituting part of the graphite with silicon to increase energy density [Heimes et al. 2021]. To estimate the potential graphite savings from (partial) substitution with silicon, a sensitivity case was developed that compares the NMC reference scenario with an additional scenario. Keeping vehicle registration and deregistration figures and the distribution of cell chemistries constant, it was assumed that replacing 10 percent by weight of graphite can increase energy density by up to 40 percent [Benchmark Minerals 2024b]. To explore the upper bound of what may be technically feasible, the maximum values cited in the sources were applied. Market-penetration trajectories for silicon-containing anodes

Comparison of primary raw material demand and secondary raw material potential for nickel in the three scenarios considered in the EU-27 in kt/a 2020–2040

Figure 3-12



Agora Verkehrswende (2025) | Source: modelling by Oeko-Institut.

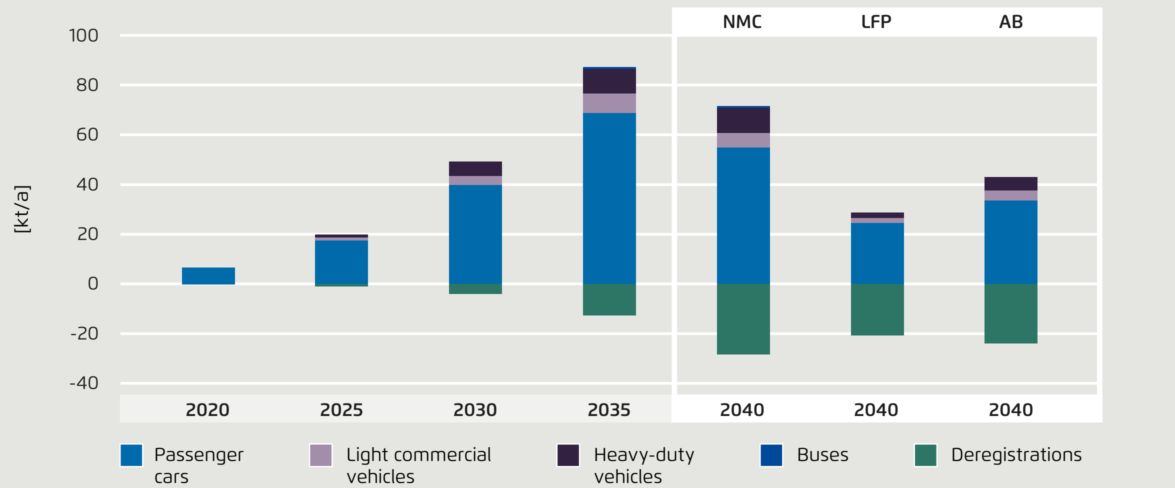
were taken from projections by Roland Berger or extrapolated from these [Roland Berger 2024].
The resulting graphite demand, with and without silicon substitution under the NMC scenario, is shown in Figure 3-15. Under these assumptions, roughly one quarter of total graphite demand in 2040 could be avoided compared with the pure NMC scenario. It must be stressed, however, that this reflects both maximal projected market penetration and maximal efficiency gains—and it remains uncertain whether the technology will achieve equal footholds in the passenger-car and commercial-vehicle segments. Across all scenarios, graphite demand far exceeds what can realistically be supplied by the European primary-material production and mining capacities discussed in Section 3.1.
Although the recovery of graphite from end-of-life LIB is being pursued in numerous research and development projects [MERCATOR 2023], the stringent purity requirements for graphite in battery quality mean that recycled graphite is far more likely to be used in other graphite applications

Taken together, the scenario results show that raw-material demand for the electrification of road transport will increase many times over across the considered time horizon compared with today. The three scenarios differ markedly in their impacts on the key raw materials examined.
The NMC scenario is the most resource-intensive of the three. While the LFP scenario has limited impact on lithium and graphite demand, it can already deliver substantial reductions in the critical raw materials nickel and cobalt using commercialised, widely deployed technologies.

As a result, batteries will contain fewer high-value materials in the future, creating a corresponding challenge as to how battery recycling can be made economically viable. The combination of the alternative technologies—sodium-ion batteries (SIB) and lithium solid-state batteries (SSB)—yields slightly smaller reductions in nickel and cobalt, but it significantly reduces graphite demand.
Apart from the positive developments in lithium mining and processing within the EU, sizeable gaps persist in the supply of primary materials under all scenarios. This makes it all the more important to harness the substantial secondary-raw-material potential for nickel, cobalt, and lithium from LIB recycling at an early stage and with high efficiency. Recycling end-of-life LIBs is unlikely to provide more than an indirect relief for the supply of battery-grade graphite, as recycled graphite is more likely to be used in other graphite products.

Comparison of primary raw material demand and secondary raw material potential for cobalt in the three scenarios considered in the EU-27 in kt/a 2020–2040

Figure 3-13



Agora Verkehrswende (2025) | Source: modelling by Oeko-Institut.

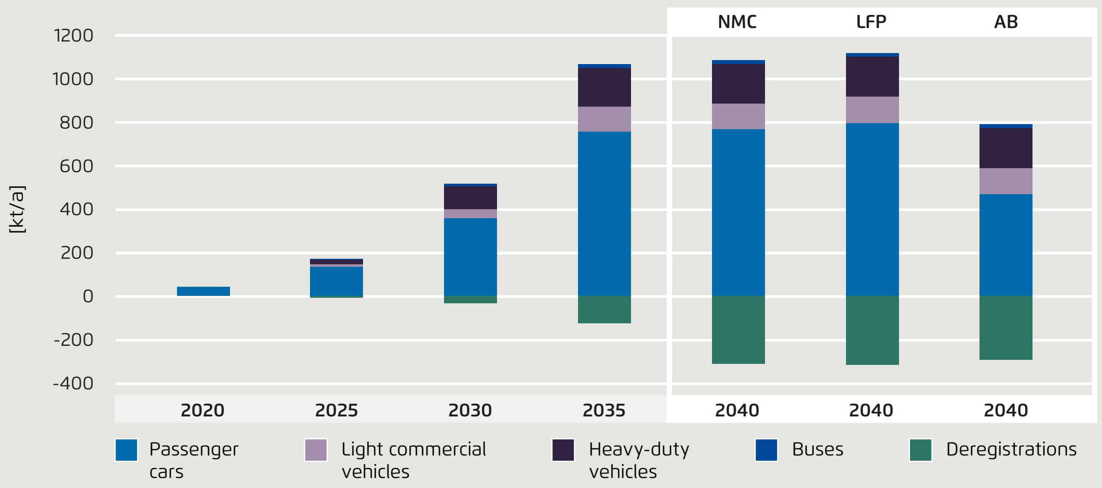
3.5 Conclusions from the analysis of value chains for the EU market

The comprehensive analysis of the current situation and the anticipated developments in LIB value chains – for both primary and secondary raw materials – reveals significant challenges for Europe. The three up-to-date scenarios for the ramp-up of electromobility in the EU-27, developed and modelled as part of this project, indicate – as previous studies have – that medium-and long-term demand (i.e. through 2040) for key materials such as lithium, cobalt, nickel and graphite will increase substantially compared with today.
Set against global developments – likewise characterised by strong growth in battery markets and their value chains, driven in particular by major industry players in Asia – Europe still shows considerable gaps across several stages of the LIB value chain. Nevertheless, Europe is also making progress, as illustrated by the commissioning of the first lithium refinery in Germany and the significant support measures adopted by the EU to strengthen domestic value chains. It is worth recalling here the strategic objectives of the Critical Raw Materials Act (CRMA) and the recently designated first set of 47 strategic projects under the CRMA to reinforce value chains for primary and secondary raw materials in Europe. The importance of LIBs is reflected in the fact that a large majority of these 47 strategic projects relate to raw materials such as lithium, cobalt, nickel and graphite.

At the same time, it is important to highlight the persistently volatile conditions in raw-materials markets, which can explain both the cancellation and, conversely, the acceleration of individual projects – often involving substantial investment volumes. The trajectory of lithium prices since 2025 in Figure 3-16 provides an instructive example, illustrating the general relationship between short-term fluctuations in raw-material prices and long-term investment decisions.
This creates a fundamental dilemma: short-term price declines can lead to the postponement of projects that require very long lead times. Developing a new mine for instance, takes many years. Consequently, rising demand for batteries and electric vehicles may again lead to temporary shortages in the future, which would in turn affect raw-material prices (see also Agora Verkehrswende 2025).

A key finding of the scenarios for the ramp-up of electromobility in the EU-27 up to 2040 – developed by the Oeko-Institut and validated with the advisory

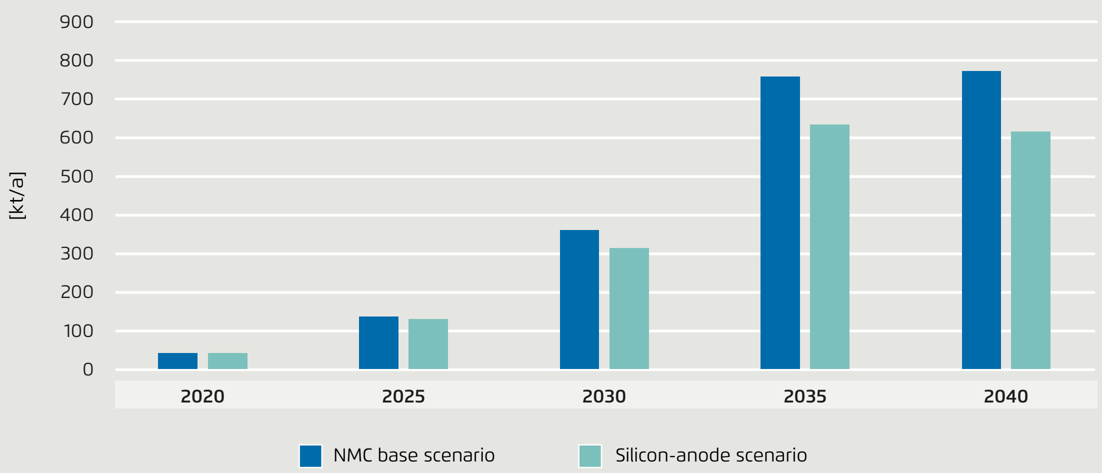
Comparison of primary raw material demand and secondary raw material potential for graphite in the three scenarios considered in the EU-27 in kt/a 2020–2040 Figure 3-14



Agora Verkehrswende (2025) | Source: modelling by Oeko-Institut.

group after extensive discussion – is the very substantial secondary-raw-material potential associated with an optimised circulation of the rapidly growing volumes of end-of-life LIBs in the EU-27 over the next ten to fifteen years. Secondary-raw-material potentials of 25 to 50 percent for lithium and nickel, and more than 60 percent for cobalt by 2040 underscore the strategic relevance of efficient recycling systems for the EU.

Comparison of graphite demand in the NMC scenario with an alternative scenario with silicon substitution in the EU-27 in kt/a 2020–2040 Figure 3-15



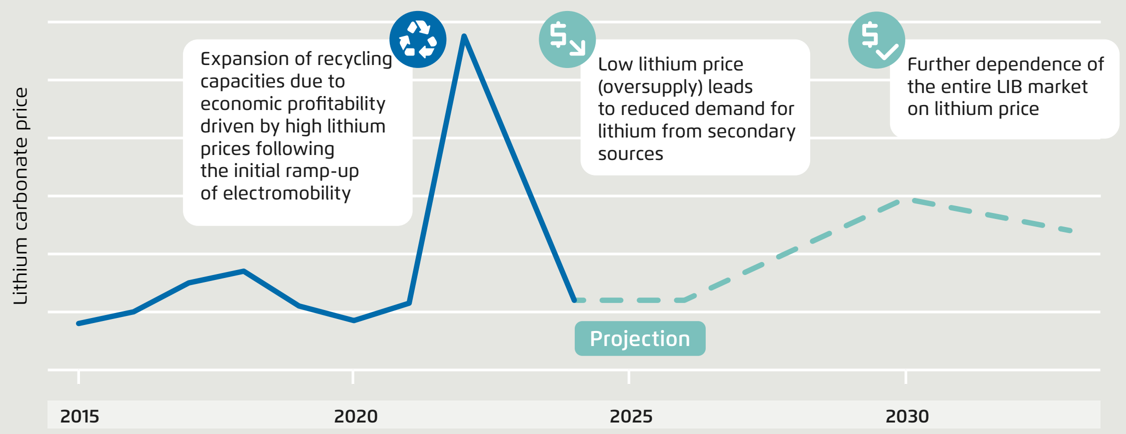
Agora Verkehrswende (2025) | Source: modelling by Oeko-Institut.

In this context, the progress being made in expanding LIB-treatment capacities within the EU – and particularly in Germany – deserves to be emphasised. This currently applies primarily to black-mass production plants (spokes); the far more capital-intensive processing plants (hubs) now need to follow. Here too, there has recently been notable activity – particularly in Central Europe – from companies whose projects could yield results in the next two to five years. As in virtually all areas, however, LIB recycling in the EU 27 must expect highly agile competition, primarily from South Korean and Chinese companies. The recycling potentials outlined above can only materialise for the EU if robust measures are implemented to prevent the outflow of batteries, intermediates such as black mass, or recovered raw materials through exports to non-EU countries (primarily in Asia).

The following chapter develops perspectives for an optimised LIB circular economy in the EU-27, taking account of all previous findings on value chains – with a focus on the potential advantages and disadvantages of different business models for LIB recycling.

Volatility of lithium prices 2015–2033 and possible impacts on investment decisions in the primary and secondary value chain

Figure 3-16



Agora Verkehrswende (2025) | Source: Benchmark Minerals (2024d).

4 | Perspectives for an optimised lithium-ion battery cycle in the EU

The following chapter analyses four conceptual alternatives for collection systems for lithium-ion batteries (LIBs). The information necessary for their development and related assumptions were compiled, among other things, on the basis of direct interviews and discussions with five different vehicle manufacturers (OEMs, original equipment manufacturers), a number of recycling companies, and representatives from industry associations, consultancy firms and non-governmental organisations.

In the development of these four alternatives of collection systems, it has been assumed that national legislation in the individual EU Member States shall not fundamentally preclude any of them. OEMs could, in principle, also operate their own system under their own responsibility.

As the chapter explains, OEMs can either source secondary material from recycling companies or process batteries into secondary material in their own facilities. In theory, an OEM could also develop a complete production line for manufacturing its own batteries; in practice, however, such batteries are usually procured as complete units from third-party suppliers or purchased as individual cells that the OEM assembles into finished lithium-ion batteries. It is generally not expected that OEMs will physically use the recycled material themselves. Instead, they will purchase such material to meet the recycled-content requirements laid down in the EU Battery Regulation.

In recent years, the European Battery Directive (2006/66/EC) was reviewed and replaced in 2023 by the new Battery Regulation [BatReg 2023]. This new regulation introduces several additional provisions that require the automotive industry to prepare for compliance. The review of the End-of-Life Vehicles Directive (2000/53/EC, the ELV Directive) is also currently under way. Although the process is not yet complete, a proposal for a new End-of-Life Vehicles Regulation was published in 2023, which is expected to bring changes for the treatment of end-of-life vehicles. As in the past, OEMs must meet their extended producer responsibilities to ensure that vehicles returned at end-of-life are treated in accordance with applicable legislation. However, new requirements under both regulatory frameworks oblige the industry to reconsider its existing structure.

Although not yet legally adopted, Article 24 para. 2 of the proposed Regulation on circularity requirements for the design of vehicles and the treatment of end-of-life vehicles [ELVRegProp 2023] stipulates that handing over an end-of-life vehicle to an authorised treatment facility (ATF, authorised treatment facility) must be free of charge for the last owner — unless certain components or parts are missing. The sole exception to this rule is the traction battery of an electric vehicle: it may, in principle, be removed before the vehicle is delivered to an authorised treatment facility. Otherwise, the ATF is obliged to remove the battery and ensure that it is treated separately. The possibility of having the traction battery removed by operators other than the ATF arises from the Battery Regulation.

Article 61 para. 1 of the Battery Regulation [BatReg 2023] concerns the collection of certain waste batteries and obliges manufacturers, among other things, to take back traction batteries from electric vehicles free of charge and to ensure their separate collection. It also stipulates that such batteries must be accepted by take-back systems and collection systems at the following collection points:

a) distributors of electric vehicle batteries in accordance with Article 62(1);
b) operators carrying out remanufacturing or repurposing of electric vehicle batteries;
c) end-of-life vehicle treatment facilities referred to in Article 65 for the waste electric vehicle batteries arising from their operations;
d) public authorities or third parties carrying out waste management on their behalf in accordance with Article 66.

Whether it will be possible in all Member States to return traction batteries to all of these collection points — or whether each country will handle returns differently — is as of yet unknown.

Another aspect of Article 61 concerns producer responsibility organisations (PROs, producer responsibility organisations): 'Member States may adopt measures to require that the entities referred to in the first subparagraph, points (a) to (d), may collect […] waste electric vehicle batteries only if they have concluded a contract with the producers or, where appointed in accordance with Article 57(1), producer responsibility organisations.'

This gives Member States the option to make PROs mandatory. For OEMs, this increases the uncertainty as to which business models they should develop in the future within individual Member States. For OEMs based outside the EU, who merely export into the EU and are less familiar with the circular-economy markets in each Member State, the challenge is even greater.
In addition, Article 8 of the Battery Regulation [BatReg 2023] sets recycled-content targets for certain industrial batteries, electric-vehicle batteries, and starter batteries for vehicles (SLI batteries, starting, lighting, ignition). For simplicity, the following sections refer exclusively to traction batteries for electric vehicles.

Article 8 paras. 2 and 3 set binding minimum-content targets for cobalt, lithium and nickel in batteries. From 18 August 2031, 16 percent of the cobalt contained in the active materials of an electric-vehicle battery – and 6 percent each of the lithium and nickel – must originate from battery-manufacturing waste or from end-of-life sources (that is, from battery-waste management). From 18 August 2036, higher targets apply: 26 percent for cobalt, 12 percent for lithium and 15 percent for nickel.

Against this background, the automotive industry is currently examining how it must organise itself to ensure the take-back and separate treatment of electric-vehicle batteries – not only to meet the extended-producer-responsibility (EPR) requirements under the

EU Battery Regulation, but also to secure a stable supply[8] of secondary raw materials for its own value chains. A central task in any case is to comply with the formal and complex reporting obligations towards the competent national authorities, enabling verification of compliance with EU requirements. This includes, not least, the submission of annual data.

The following section introduces a series of potential business models that could be deployed for this purpose. Their suitability is assessed from several perspectives.

To explore which business models could develop for the collection and treatment of electric-vehicle batteries and for sourcing secondary cobalt, lithium and nickel, information on the activities of various OEMs was reviewed and direct discussions were held with OEMs and other value-chain actors. On this basis, several possible models were developed. In doing so, the actors involved in each model, the fundamental flows of batteries and materials between them, and the respective advantages and disadvantages were taken into account. These models were subsequently discussed on 15 April 2025 in Berlin during a meeting of the project's advisory group, with the aim of clarifying further questions and strengthening the understanding of their practical feasibility. The subsections below present and discuss four potential business models that summarise the results of this process.

4.1 Recycling activities of vehicle manufacturers

Over recent years, several vehicle manufacturers (OEMs) have launched initiatives focusing on the recycling of traction batteries and the recovery of materials for these batteries. One reason for this is that large-scale recycling of traction batteries in Europe is not yet fully established as a functioning system (see chapter 3). By establishing their own recycling capacities, OEMs gain valuable technological and economic knowhow. At the same time, traction batteries account for a substantial share of a vehicle's total weight, meaning that their waste management plays an important role in meeting weight-based targets for reuse, recycling and recovery of end-of-life vehicles.[9] For many OEMs, such initiatives also represent another step in implementing their stated strategies to promote circularity in the automotive sector – strategies that are closely linked to corporate and sustainability objectives.

Given the limited capacities and throughputs of the first facilities developed and operated directly by OEMs (see chapter 3), the current motivation for OEMs to develop

8 For batteries, the focus here is on cobalt, lithium and/or nickel. Other secondary materials – such as steel – are not addressed within this study.

9 Article 7 of the ELV Directive [ELVD 2000] requires that at least 85 percent of a vehicle's weight be reused and/or recycled, and at least 95 percent of its weight be reused and/or recovered.

battery-recycling capabilities appears to lie less in securing secondary materials and more in building operational experience. That said, these facilities could also be used to recycle their own production scrap, thereby closing specific material loops internally.

In 2021, Volkswagen (VW) opened a pilot plant in Salzgitter to develop a battery-recycling process. The aim of the facility is to achieve a recycling efficiency of up to 90 percent when processing OEM batteries. The process involves mechanical treatment steps: the incoming batteries are first discharged and dismantled, during which aluminium from the housings, copper cables and plastics can be recovered. The remaining battery modules are then shredded under an inert atmosphere and subjected to various sorting and drying steps.
After several processing stages, black mass is produced containing graphite, lithium, cobalt, manganese and nickel. This material is sent to a partner facility for hydrometallurgical treatment, where the valuable materials are recovered without any loss of quality [VW Autobrander AG 2021]. The Salzgitter facility is initially designed to recycle up to 3,600 battery systems per annum, equivalent to around 1,500 tonnes. It processes end-of-life batteries and modules and could, in principle, be xpanded to handle much larger volumes as growing numbers of electric vehicles reach the end of their service life [Volkswagen AG 2024].

Mercedes-Benz has opened a battery-recycling plant in Kuppenheim in southern Germany that integrates mechanical and hydrometallurgical processing. According to the operator, the facility achieves a recovery rate of more than 96 percent and recovers lithium, cobalt and nickel. These materials can be used in the production of new batteries for the OEM's vehicles. In this respect, the facility covers both the mechanical stages — dismantling, discharging and shredding, sorting and drying — and the hydrometallurgical stages, in which lithium, cobalt and nickel are recovered in battery-grade quality. The plant has a capacity of 2,500 tonnes per annum; the recovered materials can be used to manufacture 50,000 modules for the OEM's electric vehicles [Mercedes-Benz 2024].

In addition to its recently announced partnership with SK Tes (see point 3.2.5), the BMW Group is developing a battery-recycling facility in the Lower Bavarian district of Straubing-Bogen, referred to as the Cell Recycling Competence Centre (CRCC). Construction of the facility is scheduled to begin in the second half of 2025. The plan is to recycle both battery-manufacturing scrap and complete battery cells directly. The direct-recycling process to be deployed is an in-house development by the BMW Group and represents a mechanical recycling approach. Battery-manufacturing scrap and battery cells are broken down into individual components that can then be used directly in the production of new batteries for the OEM's electric vehicles — without first having to be converted back into precursor materials. Once operational, the facility is expected to recycle a two-digit tonnage of battery-cell material per annum. According to BMW, the process is less energy-intensive than the more common chemical and thermal recycling methods. The development of the facility forms part of the BMW Group's battery-cell strategy, under which a production line for battery cells has already been established. This line will be directly connected to the new CRCC. The strategy is linked to the OEM's objective of strengthening the circularity of its operations [Marxt 2025].

Several years ago, Renault entered into a partnership with Veolia (dismantling and recycling of LIBs using a hydrometallurgical process) and Solvay (chemical recovery of battery materials) as part of its strategy to secure a stable supply of responsibly sourced battery materials. The aim of the cooperation was to recover high-purity metals that could be reused in new batteries. The project most recently entered an experimental phase involving the set-up of a pre-industrial demonstration facility [Renault Group 2021]. No further steps have since been undertaken [Scheuermann 2024].

Stellantis and Orano likewise launched a cooperation in 2023 focused on recycling end-of-life batteries from electric vehicles and production scrap from gigafactories in Europe and North America. The objective is to secure Stellantis access to recycled cobalt, nickel and lithium [Stellantis 2023].

In summary, many European OEMs are developing recycling capacities in one form or another in order to secure access to recycled materials in the future.
It remains open whether these facilities will remain small

in scale and primarily serve to generate insights into the interaction between battery design and recycling, or whether they will be expanded to achieve greater independence in the future procurement of battery materials. What is clear, however, is that OEMs recognise the need to act more proactively in order to meet the recycled-content requirements set out in the EU Battery Regulation.

This realisation is likely driven not only by regulatory developments within the EU. China has introduced similar policies, including an extended producer responsibility system that obliges manufacturers to collect end-of-life batteries. China has also implemented a platform that tracks batteries over their entire life cycle, thereby ensuring that they are collected at the end-of-life.
In addition, China has set voluntary recovery targets for lithium, cobalt, nickel and manganese – aligned with the objectives of the EU Battery Regulation [ICCT et al. 2023]. So far, OEMs have only established small-scale recycling facilities in individual Member States in which they operate. However, this analysis makes it clear that, in order to comply with the EU Battery Regulation and the forthcoming End-of-Life Vehicles Regulation, they will need to organise the take-back and recycling of batteries in every EU Member State. It appears unlikely that the same model will be applied across all countries.

This is in particular expected, as under article 61 para. 1 of the EU Battery Regulation, the Member States may decide to establish a producer responsibility organisation (PRO) as a mandatory collection and treatment system in their country. As this is an optional provision, it is unlikely that this rule will be implemented uniformly across Europe.

While it would be more efficient for OEMs to establish a single extended-producer-responsibility system across the entire EU, this appears unlikely at present given the multitude of existing systems for the treatment of portable batteries. It is far more likely that at least some of these existing systems will be further developed in order to expand their activities to include the recycling of traction batteries.

4.2 Business models for the collection and recycling of LIBs

Drawing from the insights into OEM activities and exchanges with the various stakeholder groups, four concepts for possible business models for organising the recycling of LIBs have been developed. These are presented and discussed below:

- Option 1: Vehicle manufacturer operates its own system (single-OEM)
- Option 2: Several vehicle manufacturers operate a joint system (multi-OEM)
- Option 3: Producer responsibility organisation operates a system without its own recycler (PRO without recycler)
- Option 4: Producer responsibility organisation operates a system with its own recycler (PRO with recycler)

Each model is explained below and illustrated in simplified form. Material flows consist either of end-of-life batteries or of materials recovered from battery waste management. These materials are either black mass, which still requires processing, or recovered battery-grade materials that can be used to manufacture new batteries.

Under Article 61 para. 1 of the Battery Regulation [BatReg 2023], batteries can be collected for processing and recycling from several sources. In addition to dismantlers or authorised treatment facilities (ATFs), battery distributors, refurbishers and repurposers, as well as municipal collection points, may also serve as collection points. In the models, ATF also refers both to dismantling operators that hold contracts with the respective OEM (authorised workshops) as well as to independent dismantlers. This applies all the more so as some Member States may, under Article 61 para. 1 of the Battery Regulation, decide to establish PROs as mandatory collection and treatment systems in their country.

Under Article 61 para. 2 of the Battery Regulation [BatReg 2023], take-back systems for electric-vehicle batteries of a specific OEM must cover the entire territory of a Member

State. It is therefore assumed that the business model chosen will operate in at least one Member State. Cross-border systems would be theoretically possible; however, exchanges with OEMs indicate that such systems are likely to remain the exception for the time being due to differing national requirements and varying market conditions.

The cross-border shipment of end-of-life batteries or the resulting waste fractions is further complicated by Regulation (EU) 2024/1157 on the shipment of waste. While certain wastes and waste fractions may be shipped between Member States for recovery (or disposal), such shipments must be traceable and are subject to prior notification and authorisation procedures. In other words: operators organising such transports must obtain the prior consent of all authorities in the countries concerned (country of origin, destination country and any transit countries) [EC 2024]. Since Regulation (EU) 2024/1157 was recently amended and most of the new provisions will only apply from May 2026, it is still too early to assess how these changes may affect the shipment of end-of-life batteries and associated waste fractions.

4.2.1 Option 1: Vehicle manufacturer operates its own system (single-OEM)

The first business model assumes that an OEM organises battery disposal independently (see figure 4-1). The OEM may either carry out the entire process itself – from collecting batteries from various dismantlers or collection points through to recycling (variant 1a) – or contract a third party to carry out the recycling (variant 1b); the latter is referred to as recycling as a service.

In a recycling-as-a-service arrangement, the service provider formally assumes full responsibility for collecting, dismantling and recycling the OEM's batteries. This relieves the OEM from contracting the various actors involved in the process (for example dismantlers or other collection points, logistics providers, recyclers). Although the same service provider may offer its services to other OEMs as well (and could benefit from economies of scale), the systems remain formally separate. All data must be managed separately. The formal reporting obligation to the competent national authority remains with the OEM in both variant 1a and variant 1b.

The single-OEM model is likely to be particularly relevant in countries where the OEM is well-established and highly familiar with the actors in the local value chain. The OEM may either operate its own recycling facility or commission recycling services as part of the system. This model offers the OEM the highest degree of control over the system and its functioning – including the flows of end-of-life batteries and the recovered materials. It also allows for optimisation of packaging and logistics. At the same time, this model is expected to entail the greatest administrative burden for the OEM in terms of contracting, liability issues, and fulfilling all reporting and legal obligations independently.

While system transparency may be advantageous for the OEM, this model is likely to generate the highest cost per battery (or per unit of recycled material). As a single-OEM system, it is expected to benefit least from economies of scale.

If an external recycler is commissioned (variant 1b), it remains uncertain whether that recycler would process only the OEM's[10] batteries or also those of competitors – and what this would imply for the materials ultimately made available to the OEM.

10 Discussions with various stakeholders indicate that questions of ownership are not straightforward. In the authors' view, regardless of the OEM's extended producer responsibility (EPR), the ownership of a vehicle and all of its components passes to the purchaser when the vehicle is sold. Under the current legal framework, a consumer handing over a vehicle at end-of-life to an ATF typically receives compensation from the ATF, provided that no parts are missing. The ATF is then obliged to remove certain materials or components before selling the depolluted body shell to a shredder, while it may voluntarily remove additional components if a profit is likely. In this sense, ownership of the vehicle and its parts – including the traction battery – transfers from one actor to the next along the value chain. One exception in the past concerned certain Renault models for which the traction battery was leased to the vehicle purchaser; this leasing model has since been discontinued. Whenever this report refers to OEM batteries or a given OEM's batteries, it does not imply any ownership right held by the OEM. Rather, it refers simply to traction batteries removed from vehicle models of that OEM.

This may depend on the relationship between the volume of batteries of that OEM to be collected and treated in a given Member State and the recycler's available treatment capacity. While so-called spokes – facilities producing black mass – are now relatively widespread, there is currently only a limited number of specialised facilities in the EU for black-mass processing (hubs), and these still operate with relatively small capacities. External facilities are therefore likely to process batteries from multiple OEMs.

This means that, at the current early stage of the circular economy for traction batteries in the EU, an OEM may not necessarily be able to access either the batteries it originally placed on the market or the materials recovered from those batteries. This could also result in higher effort in the dismantling phase – due to the need for highly varied dismantling processes for the diverse EV batteries produced by different OEMs – and[11] in the downstream, treatment of a wide range of battery modules and cells during recycling.

The Battery Regulation stipulates that, in the case of a PRO, participation fees should be structured according to certain ecological criteria (eco-modulation) in order to incentivise improvements in these areas. Examples for criteria include recyclability or the CO_2 footprint. Since PROs do not play a role in the single-OEM model, no eco-modulation can be introduced here, which may be viewed as a drawback of this model. On the other hand, OEMs can be expected to have an inherent incentive to optimise at least certain aspects of their batteries when these batteries are returned to them for recycling. Even if the OEM does not carry out recycling itself, the market can be expected to regulate such incentives. Table 4-1 summarises the strengths, weaknesses, opportunities and risks of the single-OEM model.

11 The battery modules and cells used by different OEMs may vary considerably in terms of chemistry and individual components, and recycling processes for heterogeneous batteries can therefore be more complex than for the more uniform or at least similar modules or cells of a single OEM.

4.2.2 Option 2: Several vehicle manufacturers operate a joint system (multi-OEM)

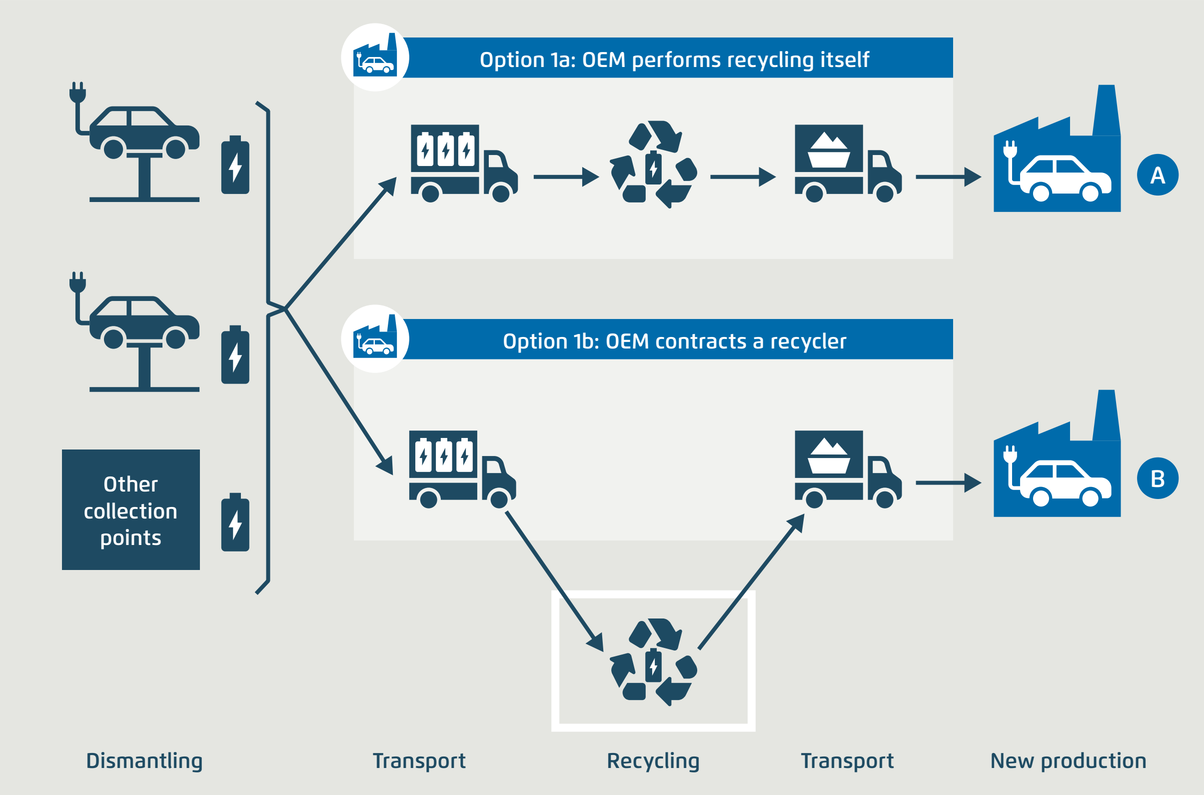
The second business model closely resembles the first, except that it is developed and administered by several OEMs rather than by a single manufacturer (see figure 4-2). Discussions with stakeholders indicated that OEMs operating entirely independently of one another would only participate in such a model if it were run by an independent third party. For legal reasons, several companies that do not belong to the same corporate group cannot jointly operate a system, as this would grant them access to information about the business volumes of competitors, potentially raising antitrust concerns. Stakeholders pointed to the Norwegian recycling systems as a practical example of such an approach: there, the association of passenger car importers serves as a neutral intermediary between OEMs and in this way ensures the system's legal compliance.

Table 4-2 summarises the strengths, weaknesses, opportunities and risks of the multi-OEM model. Because several OEMs participate, this model is expected to offer advantages over single-OEM systems. In particular, the volumes of batteries and recovered materials handled would be larger and could lead to lower unit costs due to economies of scale.

One could argue that a business model involving a PRO capable of serving all OEMs (see chapter4.2.3) would be the preferred solution, precisely because of these economies of scale. However, the multi-OEM model may still offer benefits, as the recovered quantities are shared only among the participating OEMs and not across the entire market.

Stakeholders also discussed how OEMs participating in such a model could demonstrate compliance with the recycled-content targets for their batteries. Verification must take place along the value chain. While the quantity of recycled material is known, the key question is how to allocate that material to specific batteries at the start of the process in order to attribute the correct amount of recycled material to each participating manufacturer. In practice, this should not pose any insurmountable challenges, as recyclers routinely analyse their input streams for raw-material content for economic reasons. Stakeholders therefore considered this issue manageable – certainly not a problem unique to this

Battery recycling, option 1: Vehicle manufacturer operates its own system (single OEM) Figure 4-1



Agora Verkehrswende (2025) | OEM = vehicle manufacturer (original equipment manufacturer); illustration based on Oeko-Institut drafts.

model. The Norwegian system already mentioned was cited as a functioning real-world example.

4.2.3 Option 3: Producer responsibility organisation operates a system without its own recycler (PRO without recycler)

In the third business model, one OEM – or several OEMs – commissions a producer responsibility organisation (PRO) to operate the system (see figure 4-3). A PRO is an entity established by manufacturers or local authorities to fulfil their statutory waste-management obligations, meaning the collection, recycling and disposal of waste arising from the manufacturers' products. PROs operate independently of the companies that created them and ensure compliance with the laws and regulations governing waste. They may act for a single company or for multiple companies within a product group.

In addition to ensuring legal compliance, their tasks include reducing costs for participating companies or local authorities, raising consumer awareness, reporting on waste-management outcomes, and advising on waste prevention and ways to improve product recyclability [RLG 2025b].

Stakeholder discussions also highlighted that PROs are generally – though not necessarily – non-profit organisations. This was noted as a difference compared with the multi-OEM model (see chapter 4.2.2), where the functions are carried out by an external operator (for example, the passenger-car importers' association in Norway).

In the PRO-without-recycler model described here, the OEM (or multiple OEMs) either establishes a new PRO or appoints an existing one to assume the extended producer-responsibility obligations on behalf of that OEM (or those OEMs). In other words: the PRO organises the collection, logistics, treatment and recovery of waste and fulfils the additional statutory obligations associated with extended producer responsibility.

For traction batteries from electric vehicles, this model assumes that the PRO organises the collection of end-of-life batteries from multiple authorised treatment facilities (ATFs) and other collection points, transports them via a dedicated logistics system to recyclers for black-mass production and then arranges their subsequent refining into battery-grade recovered materials. The recovered materials are then allocated to the OEMs participating in the system. The PRO's services are remunerated in accordance with the contractual arrangements made with the OEMs. In this model, the recycling plant is not an integrated component of the PRO; accordingly, recyclers remain free to cooperate with other parties while also working with the PRO. As outlined above, the PRO's system may provide OEMs either with recovered materials[12] or – in the case of an OEM operating its own recycling facility – with end-of-life batteries.

The PRO organises the system in both logistical and contractual terms. This means that an OEM only needs to conclude a single contract with the PRO to fulfil its obligations, while the PRO manages all contractual arrangements with the other actors in the system (such as dismantlers and collection points, transport and storage providers, and recyclers). This relieves the OEM of the substantial administrative effort involved in handling contractual relationships with all participating actors. At the same time, the OEM generally pays the PRO a fee for the waste collected and treated (per end-of-life battery or per tonne of batteries). Through the PRO, the OEM is also likely to gain access to a far larger network of collection points than under the single-OEM model, and thus to a larger pool of end-of-life batteries.

However, because several OEMs usually work with the same PRO, the recovered materials must be shared among all participating OEMs. Depending on how the system is organised, this may mean that an OEM receives fewer recovered materials than originally returned from its own batteries via the system. There is also a possibility that an OEM feeding comparatively high-quality

12 The OEM does not necessarily receive the recovered mate-rial physically; instead, it will often be the case that the external recycler contracted by the PRO transfers volumes of recovered material – which can be credited towards the OEM's regulatory obligations – to the OEM's relevant partners in the battery value chain.

SWOT analysis for business model 1: Single-OEM — Table 4-1

STRENGTHS	WEAKNESSES
• Greater transparency and control for the OEM over the system with respect to actual costs and the flows of batteries and materials.	• Expected to have the highest cost per battery or per unit of material (for example logistics costs, contractual expenditures). • The OEM is responsible for fulfilling the reporting obligations at Member State level.
OPPORTUNITIES	**RISKS**
• The ability to source OEM-owned batteries may enable more efficient recycling, with an appropriate material mix being recovered and directed straight into the production of new batteries. • Optimisation of packaging and logistics is potentially possible, including through direct access to data on battery condition.	• The OEM remains responsible for the system but does not have direct control over processes carried out by third parties (for example logistics providers or external recycling companies). • The generally limited size of the system can be considered a risk insofar as it may not always be sufficient to ensure that the OEM has access to adequate quantities of batteries or materials.

Agora Verkehrswende (2025) | Source: Compiled by Oeko-Institut.

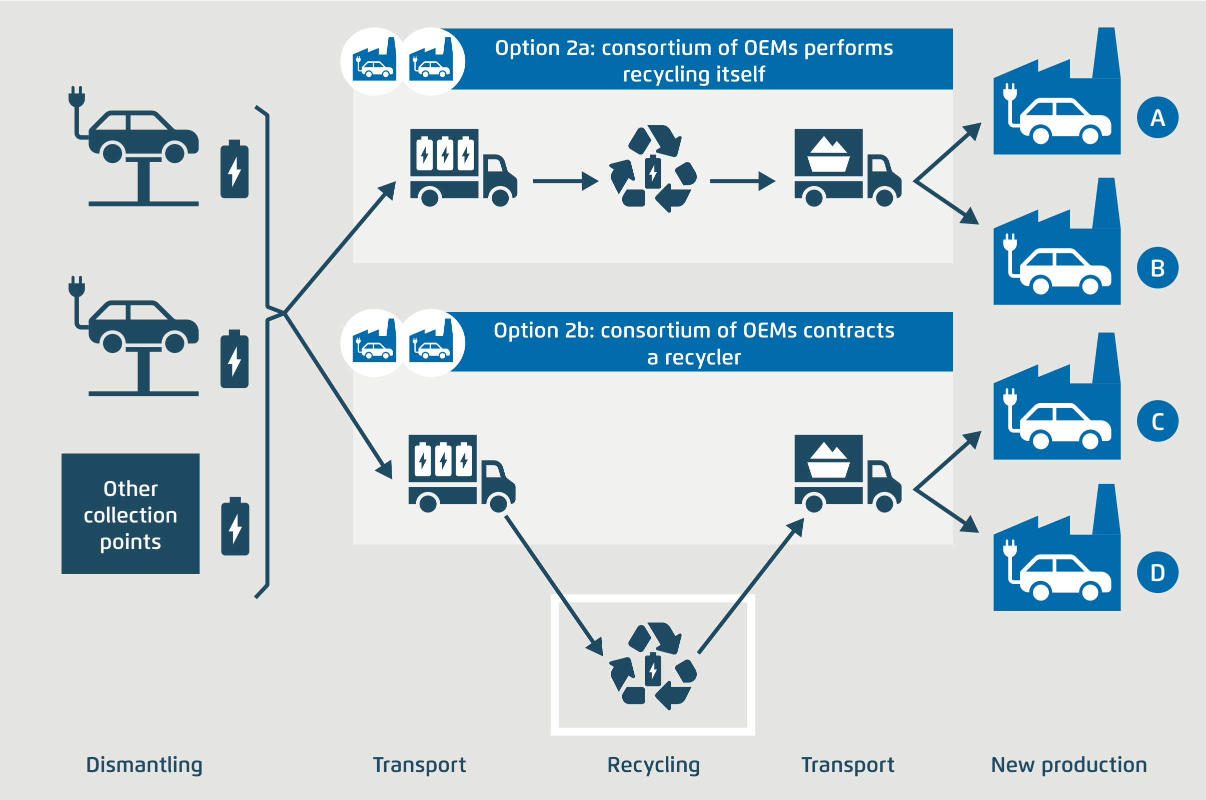
batteries into the system could, in certain circumstances, be disadvantaged vis-à-vis an OEM supplying batteries of lower quality. In addition, the OEM may receive a mix of materials recovered from all participating OEMs' batteries, rather than material specifically sourced from its own batteries.[13]

This could, however, differ in a system design where the PRO supplies OEMs directly with batteries or battery materials. In such a case, the OEM would be expected to use the PRO to secure targeted access to the batteries collected from its own vehicles. The PRO is responsible for the statutory reporting obligations and also for ensuring that the system functions properly. This does, however, require participating OEMs to relinquish some degree of transparency and direct operational control.

This model becomes particularly relevant once a country mandates the use of a PRO (see the beginning of chapter 4). Beyond this, discussions with OEMs indicated that the model is especially pertinent in countries where OEMs are unfamiliar with the actors in the local value chain. For electric-vehicle batteries, this could apply, for example, to new market entrants from Asia that have only recently entered the EU market and are not yet well established. The model may also be relevant for EU-based OEMs in

13 It should be noted that, in practice, reporting is not expected to be based on the precise composition of an OEM's batteries or on the exact recoverable fractions. Rather, these uncertainties are factored into negotiations between OEMs and PROs when determining both the per-battery fee payable by OEMs and the quantities of recovered materials to which the OEMs will be entitled.

Battery recycling, option 2: Several vehicle manufacturers operate a joint system (multi-OEM) — Figure 4-2



Agora Verkehrswende (2025) | OEM = vehicle manufacturer (original equipment manufacturer); illustration based on Oeko-Institut drafts.

SWOT analysis for business model 2: Multi-OEM — Table 4-2

STRENGTHS	WEAKNESSES
• Greater transparency and control over the system for OEMs with respect to actual costs and the flows of batteries and materials. • This business model enables economies of scale; in other words, lower costs per unit.	• Expected to have higher costs per battery or per unit of material (for example logistics costs, contractual expenditures). • The OEMs are responsible for fulfilling the reporting obligations at Member State level.
OPPORTUNITIES	**RISKS**
• The ability to source OEM-owned batteries may enable more efficient recycling, with an appropriate material mix being recovered and directed straight into the production of new batteries. • Optimisation of packaging and logistics is potentially possible, including through direct access to data on battery condition.	• The OEMs remain responsible for the system but do not have direct control over the processes carried out by third parties (for example logistics providers or external recycling companies). • The business model is considered legally risky, if not impossible, for brands that do not belong to the same corporate group, unless a neutral third party acts as an intermediary between the members (as is the case in Norway).

Agora Verkehrswende (2025) | | Source: Compiled by Oeko-Institut.

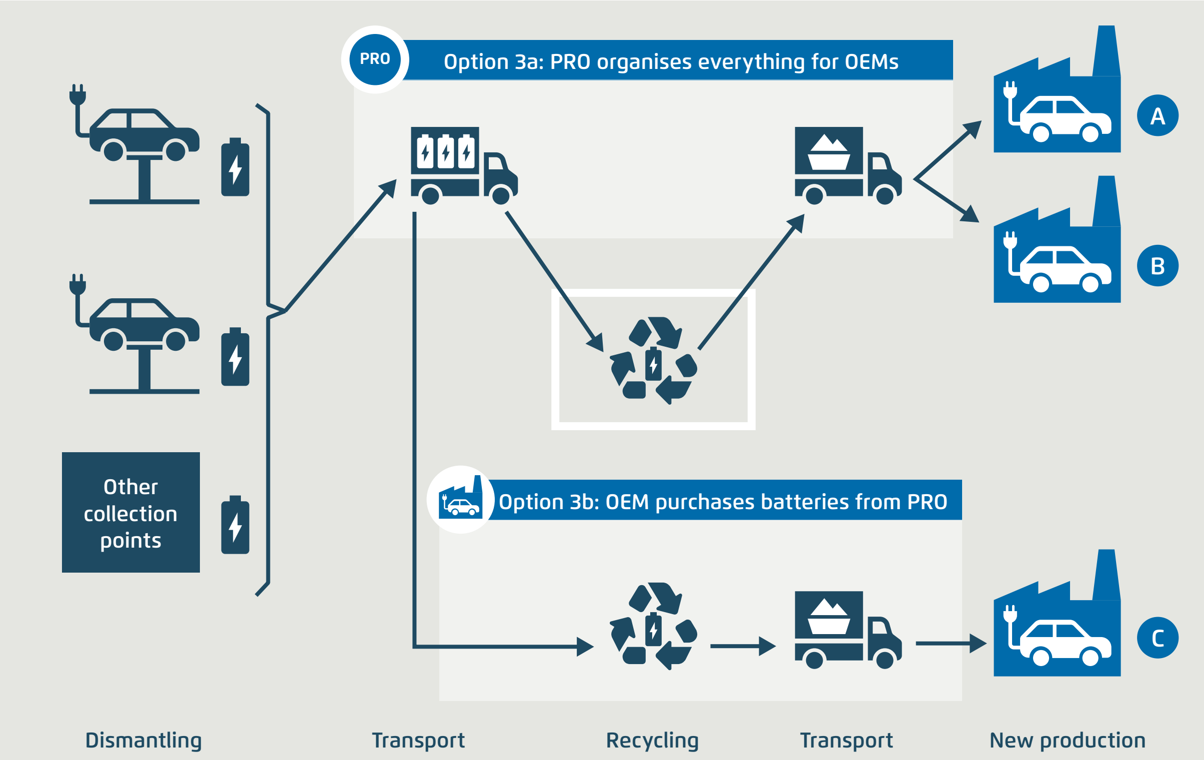
countries where they have only a limited presence. If the PRO also provides collection and transport services for the batteries of the respective OEM, this could help the OEM to collect its own battery models from the market and potentially give it access to a far larger number of collection points than if a vehicle manufacturer were to operate its own system (see the single-OEM model). Stakeholders also noted that this system may be particularly attractive for importers.

In discussions with stakeholders, some expressed concern that involving a third party in the system – in this case the PRO – could make access to recovered materials more difficult and lead to an unfair distribution of materials. This could relate to the quantity of batteries collected or to their quality. However, not all stakeholders shared this view. Others pointed out that, while the PRO is responsible for organising the system, it does not have direct control over the quality of the recovered materials.

Experience from other extended producer responsibility systems shows that contracts between PROs and recycling companies may also cover the quality of the delivered recovered materials, which could, over time, lead to an increase in material quality. Various scenarios are conceivable in this regard, both technical and contractual. OEMs and PROs can therefore set clear quality requirements for recycled materials in their contractual arrangements. Many recycling facilities are capable of supplying materials of different grades, which is reflected in different price levels. The more decisive question, however, is whether sufficient recycled material will be available in Europe over the coming years at all. Although an increasing number of spoke facilities (for the production of black mass) are being established, only a few hubs (for the production of battery-grade materials) are currently operating in the EU, and the development of additional hubs with relevant capacities in the near future remains uncertain (see chapter 3).

In the stakeholder discussions, a JRC study was referenced that examined verification methods for compliance with the secondary-material content targets set out in the Battery Regulation. The methods assessed in the study are based primarily on mass-balance accounting. Stakeholders criticised these proposed models for their reliance on mass balance, arguing that the approach could allow producers to claim credit for material not actually contained in a battery – and vice versa. A position paper by several environmental organisations [DUH et al., 2025] provides a concrete example: an OEM producing for both EU and non-EU markets could, through permissible allocation rules, report higher recycling shares than are physically present in the product – for instance by assigning

Battery recycling, option 3: Producer responsibility organisation (PRO) operates the system without its own recycler (PRO without recycler) Figure 4-3



Agora Verkehrswende (2025) | vehicle manufacturer (original equipment manufacturer); PRO = producer responsibility organisation; illustration based on Oeko-Institut drafts.

a zero-percent share to batteries destined for non-EU countries while attributing a higher-than-actual share to batteries placed on the EU market. Although this point is not explicitly raised in the paper, the underlying argument suggests a concern that manufacturers might meet their recycling-content targets more easily by concentrating the accounted for recycled fractions of their entire production in batteries destined for the EU market, thereby reducing any real incentive to increase the overall use of recycled materials. The various aspects of the PRO-without-recycler model are summarised in table 4-3.

4.2.4 Option 4: Producer responsibility organisation operates a system with its own recycler (PRO with recycler)

The fourth business model differs from the third in one decisive respect: the recycler is directly integrated into the system (see figure 4-4). This may take the form of a time-limited contract with a recycling company to ensure that all end products (or a defined share of them) are handed over to the PRO and subsequently allocated to the participating OEMs.

An alternative raised in stakeholder discussions is that the PRO could itself initiate and finance the construction of a recycling facility. While this could in principle be feasible for a plant producing black mass, the capital expenditure required to establish a refining facility for battery-grade materials is significantly higher. For this reason, many stakeholders view this model variant as relatively unlikely. Stakeholders participating in the advisory group considered the option of a PRO initiating and financing its own recycling plant to be improbable.[14]

14 It is conceivable that, in 10 to 15 years – assuming a steep increase in electromobility – the significantly higher

SWOT analysis for business model 3: PRO without recycler — Table 4-3

STRENGTHS	WEAKNESSES
• Depending on the number of participating OEMs, lower costs per battery or per unit of material (for example logistics costs, contractual expenditures) can be expected for the OEM. • Particularly attractive for OEMs that are not familiar with the domestic value chain, as well as for new OEMs and importers. • The PRO is responsible for the system and takes over the reporting obligations.	• As PROs collect a mix of batteries for which they do not necessarily know the precise composition, and this mixed battery stream is then passed on to the external recycler, this may negatively affect the efficiency of the recycling process and the economic performance of the PRO system.
OPPORTUNITIES	**RISKS**
• The possibility of sourcing OEM-owned batteries may give OEMs an advantage in countries where they operate their own recycling facilities. • As the PRO is assumed to hold a strong position in its domestic market, it may, over time, pay more for higher-quality output materials, which would help optimise the value chain.	• The distribution of recovered materials among the participating OEMs may differ from the materials that could be recovered from the batteries collected by any given OEM. • As recycling takes place outside the system, a PRO may at times face competition from other PROs or OEMs, which can affect the volume of materials acquired for system members.

Agora Verkehrswende (2025) | Source: Compiled by Oeko-Institut.

At the same time, it is assumed that the direct integration of the recycler could offer advantages in terms of lower costs per battery or per unit of recovered material. It could also reduce risks linked to the recycler's cooperation with third parties (see table 4-3). However, stakeholders also cautioned that embedding a recycler within the organisational structure could create a dominant market position, potentially jeopardising fair competition.

4.3 Additional relevant aspects

As noted in the model descriptions, it remains uncertain whether external recyclers – both black-mass producers (spokes) and refiners (hubs) – would process batteries from a single OEM or from multiple OEMs. This will largely depend on the balance between the volumes of end-of-life batteries requiring treatment and the available processing capacities.
Stakeholders also raised the question of how important it is for an OEM to secure targeted access to materials originating specifically from its own batteries. From the perspective of external recyclers, it is doubtful whether OEM-specific material streams could be segregated within the system – even with the support of the planned digital battery passport, which may make it possible to identify particular battery models and brands.

Nonetheless, the available evidence from OEM-operated recycling facilities suggests that certain efficiencies can be achieved through OEM-specific recycling. OEMs possess detailed knowledge of the design and disassembly of their own batteries, as well as of material combinations that may be particularly well suited for direct reuse in new batteries.

In such cases, it may not be necessary to recover individual elements, provided that the amounts of material reused in producing new batteries can be quantified into the elements relevant for the recycling-content targets (for reporting purposes). Stakeholders also

return volumes of end-of-life batteries might make this option more realistic than it appears today, driven by economies of scale and a reduced risk of under-utilising a large-capacity facility.

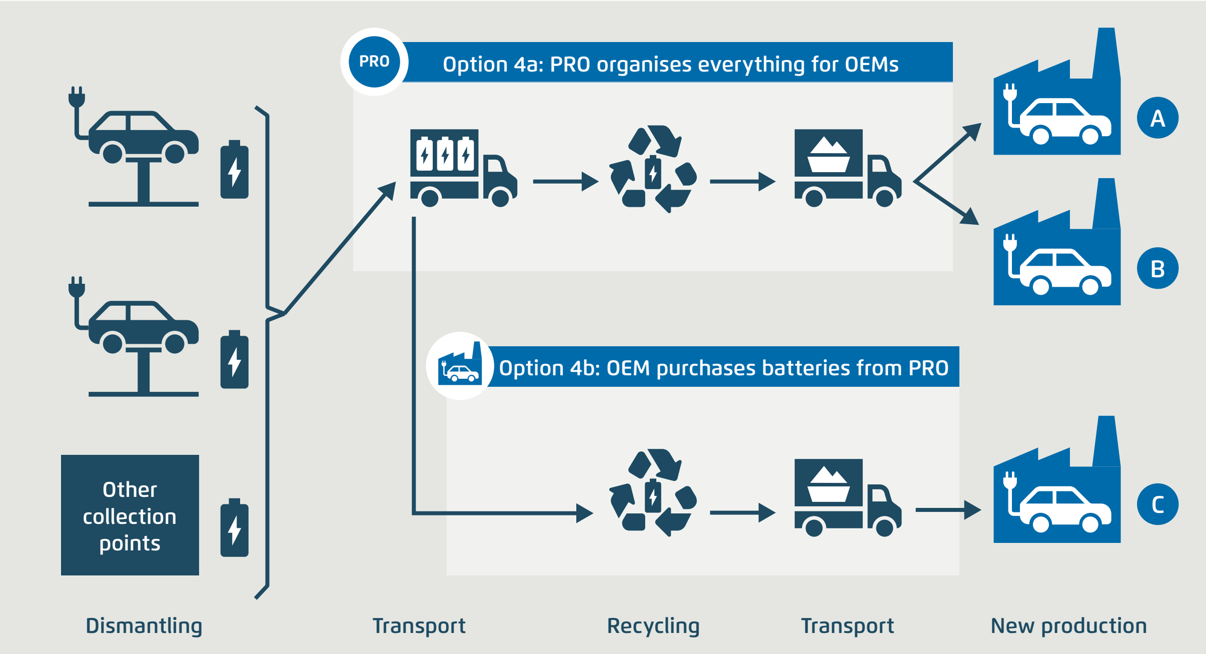
emphasised the time lapse between placing an electric-vehicle traction battery on the market and the end of its service life. Given the rapid pace of technological development, it is likely that battery chemistries – and thus the relevance of recovered materials for new battery production – will have changed by the time today's batteries reach the recycling stage. In other words: significant uncertainty remains.

It is currently unclear whether OEM-operated recycling will remain confined to small-scale facilities or whether it may eventually expand to the recycling of larger volumes of OEM end-of-life batteries in individual Member States. This will depend in part on the future development of additional hubs and integrated spoke-and-hub systems in the EU. If the expansion of recycling capacities (particularly hubs) progresses too slowly, OEMs may be incentivised to increase their own recycling capacity or adopt strategies based on procuring recycled materials or purchasing battery cells with the required recycled content. These developments will, in turn, depend on the incentives adopted at EU level to support battery recycling.

PROs considering the development of a collection and treatment system in a particular Member State should, at this stage, consult local OEMs to determine whether they prefer to receive recycled materials via the system or to maintain direct access to end-of-life batteries collected independently.

Experience from other waste streams shows that some tyre-retreading companies that collect and sort tyre casings offer tyre manufacturers the option of receiving casings of their own brands. This provides an additional revenue stream for the retreader while supporting the targeted return of brand-specific carcasses to manufacturers with their own retreading facilities. In other words: using the logistics system of a PRO to supply brand-specific batteries to a given OEM may make it possible to include more OEMs in the system without limiting their choice of recycling approach.

Battery recycling, option 4: Producer responsibility organisation operates the system with its own recycler (PRO with recycler) — Figure 4-4



Agora Verkehrswende (2025) | OEM = vehicle manufacturer (original equipment manufacturer); PRO = producer responsibility organisation; illustration based on Oeko-Institut drafts.

Given that the recycling facilities operated by Volkswagen and Mercedes-Benz reportedly employ more energy-efficient processes than standard hydrometallurgical methods [Volkswagen AG 2024; Mercedes-Benz 2024], this option may gain importance in the future – particularly as OEMs face growing pressure to reduce emissions.

If a PRO becomes established in a Member State while individual OEMs have opted for OEM-specific models (variant 1: single-OEM), this could make it more difficult for those OEMs to secure their own batteries for treatment and recycling, affecting cost structures and the economic efficiency of OEM-specific systems.
This is based on the assumption that a PRO can rely on a more extensive collection network – with a greater number of authorised treatment facilities (ATFs) and collection points – and on downstream operators. The PRO may also collect batteries from all OEMs without differentiating by brand in order to guarantee minimum delivery volumes of recycled content to its member OEMs. This could mean that individually organised OEMs have reduced access to their own batteries, with consequences for the economic viability of their systems.

Furthermore, the fact that the Battery Regulation permits the delivery of an electric vehicle to an ATF without its traction battery may further limit the availability of end-of-life batteries for recycling – with potential implications for the financial feasibility of both OEM- and PRO-based systems. It also remains unclear how many batteries will be removed from vehicles at the end of their service life for second-life applications.
The future development of this practice is uncertain and represents an additional variable for the sector's evolution.
Finally, a particularly relevant aspect must be emphasised: the dynamic changes in LIB composition, especially with regard to cathode-active materials. Over the next 10 to 15 years, the share of LFP batteries in new vehicles is expected to increase significantly in the EU, replacing today's still-dominant NMC batteries (see chapter 3). LFP batteries tend to offer cost advantages during production because they contain

SWOT analysis for business model 4: PRO with recycler — Table 4-4

STRENGTHS	WEAKNESSES
• Depending on the number of participating OEMs, this model is expected to deliver the lowest costs per battery or per unit of material (for example logistics costs, contractual expenditures) for the OEM. • Particularly attractive for OEMs that are not familiar with the domestic value chain, as well as for new OEMs and importers. • The PRO is responsible for the system and takes over the reporting obligations. • Greater security of supply for recovered materials through direct contractual relationships with the recycler.	• The distribution of recovered materials is likely to take place at the level of the individual materials, meaning that the recycling efficiency may be lower than in the OEM's own recycling facilities.
OPPORTUNITIES	**RISKS**
• The possibility of sourcing OEM-owned batteries may give OEMs an advantage in countries where they operate their own recycling facilities. • As the PRO is expected to hold a strong market position in the country in which it operates, it may, over time, pay more for higher-quality output materials, thereby increasing incentives along the value chain. In other words, this could accelerate market development towards more efficient processes.	• The distribution of recovered materials among the par-ticipating OEMs may differ from the materials that could be recovered from the batteries collected by any given OEM. • Under certain conditions, including the recycler within the system could lead to unfair competition and thus to legal issues. It may also influence market prices.

Agora Verkehrswende (2025) | Source: Compiled by Oeko-Institut.

no nickel or cobalt. When these batteries are recycled, however, this production advantage becomes a disadvantage for the actors concerned, as the revenues from recovered materials are significantly lower for LFP batteries. The implication is clear: regardless of which of the four business models is considered, the entire circular system will have to operate with ever-increasing efficiency to counteract the long-term decline in revenues from secondary raw materials. Systems that can unlock greater economies of scale are likely to offer the strongest advantages in the future.

5 | Conclusions

Building on the preceding analytical work conducted in this study — together with extensive dialogue with stakeholders including OEMs, recycling companies, industry associations and non-governmental organisations — this chapter summarises a number of conclusions and sets out recommendations.

5.1 Market overview and value chains

- The foreseeable continued growth of electromobility in the EU means that by 2035 the annual battery demand for new vehicles is expected to reach around 1,200 GWh — roughly six times the demand in 2025 — irrespective of the three scenarios assessed in this project.
- With rising battery demand, a significant increase in demand for key materials such as lithium, nickel, cobalt and graphite is very likely by 2035.
- The increasing share of LFP batteries in the mix — for passenger cars, light commercial vehicles and heavy-duty vehicles — will temper the rise in demand particularly for cobalt, and to a lesser extent for nickel. For graphite and lithium, the effect will be marginal.
- By optimising the circular flow of the steadily increasing volumes of end-of-life LIB within the EU-27, a significant secondary-raw-material potential will emerge over the next 10 to 15 years. By 2040, this potential ranges between 25 and 50 percent for lithium and nickel and exceeds 60 percent for cobalt. These figures underline the strategic relevance and necessity of efficient recycling systems for the EU.
- However, Europe still exhibits significant gaps across the individual stages of the LIB value chain — from raw material extraction to cathode-active-material production, cell manufacturing and the industrial recycling of black mass.
- European manufacturers of traction batteries face intense competitive pressure from dominant Asian players. To secure access to value chains for key battery raw materials at competitive cost and to close material loops within the EU, optimised recycling processes and appropriate business models are essential.
- The EU must also ensure that valuable intermediate products — especially black mass — are not lost through undesirable exports, using regulatory measures that support the aims of the EU Battery Regulation and the Critical Raw Materials Act. At the same time, EU funding instruments must strategically support the substantial investments needed to build facilities that truly close battery loops, offering investors a degree of risk mitigation.

5.2 Circularity of LIB

Chapter 4 set out four variants of business models for organising the recycling of LIB in the EU and discussed their potential advantages and disadvantages. Variants 1 and 2 describe systems operated by OEMs themselves. Variants 3 and 4 describe systems in which one or several OEMs transfer the full responsibility for end-of-life LIB flows to a producer responsibility organisation (PRO). Based on discussions with the advisory group and interviews with OEMs, among others, the following conclusions can be drawn:

- A business model covering many Member States — or even the entire EU-27 — is unanimously considered unrealistic. For larger Member States, models covering one or a small group of countries are far more plausible.
- However, the present fragmentation into up to 27 separate systems significantly limits the realisation of crucial economies of scale — which are essential for building efficient recycling cycles in the EU.
- None of the four business models offers only advantages or only disadvantages. It is more likely that OEMs will prefer different models depending on the Member State and their market relevance there. Experts emphasise that, for both OEMs and PROs, strong networks and in-depth knowledge of national circular-economy actors are decisive factors for success.
- Where national legislation requires the use of PROs, variants 1 and 2 (OEM-operated systems) are ruled out in those countries.
- OEM market presence varies considerably across the EU. These differences will influence OEM decisions when selecting suitable business models. Regardless of the differences between the four models, all

systems will need to become more efficient in the future to counter the potentially declining value of recovered materials (due to the rising share of LFP, among other factors).

The following OEM recommendations can be made with regard to business models:

- OEMs that have only a limited presence in certain Member States – and correspondingly little insight into, or experience with, the local circular-economy actors (dismantlers, logistics providers, recyclers) and associated value chains – would generally be ill advised to operate their own systems in those countries. The risk of logistical overload – and in the worst case, failure to meet extended producer-responsibility obligations – is significant. Discussions also indicated that importers or new market entrants (i.e. OEMs recently entering the EU market) are likely to be well advised to appoint a suitable PRO in such countries.
- OEMs must become thoroughly familiar with the EU regulatory framework (EU Battery Regulation, the ongoing revision of the EU End-of-Life Vehicle Directive, etc.) and with national implementation approaches, including whether PROs are mandatory in certain countries.
- For larger OEMs with a strong market presence and well-established networks in the circular-economy sector of the relevant Member States, it may be sensible – given the still very early stage of the end-of-life LIB cycle – to begin with an OEM-run system in order to build valuable internal know-how. At the same time, these OEMs should factor the development of electromobility and the rapidly increasing volumes of end-of-life LIB into their strategic planning. In this early phase, with still very limited return flows of LIB, an OEM-operated system can in some cases be managed with comparatively modest logistical effort. But with a tenfold, hundredfold or even greater increase in return volumes, logistical complexity will rise sharply. In such circumstances, contracting an appropriate PRO may become a sound option
- When opting for variant 2 (multi-OEM), the participating OEMs must strictly observe antitrust requirements.

PRO

The following PROs recommendations can be made with regard to business models:

- PROs should initially offer their business models in Member States where they already have excellent networks and extensive experience with local circular-economy actors.
- PROs can develop valuable know-how in the first Member States in which they operate, particularly with regard to the specific requirements of recycling end-of-life LIB from the vehicle sector. These insights can subsequently be applied in other Member States. It is also important to recognise that end-of-life LIB from vehicles entail logistical requirements that differ markedly from those of, for example, end-of-life LIB that are integrated in appliances.
- For PROs, it is very likely to be attractive to offer their services prioritising OEMs that enter a market as importers or new market participants, thereby enabling these manufacturers to reliably meet their extended producer-responsibility obligations in the respective Member States.

§

The following recommendations can be given to policymakers to help strengthen LIB value chains and close battery loops in the EU:

- The objectives of the Critical Raw Materials Act (CRMA) aimed at enhancing the resilience of European value chains must be underpinned by robust operational measures for the key raw materials, in-termediate products, components and strategic goods relevant to LIB considered in this study. The selection of the first strategic projects under the CRMA in spring 2025 covers numerous initiatives across the lithium-ion battery value chain. These projects must be accompanied by ongoing support and monitoring to ensure that stated objectives translate into measurable outcomes.
- In Germany, the funding instruments of the National Raw Materials Fund should be used in a targeted manner to strengthen the domestic LIB value chain (BMWI 2024).
- The EU, the German Federal Government and the governments of the other Member States must pursue an integrated strategy for developing stable value chains. Weaknesses must be identified promptly

through continuous monitoring, and measures to address them must be initiated without delay. Strengthening all stages of the value chain is essential if these chains are to contribute meaningfully to the EU's resilience. Merely extracting and processing battery raw materials within the EU will not unlock the full potential unless European companies also establish gigafactories for the production of lithium-ion cells within the EU.
- The targets set out in the EU Battery Regulation must be monitored continuously by the EU and its Member States, and their implementation must be demanded by market participants.
- The export of intermediate products such as black mass — materials that are essential for resilient value chains — must be robustly prevented through appro-priate measures, including the consistent application of newly introduced waste-classification codes.
- Member States that demonstrably fail to meet their obligations in these areas (for example with regard to export restrictions to non-OECD countries), thereby weakening European interests, must be guided back onto the EU's agreed trajectory through the sanctions available and permitted at EU level.

5.3 Discussion and further considerations

The analytical framework applied to the business models examined in this study is idealised, as it assumes a closed system: vehicles placed on the EU market are sold to dismantlers within the EU, and the materials they contain are ultimately recycled within the EU as well. While this assumption is useful for identifying the advantages and disadvantages of the different business models, closing material loops in practice is far more complex. Moreover, the entire field of traction batteries is evolving extremely rapidly.

On the one hand, the material flows associated with used and end-of-life vehicles are global — including the illegal shipment of end-of-life vehicles to countries outside the EU. The export of used electric vehicles would permanently remove these raw materials from the European circular economy. The legal provisions governing the export of used vehicles are currently being revised and may be tightened in the future. However, the export of used electric vehicles — which remains very limited at present — continues to raise research and policy questions, particularly with regard to destination countries such as those in Africa. In this context, the political goals and instruments pursued by these African partner countries to decarbonise their transport sectors must also be taken into account [Agora Verkehrswende 2025].

At the same time, the overall system is subject to considerable dynamics. Ongoing developments in battery chemistries and the long investment horizons required for the economically viable operation of recycling plants create uncertainties regarding the specific technical requirements for recycling facilities and the economic viability of recycling.
This study underscores the need for continuous and intensified exchange and dialogue along the entire value chain of battery recycling, to ensure that stakeholders can respond in a timely and appropriate manner to the inherent and dynamic developments in the system.

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Lithium content of various lithium compounds occurring in lithium extraction — Table 7-1

Name	Lithium carbonate (LCE)	Lithium hydroxide	Lithium hydroxide monohydrate
Chemical formula	Li_2CO_3	LiOH	$LiOH*H_2O$
Conversion factor Li	5,32	3,42	6,06

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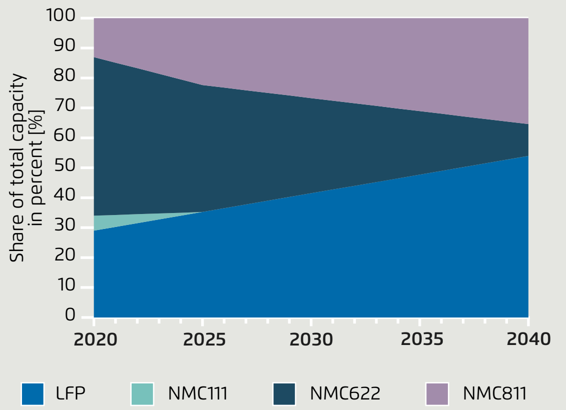
Scenario assumptions for light commercial vehicles (LCV) in the NMC scenario, 2020–2040 — Figure 7-1a



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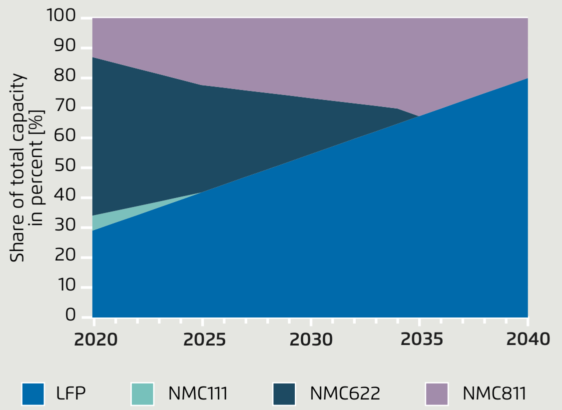
Scenario assumptions for light commercial vehicles (LCV) in the LFP scenario, 2020–2040 — Figure 7-1b



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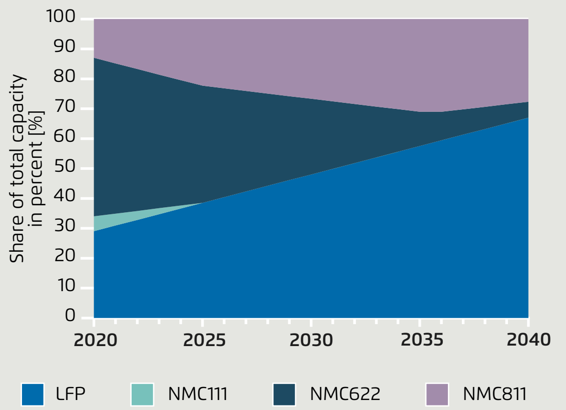
Scenario assumptions for light commercial vehicles (LCV) in the AB scenario, 2020–2040 — Figure 7-1c



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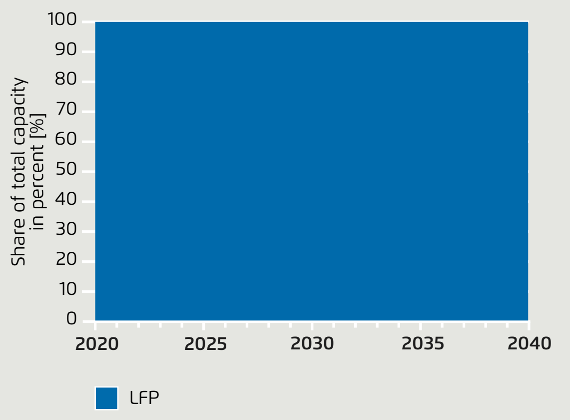
Scenario assumptions for heavy-duty vehicles (HDV 1) in the NMC scenario, 2020–2040

Figure 7-2a



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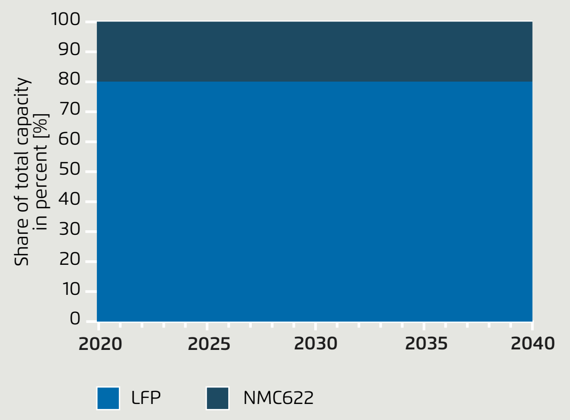
Scenario assumptions for heavy-duty vehicles (HDV 2) in the NMC scenario, 2020–2040

Figure 7-2b



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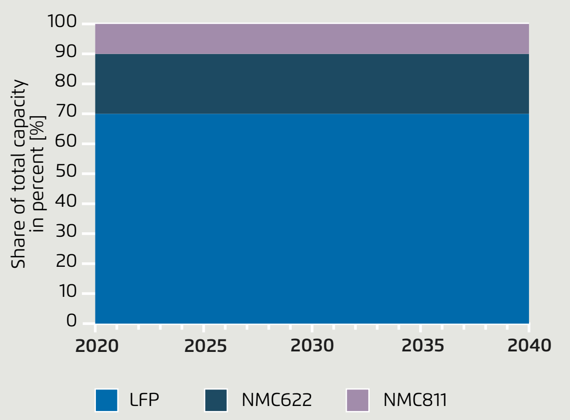
Scenario assumptions for heavy-duty vehicles (HDV 3) in the NMC scenario, 2020–2040

Figure 7-2c



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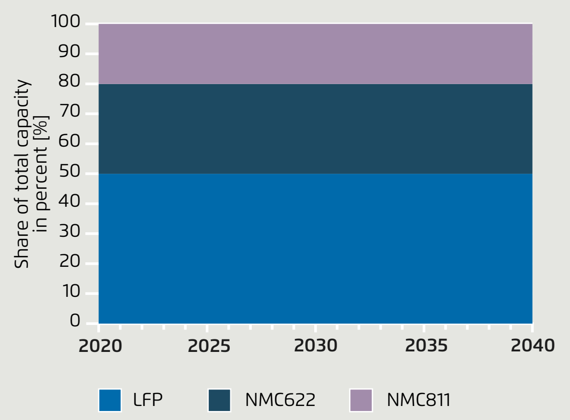
Scenario assumptions for heavy-duty vehicles (HDV 4) in the NMC scenario, 2020–2040

Figure 7-2d



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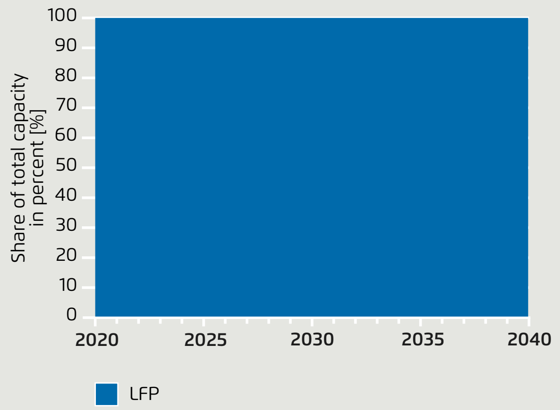
Scenario assumptions for heavy-duty vehicles (HDV 1) in the LFP scenario, 2020–2040 — Figure 7-3a



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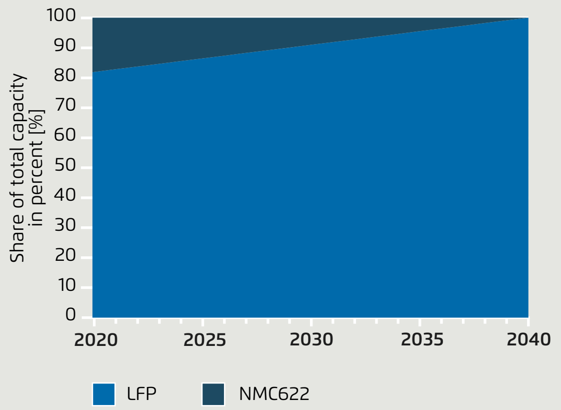
Scenario assumptions for heavy-duty vehicles (HDV 2) in the LFP scenario, 2020–2040 — Figure 7-3b



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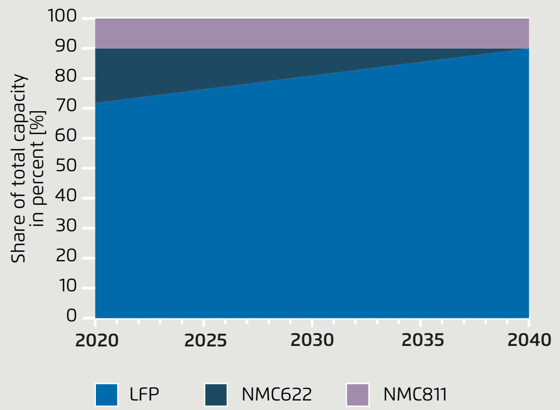
Scenario assumptions for heavy-duty vehicles (HDV 3) in the LFP scenario, 2020–2040 — Figure 7-3c



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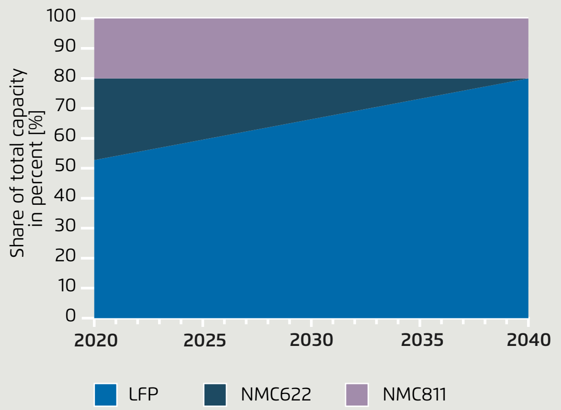
Scenario assumptions for Heavy-duty vehicles (HDV 4) in the LFP scenario, 2020–2040 — Figure 7-3d



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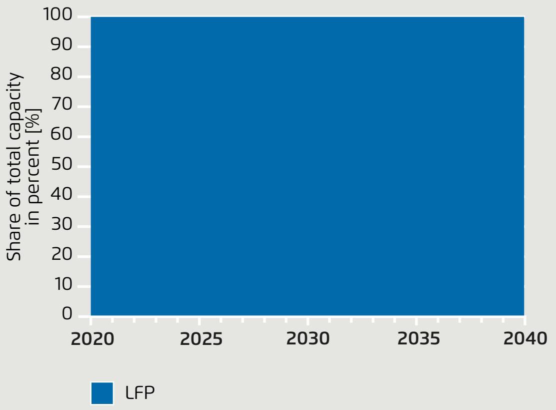
Scenario assumptions for heavy-duty vehicles (HDV 1) in the AB scenario, 2020–2040

Figure 7-4a



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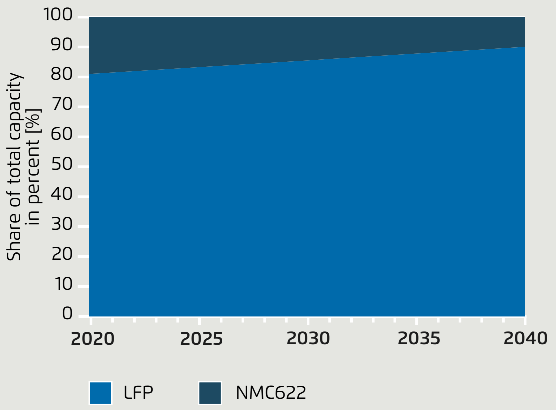
Scenario assumptions for heavy-duty vehicles (HDV 2) in the AB scenario, 2020–2040

Figure 7-4b



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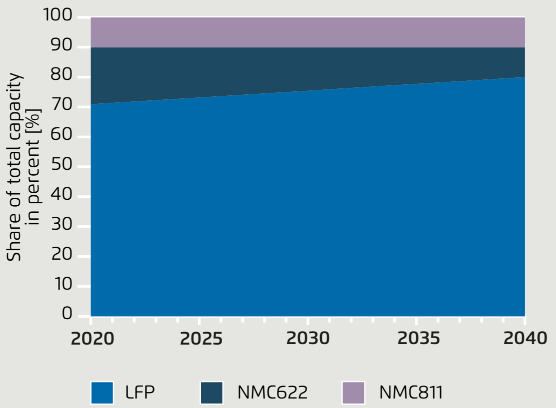
Scenario assumptions for heavy-duty vehicles (HDV 3) in the AB scenario, 2020–2040

Figure 7-4c



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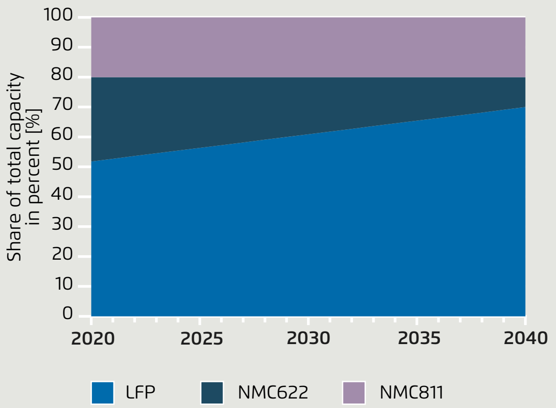
Scenario assumptions for Heavy-duty vehicles (HDV 4) in the AB scenario, 2020–2040

Figure 7-4d



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