

REPORT - December 2024

From waste to value

Why battery recycling is Europe's chance for resource sufficiency and a low-impact supply chain

Transport & Environment

Published: December 2024

Author: Alina Racu & Julia Poliscanova Modelling: Yoann Gimbert Expert group: Julia Poliscanova, Lucien Mathieu, Yoann Gimbert

Editeur responsable: William Todts, Executive Director © 2021 European Federation for Transport and Environment AISBL

To cite this report

Transport & Environment. (2024). From waste to value: Europe's opportunity for self-sufficiency and a low-impact supply chain

Further information

Julia Poliscanova Senior Director, Vehicles & Emobility Supply Chains Transport & Environment julia.poliscanova@transportenvironment.org Mobile: +32 471449643 www.transportenvironment.org | @transenv | fb: Transport & Environment

Acknowledgements

The findings and views put forward in this publication are the sole responsibility of the authors listed above.



Executive summary

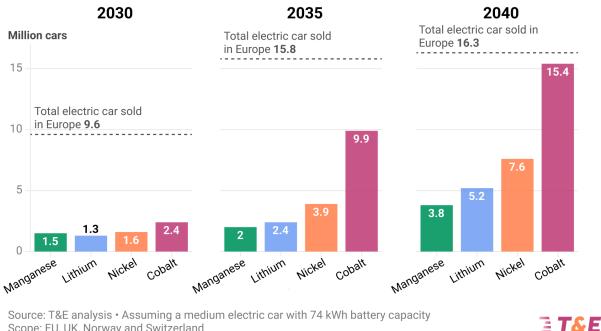
Locally recycled batteries can provide metals for over 2mln EVs in 2030

More recycled battery materials - cobalt, lithium, manganese and nickel - will come from the electric cars (EV) stock and planned battery gigafactories across Europe. This represents an enormous opportunity for the EU and the UK to source materials locally and sustainably, but strong policies will be needed to make this happen.

T&E's new analysis finds that:

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

Potential BEV production from recycled materials in Europe Recycled material used to produce electric cars



Scope: EU, UK, Norway and Switzerland

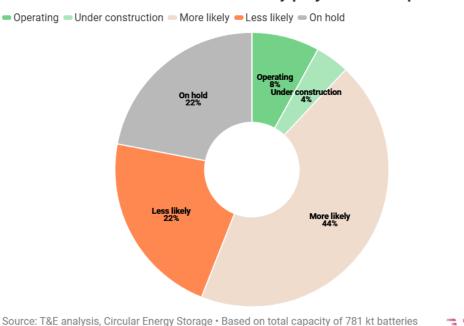
The expected volumes of locally recycled secondary materials will be more than enough to meet the recycled content targets for lithium, nickel and cobalt in the new EU Battery regulation.



- The locally recycled battery materials can also replace the need for primary ores, avoiding the need to build 12 new mines globally by 2040 (4 lithium, 3 nickel, 4 cobalt, and 1 manganese mine of average size).
- Recycling lithium in Europe can save almost a fifth of CO₂ compared to lithium being extracted from spodumene in Australia and refined in China.

Today, Europe is not ready to capture the resilience and sustainability potential from battery recycling.

But despite this considerable potential, today neither the EU nor the UK are ready to capture this opportunity. The existing recycling capacity across Europe is 10 times below where it needs to be in 2030, or in 5 years time. Over 30 material recovery projects have been announced or are being built, but due to higher energy costs, lack of mature technical expertise or financial support almost half of the capacity announced is either on hold or not certain to go ahead.



Status of announced material recovery projects in Europe

Source: T&E analysis, Circular Energy Storage • Based on total capacity of 781 kt batteries equivalent by 2030 (November 2024 assessment).

∃**T&E**

Europe should urgently mainstream support for circularity and recycling across its policies and treat it as another clean tech. Beyond the effective Battery Regulation and the Critical Raw Materials Act, the upcoming Circular Economy Act should support scaling of local recycling factories, introduce measures to restrict exports of battery waste and simplify intra-EU shipment of end-of-life products. EU and national funding schemes should equally prioritise integrated material recovery projects, including for commercialisation and technology gaps.



Table of contents

Transport & Environment	2
Executive summary	3
Locally recycled batteries can provide metals for over 2mln EVs in 2030	3
Table of contents	5
1. Introduction	6
2. Recycling feedstock in Europe	6
2.1 Evolution of battery chemistries	10
3. Impacts for Europe	11
3.1 Recycling potential	11
3.2 Can the EU Battery Regulation targets be met?	12
3.3 Impacts on primary extraction	14
3.4 Carbon footprint benefits	17
4. Building the European recycling industry	18
4.1 Future feedstock availability and capacities	18
4.2 Challenges to scale recycling capacities	19
Policy recommendations	22
Annex 1: Methodology	24
1.1 Recycling model assumptions	24
1.2 Battery chemistry mix	25
1.3 Recycling potential	26
1.4 Impacts on primary ore extraction	26

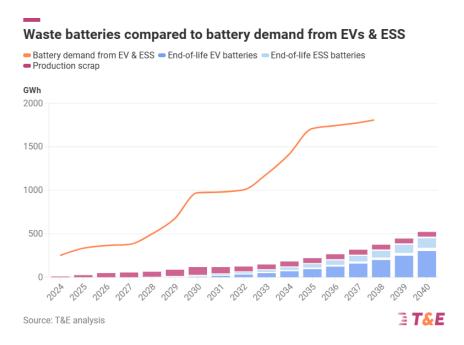
1. Introduction

Battery recycling represents a key opportunity for Europe to build a sustainable electric vehicle industry, addressing pressing challenges in the critical minerals space, such as resource scarcity, regional dependency and environmental impact. By recycling lithium-ion batteries, Europe can reduce its reliance on virgin raw materials, alleviating environmental burdens associated with mining and extraction. From a geopolitical perspective, battery recycling also paves the way to material sufficiency and supports local economies.

However, several questions arise when considering Europe's recycling potential. What is Europe's potential in terms of feedstock availability and recycling capacities? How many EVs can recycling enable in the long run? And what is the environmental footprint of recycling activities compared to ore mining and processing? These are the questions T&E addresses in this report, along with policy recommendations to advance the circular economy in the EV sector.

2. Recycling feedstock in Europe

According to T&E's latest estimates, battery demand from electric vehicles (EVs) and energy storage systems (ESS) in Europe will reach around 970 GWh by the end of the decade, expanding to nearly 2 TWh by 2040.¹ This surge in battery demand also means that these batteries will need to be managed and recycled once reaching end-of-life (EoL), becoming a crucial source of raw materials. The influx of EoL batteries will start to accelerate significantly after 2030, with around 170 GWh of batteries available for recycling in 2035, rising to 470 GWh by 2040.²



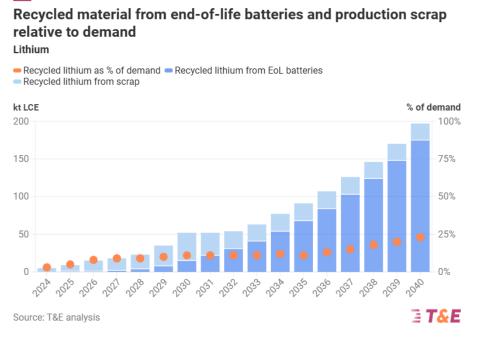
¹ Figures were updated compared to previous T&E reports based on new data from BNEF on ESS.

² Assuming 100% collection rate, EV batteries lasting up to 12 years in 1st life, with 40% of NMC and 70% of LFP batteries reused in 2nd life applications for an additional 5 years; assuming ESS battery lasting 10 years; and assuming recovery rates of 80% for lithium and 95% for nickel, cobalt, and manganese.



In parallel, the rise of gigafactories across Europe is expected to generate substantial volumes of production scrap (i.e. from non-compliant products and batteries allocated for testing, maintenance and refurbishment unrelated to sales), which will significantly contribute to the recycling feedstock, especially in the near term. By the end of the decade, over 100 GWh of production scrap will be available for recycling, representing the primary source of feedstock. This is also the time when the scrap volumes are expected to peak and then stabilise as companies ramp up production and mature, achieving operational efficiency. Starting with the mid-2030s the influx of EoL batteries will progressively start to dominate the recycling stream, making up for 72% of the feedstock by 2035 and 88% by 2040.

Lithium: As a critical element in all lithium-ion battery chemistries, whether NMC (nickel manganese cobalt), LFP (lithium iron phosphate) or other, lithium will be needed in batteries for a long time. T&E estimates recycled lithium to meet about 11% of demand during 2030-2035, increasing to 23% by 2040. The volume of recycled lithium from scrap is projected to peak around 2030 and then stabilise as gigafactories reach full operational efficiency. Meanwhile, the recovery of lithium from EoL batteries will significantly increase after 2035, becoming the main source of feedstock.



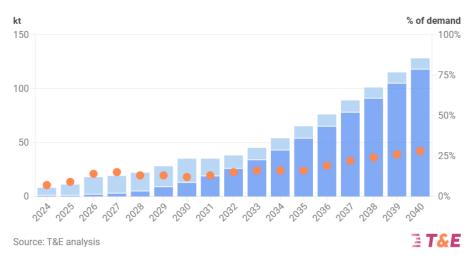
Nickel: Nickel's high energy density enhances driving range in batteries, leading to increased use in NMC chemistries. Recently, however, the trend toward higher nickel content is being moderated by the growing adoption of nickel-free LFP and LMFP (lithium manganese iron phosphate), as well as new manganese-rich chemistries with minimal nickel.

Despite this shift, nickel will remain part of the chemistry mix. As European gigafactories scale up production of high-nickel NMC batteries, significant volumes of production scrap are expected to become available for recycling in the late 2020s. By the early 2030s, recycled nickel is expected to cover 12% of demand. Over time, as EoL batteries become more prevalent, the share of recycled nickel relative to demand is expected to increase to 16% by 2035 to 28% by 2040.

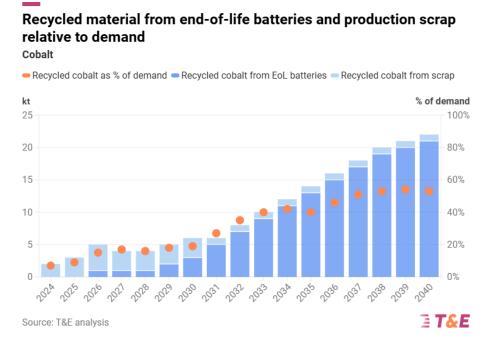


Recycled material from end-of-life batteries and production scrap relative to demand Nickel

Recycled nickel as % of demand — Recycled nickel from EoL batteries — Recycled nickel from scrap



Cobalt: Cobalt in batteries provides thermal stability and enhanced performance, but due to past price volatility and ethical concerns associated with mining practices in the Democratic Republic of the Congo, its use in NMC chemistries has been reduced in favour of nickel. Despite this, cobalt will continue to play a key role in high-performance EV batteries, including NMC, NCA (nickel cobalt aluminium) and their variants like NMCA (nickel manganese cobalt aluminium) and LMR-NMC (lithium-manganese rich nickel manganese cobalt), though in smaller quantities.

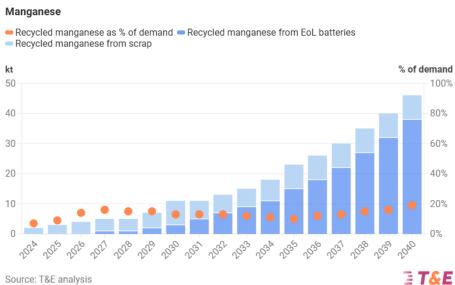


By 2030 already, recycled cobalt could meet up to 19% of the demand. As batteries with legacy chemistries higher in cobalt content reach end of life and cobalt demand from EV and ESS batteries start plateauing around 2035, the share of recycled cobalt relative to total demand is projected to double to 40% by 2035 and reach 53% by 2040.



Manganese: In response to the diverse needs for performance and affordability, manganese-containing chemistries are emerging as a middle ground alternative, providing longer driving ranges than LFP batteries, while being cheaper than nickel-rich alternatives. A theoretically abundant and lower cost raw material, manganese can partially replace cobalt or nickel in certain chemistries like LMR-NMC or NMCA, and can improve the driving range of LFP batteries (the so-called LMFP batteries). Nonetheless, despite its relative abundance in earth's crust, the future broader adoption of manganese may be constrained by the limited global capacity for producing high-purity manganese sulphate. In this context, recycling manganese becomes increasingly important in addressing potential shortages in the long term. Historically, economic incentives for recycling manganese were limited, but advancements in technology now enable recovery rates of up to 95% from spent batteries.

As gigafactories increase production of manganese-rich chemistries like LMR-NMC, NMCA, and LMFP in the late 2020s, the share of recycled manganese is expected to rise and reach 13% of demand by 2030, decline to 10% by 2035 due to increased demand and rise again to 19% by 2040, with fluctuations during this period reflecting the fast-evolving market.



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

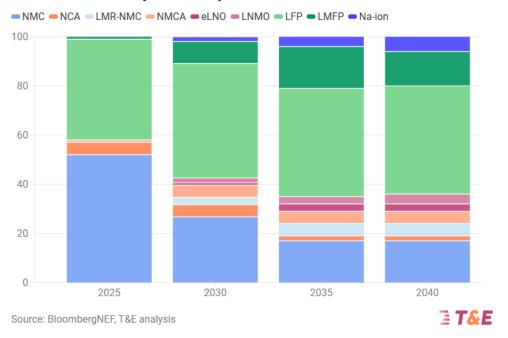
All in all, the recycling of production scrap from gigafactories and EoL batteries plays an important role in reducing reliance on virgin raw materials and bridging the supply-demand gap in Europe. Cumulatively, recycling could supply about 105 kt of lithium (LCE), nickel, cobalt and manganese by 2030, with volumes potentially more than tripling to 390 kt by 2040. These recovered materials could meet 11%-19% of the demand from EVs and ESS by 2030 and 19%-53% by 2040, depending on the metal and evolving battery chemistries.



2.1 Evolution of battery chemistries

While NMC chemistries currently dominate battery demand in Europe, the mix is expected to shift in the coming years. Nickel-containing chemistries will account for 39% of the market in 2030, decreasing to 31% by 2040. Within this segment, emerging nickel-based chemistries, such as LMR-NMC, NMCA and LNMO, which have higher manganese content to improve thermal stability and reduce costs, are expected to gain market share. Iron-based chemistries (LFP, LMFP) will be increasingly adopted in light- and heavy-duty electric vehicles and ESS applications, thanks to their overall safety, low cost and recent improvements in energy density. By 2030, LFP and LMFP are expected to capture 59% of the market, growing to 63% by 2040. Sodium-ion batteries, still in early stages, are projected to make up around 2%-6% of demand, mainly in energy storage systems and smaller electric vehicles where cost considerations outweigh energy density requirements.

The evolution of battery chemistries and their adoption is relevant in the context of battery recycling as they determine the composition of future feedstocks and influence the recycling methods used by the industry. With the increasing adoption of iron-based chemistries like LFP and LMFP, recyclers will encounter feedstocks without cobalt and nickel content, which have traditionally been the most valuable metals recovered. As a result, recycling companies will need to adapt their processes to efficiently recover elements like lithium, iron and manganese to maintain profitability (more details in section 4.2). Additionally, as new chemistries emerge, recycling facilities must adapt to handle these diverse feedstocks, maximise material recovery and minimise waste and material loss.



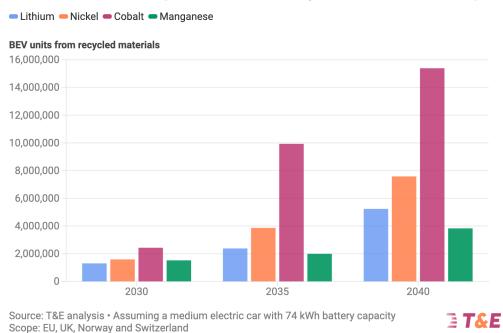
Evolution of battery chemistry mix for EVs and ESS



3. Impacts for Europe

3.1 Recycling potential

As shown in section 2, Europe holds a great potential to recycle raw materials for reuse in new batteries. The estimated recovery of 105 kt of lithium (LCE), nickel, cobalt and manganese from recycling in Europe by 2030 could enable the production of 1.3 to 2.4 million battery electric cars (or 14% to 25% of the projected battery electric cars sales³), assuming a medium sized electric car with a battery capacity of 74 kWh and the average car chemistry mix in that year. This range depends on the metal: for example, lithium can support the production of around 1.3 million BEVs due to its presence across virtually all chemistries (except sodium-ion batteries), whereas the production potential from recovered cobalt is on the higher side of the range due to higher feedstock availability driven by legacy chemistries.



Potential electric car production from recycled materials in Europe

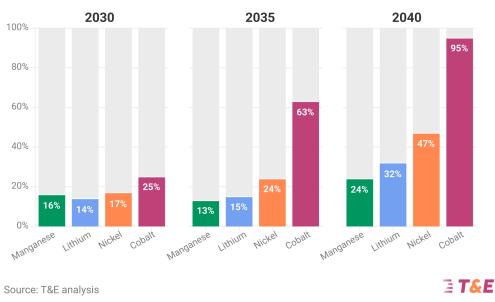
As more batteries reach end of life and recycling feedstock grows, this potential will increase too. By 2035, recycled metals could power between 2.0 and 9.9 million electric cars in Europe (or 13% to 63% of sales), rising to 3.8 to 15.4 million electric cars (or 24% to 95% of sales) by 2040. Interestingly, in 2040 the lower end of the range corresponds to manganese due to its increasing adoption in both nickel- and iron-based chemistries, resulting in fewer cars produced from the available recycled manganese.

³ Battery electric car sales are projected to reach 9.6 million in 2030, 15.8 million in 2035 and 16.3 million in 2040, according to T&E's in-house EUTRM tool, which models the uptake of electrification in light-duty and heavy-duty vehicles based on the EU's CO₂ emission standards.



Potential BEV production from recycled materials in Europe

% of electric cars that could be produced

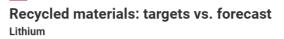


3.2 Can the EU Battery Regulation targets be met?

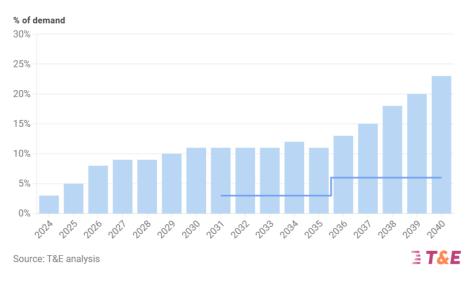
The EU's Battery Regulation, which took effect in 2023, sets targets for minimum recycled contents to be achieved by 2031 and 2036. This regulation is a pivotal step in promoting sustainability and reducing reliance on virgin materials. However, the challenge lies in whether Europe can meet these targets. Achieving the recycled content levels will require advancements in recycling technology, improvements in collection and processing infrastructure and robust industry-wide cooperation.

Lithium: Historically, lithium recycling has been rather overlooked due to technical challenges and lack of economic incentives. However, it is now becoming a central focus of innovation and policy. The Battery Regulation has set the targets for minimum recycled lithium content in lithium-ion batteries at 6% by 2031 and 12% by 2036. While these goals are within reach (11% in 2031 and 13% in 2036, respectively), there is even considerable upside potential if recovery rates improve beyond the regulatory benchmarks of 50% by end of 2027 and 80% by end of 2031, which is feasible with advancements in new technologies. T&E believes a minimum of 90% of lithium should be recovered from factory scrap and end of life batteries.

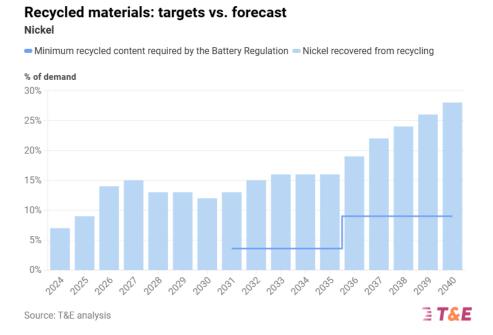




- Minimum recycled content required by the Battery Regulation - Lithium recovered from recycling



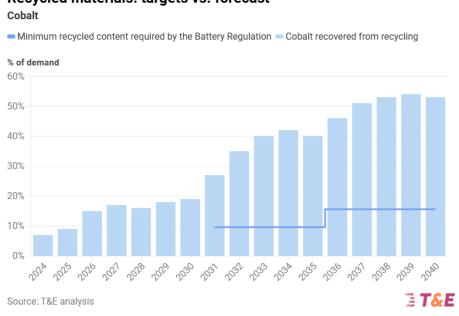
Nickel: The minimum recycled contents for nickel, 6% by 2031 and 15% by 2036, are also achievable, compared to the forecast 13% and 19% respectively. Considering that nickel-containing chemistries have historically been favoured in Europe over alternatives like LFP, the scrap pool available over the next decade will provide important feedstock for nickel recovery. In addition, advancements in recycling technologies now enable the extraction of up to 95% of the nickel from spent batteries.



Cobalt: The Battery Regulation requires at least 6% of recycled content by 2031 and 12% by 2036. Cobalt is expected to account for even higher shares of battery demand than lithium and nickel (i.e. 27% and 46% respectively) due to a combination of factors. Firstly, cobalt has been a critical component in many lithium-ion batteries and its high economic value enabled maximisation of its recovery rates from batteries. The Battery Regulation mandates cobalt recovery rates of 90% by 2027 and 95% by 2031 from batteries, which is feasible with the



current technologies. Secondly, due to price volatility and sustainability issues, the cobalt content in batteries has been reduced over time, impacting the demand for cobalt. Considering the variety of alternative chemistries emerging, T&E estimates the demand for cobalt to stagnate over the long term, with the % share of recycled cobalt to demand increasing.



Recycled materials: targets vs. forecast

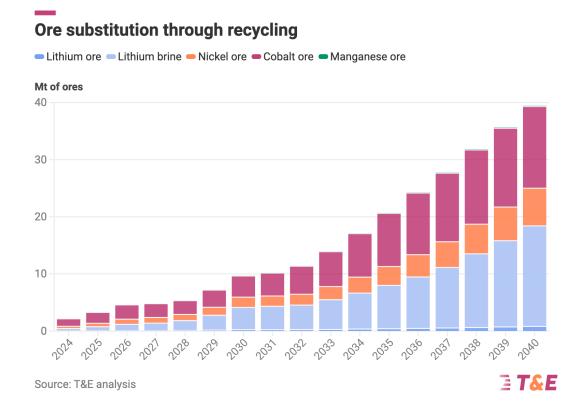
3.3 Impacts on primary extraction

By recovering the valuable metals, recycling reduces the need for new mining and its associated environmental and social impacts. This is especially important as ore grades decline, requiring more waste rock to be moved and processed to obtain the same amount of metal, which increases the environmental footprint of mining operations.

Lithium is extracted from both hard rock sources and from brines in salt flats. Around two-thirds of global lithium production comes from hard rock mining, with spodumene being the most common lithium-bearing mineral. However, as lower grade sources are increasingly tapped, the average lithium content globally is expected to decrease over time, meaning more ores will need to be mined for 1 tonne of lithium product. T&E estimates that battery recycling in Europe could save around 0.2 Mt of lithium ore by 2030 and 0.8 Mt by 2040.

In addition to mining, about one-third of global lithium production comes from salt flats where lithium is extracted through brine evaporation in ponds. Due to the relatively low concentration of lithium in brine, large volumes of brines are required to produce lithium products. Lithium recovered from battery recycling operations in Europe could reduce the need for brine extraction by substituting around 3.9 Mt of brine by 2030 and 17.6 Mt by 2040. Altogether, the estimated recycled lithium available in Europe could substitute 1 brine or hard rock mining operation by 2030 and 4 by 2040, based on an <u>average mine size of 45 kt LCE output per year</u>.



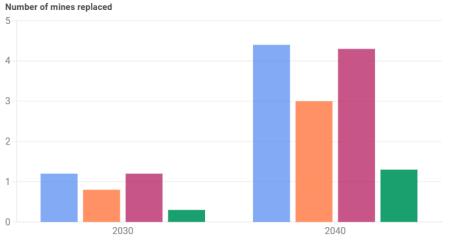


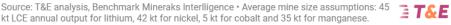
Nickel is extracted from two main types of deposits: sulphide ores and laterite ores. Sulphides can tend to have higher nickel content and are found in various locations globally including Canada, Russia, Australia, while laterite ores are more abundant, but have a lower nickel content and are typically located in tropical regions. In the last decade, laterite mining, often associated with higher environmental impacts, has increased significantly due to Chinese investments in Indonesia. This growth has recently led to an oversupply, which has depressed prices and put on hold some operations outside Indonesia and China that might have better environmental profiles. Recycling nickel from EV and ESS batteries in Europe could replace the output of nearly 1 average-sized nickel mine (42 kt output per year) by 2030 and up to 3 mines by 2040. In terms of ore extraction, this could save 1.8 Mt of ores in 2030 and 6.6 Mt in 2040.



Mines replaced through recycling

Recycled lithium – Recycling nickel – Recycled cobalt – Recycled manganese





Cobalt is generally mined as a by-product of nickel or copper operations, with the only primary cobalt operation being a mine in Morocco. While the DRC remains the predominant source of cobalt, supply from Indonesian laterite sources is expected to increase its market share, driven by expansions in nickel projects. Recycling cobalt from batteries in Europe could avoid the mining of 3.7 Mt by 2030 and 14.3 Mt by 2040, potentially substituting the output of 1 average cobalt mine (5 kt per year) by 2030 and 4 mines by 2040.

Manganese, which is more abundant in Earth's crust and occurs in higher concentrations within ores, is predominantly mined in South Africa. The country is expected to expand its global share of manganese production in the long term. Recycling manganese could potentially replace up to 0.1 Mt of ores by 2040, replacing the production output of 1 average manganese mine by 2040.⁴

Overall, T&E estimates that the recovery of these raw materials from battery recycling operations could enable the substitution of up to 4 mines and save up to 9.7 Mt of ores and brines by 2030, rising to at least 12 mines replaced and nearly 40 Mt of ores by 2040. This reduction would alleviate resource strain and minimise environmental impacts associated with primary mining.

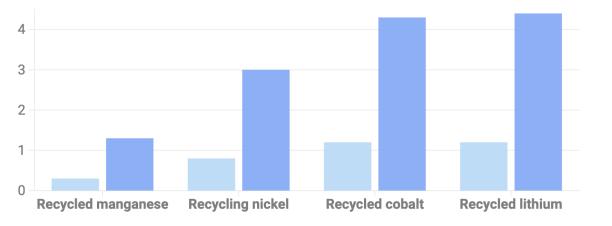
Ξ**Τ**&Ε

⁴ Assuming an average mine size of 35 kt Mn.

Mines replaced through recycling

2030 - 2040

Number of mines replaced



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

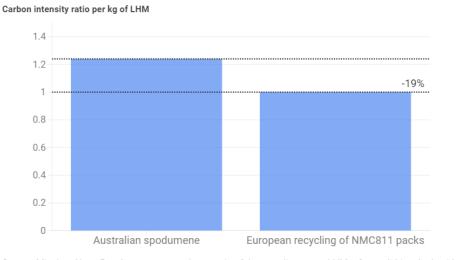


∃**T&E**

3.4 Carbon footprint benefits

Recycling batteries generally has a lower carbon footprint than mining and refining raw materials due to the high emissions associated with extraction and processing. A recent life cycle assessment (LCA) by Minviro, commissioned by T&E, examined the carbon intensity of lithium hydroxide production from virgin minerals and from recycled batteries based on current technologies/energy mix.

Extracting lithium from spodumene in Australia and then processing it into battery-grade lithium hydroxide in China consists of energy-intensive steps such as pyrometallurgy, particularly calcination, typically powered by coal and natural gas. In contrast, recycling NMC 811 battery packs in Europe using the average European grid produces 19% less CO₂ emissions compared to lithium hydroxide from virgin sources.



GHG emissions from lithium hydroxide monohydrate production

Source: Minviro • Note: Results are presented as a ratio of the recycling route. LHM refers to lithium hydroxide monohydrate (LiOH·H₂O). Cradle-to-gate life cycle assessment using an economic allocation approach for the **T&E** recycling route. The Australian spodumene route includes mining in Australia and refining in China.

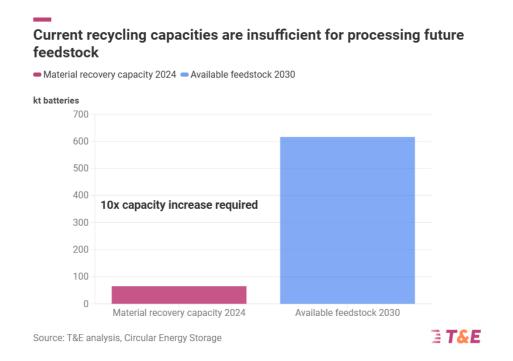
An economic allocation based on a 3-year average of each material price (2021-2024) is used for the analysis by Minviro, as this is a standard approach in the industry. The carbon footprint of the whole recycling process is allocated to the different materials (lithium, nickel, cobalt, ...) based on their economic value. This means that changes in material prices in the future will also change the final results. Minviro applied a cradle-to-gate approach, where the cradle is the point of extraction of raw materials and the treatment of spent batteries in the case of recycling. The end gate is set at the point of production of battery grade lithium hydroxide monohydrate. CO₂ emissions from recycling are largely due to the reagents required for hydrometallurgical recycling and the combustion of gas for heating processes. In the future, further emission reductions could be achieved in Europe through electrification of some processes (and the use of renewables), and better integration of recovery into the process, such as the recycling of waste and the conversion of sodium sulphate into sulphuric acid for re-use in the processe.



4. Building the European recycling industry

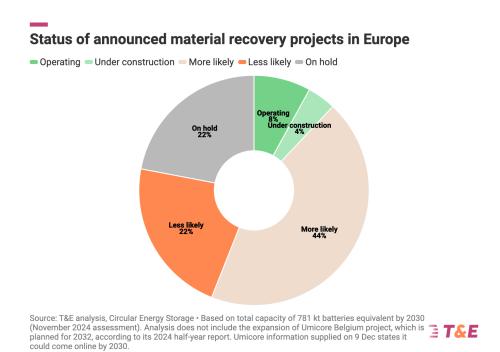
4.1 Future feedstock availability and capacities

To manage the growing volume of spent batteries, Europe will need to significantly scale up its recycling capabilities, especially in the material recovery stage, which involves hydrometallurgical processes. Currently, less than 100kt of battery recycling capacities, including a Umicore plant in Belgium, are available across Europe. In fact, by 2030, the existing recycling capacities will need to increase 10 times to handle the anticipated volume of feedstock available for recycling.



As of the latest count, 34 material recovery projects (both integrated and hydrometallurgical recycling plants, excluding plants focused on pre-processing only) have been announced across Europe by 2030, with a combined capacity of around 780 kt batteries. Notable market players in these projects include: Northvolt (Sweden), Aurubis (Belgium), BASF (Germany), Altilium (UK), Fortum (Finland) and Orano (France). The analysis does not include the expansion of the Umicore Belgium project (up to 150 kt), which is the largest but is planned for 2032, according to its 2024 half-year report. Only 1% of the total capacity is planned by Asian players, whereas their presence is more prevalent in the pre-processing stage of recycling (16% of the planned capacities in 2030). This suggests that Asian companies overseas may prefer to process batteries into black mass and export it back home for further material recovery, rather than investing in capital- and opex-intensive material recovery plants in Europe.





Overall, around 44% of the announced material capacities in Europe face significant risks or have already been on hold (e.g. projects by <u>BASF</u> and <u>Eramet and Suez JV</u>) due to project complexity and high capital and operating costs in a still-developing market. Uncertainty around financing and permitting may lead to some project delays, but those integrated with pre-processing or related to battery materials or metal production are relatively better positioned for success.

If the high risk projects do not come online, only around half of the available feedstock by 2030 can be processed locally, resulting in significantly less locally sourced recycled content available.

4.2 Challenges to scale recycling capacities

Circularity and materials recycling in particular have been recognised by many, including the recent Draghi report on EU competitiveness as the sector where Europe can have a competitive advantage and keen an innovative edge globally. But despite much potential, commercial recycling operations still face barriers scaling up and require targeted industrial support. This section looks at some of the challenges in scaling European plans.

Recovery rates. As battery recycling is scaled up, maintaining high efficiency in recovering valuable materials can be challenging due to the complexities of handling large volumes and diverse material compositions. In pyrometallurgy, the recovery rates for nickel, cobalt and copper can reach 95%. However, lithium (and manganese) can be lost in the remaining slag and require additional processing through hydrometallurgy, where lithium recovery can exceed 70%. At the same time, graphite from anode is typically burned off.

On the other hand, hydrometallurgy, which includes a pre-processing step, is more selective and efficient but it involves complex chemical processes. Hydrometallurgy offers high recovery rates of up to 95% for cobalt, manganese and nickel present from the black mass. Lithium



recovery has also been improving, on average up to 90% at commercial scale, according to BloombergNEF, with some <u>Western companies</u> achieving even 95%. Additionally, efforts by companies like <u>Fortum</u> in Finland are underway to develop methods for recovering graphite, solvents and other components via hydrometallurgy.

In Europe, pyro-hydrometallurgy has been pioneering in establishing battery recycling methods but is somewhat outdated, while hydrometallurgy is expected to become the dominant method in the future due to its higher efficiency in recovering valuable materials, particularly in light of the growing demand for critical minerals. Policy, research and industrial support on scaling efficient hydrometallurgy processes should be continuously pursued at EU and national levels.

Cost differences. In today's competitive climate, recycling players in Europe continue to face financial pressures, higher energy costs and extended project timelines, making it difficult to compete with Chinese companies who started earlier and have benefitted from lower costs and government support for a longer time.

The operational expenses (Opex) for recycling NMC811 cell packs at integrated plants in Europe average around 14 \$/kWh, compared to 11 \$/kWh China - a 25% cost disparity, according to BloombergNEF data. For LFP recycling, the difference is even wider, with Opex in Europe at around 7 \$/kWh, versus just 4.5 \$/kWh in China, marking a 56% cost gap.⁵ These disparities largely come from higher costs for electricity, utilities and labour. For example, European recyclers incur 60% higher electricity costs than their Chinese counterparts, 35% higher labour costs, while utility costs can be 5 times more expensive.



While legislation - e.g. limiting black mass exports outside the EU - aims to create a more level playing field, companies recycling in Europe also need targeted financial, de-risking and industrial support to compete with their Chinese counterparts on the global scene.

LFP recycling. While nickel-rich NMC recycling has traditionally received a lot of focus given the mature (and economically attractive) recovery of nickel and cobalt, lithium-iron-phosphate (LFP)



⁵ Opex estimates exclude transportation costs.

batteries are recycled a lot less, despite becoming increasingly relevant on the European EV and energy storage markets.

Overall, there appears to be two questions when it comes to LFP recycling: whether or not it is technically feasible to recycling key elements such as phosphate, iron and graphite (more relevant in LFP given its weight compared to NMC⁶), and whether it is economically viable to recycle this battery chemistry.

First, when it comes to technical feasibility, advancements in hydrometallurgical methods have made it possible to separate and recover key elements of LFP batteries. Selective leaching extracts the lithium (as lithium carbonate) from the iron phosphate structure, allowing the latter to be filtered out.

Graphite recycling has also become technically feasible, especially with hydrometallurgical processes that can recover graphite without burning it off as in pyrometallurgical methods. Obtaining battery-grade graphite requires strict purification due to contaminants that accumulate over the battery's lifetime. However, companies like Fortum and Altilium are developing recycling facilities capable of producing such a product that meets specific anode specifications, either via cooperation with OEMs or with graphite/anode producers. From a geopolitical perspective, graphite recycling enables the diversification of a supply chain that is heavily dominated by China and represents an opportunity for Europe to achieve some level of self-sufficiency.

Second, while LFP batteries might be technically feasible to recycle with time, the economics of recycling appear to be less attractive, due to their lower content of valuable metals compared to NMC batteries. e.g. phosphorus is an abundant fertiliser material with no secondary market today. With lithium as the main valuable metal typically recovered today, LFP batteries recyclers are heavily reliant on lithium prices.

Some strategies to improve the overall economics of LFP batteries recycling include:

- Implementing upfront fees, as part of Extended Producer Responsibility (EPR) schemes, with funds designated for end of life recycling.
- Battery design optimised for recycling (e.g. standardised cell formats) to facilitate automation in pre-processing and reduce costs.
- Achieving higher recovery rates for lithium along with recovering of iron phosphate to maximise the overall value extracted from the batteries.
- Processing recovered materials into battery grade materials to capture higher market premiums.
- Commercialisation of graphite recycling processes alongside policies to disincentivise primary use to increase the amount of valuable materials in LFP batteries.
- Adopting an <u>integrated business model</u> to retain profits from processing both black mass and metals like copper and aluminium, the latter being recovered during shredding.

⁶ LFP batteries contain up to 47% more graphite by mass compared to NMC 811 batteries, according to <u>VC</u> <u>Elements</u>.



With LFP and LMFP batteries projected to meet a significant share of Europe's demand in the coming years (56% by 2030 and 59% by 2040), and more gigafactories announcing LFP production, European recycling businesses must adapt to process these chemistries. Developing policies that require that, as well as infrastructure capable of handling diverse battery types will be crucial. On the policy side in particular, European regulations should enforce recycling efficiency targets for all battery chemistries, including emerging ones, ensuring a sustainable and adaptable recycling framework.

Policy recommendations

1	The EU should develop a European Single Recycling market, mainstreaming and prioritising circularity across policy areas and funding streams.
2	Prioritise strategic projects focusing on recycling, in particular integrated recyclers with material recovery under the implementation of the EU Critical Raw Materials Act (CRMA) and its 25% recycling 2030 benchmark.
3	Effectively and ambitiously implement the circularity provisions in the EU Battery Regulation to ensure all battery chemistries achieve the recycling efficiency target and more materials are being recycled; and make sure local recyclers benefit from EU recycled content rules.
4	Ensure end-of-life batteries and black mass stay in Europe to help scale recycling capacities: by defining these waste streams as hazardous to limit their exports, ensuring effective market surveillance at the border and monitoring trade flows via dedicated HS codes.
5	The new Circular Economy Act should further simplify intra-EU shipment of end-of-life products and put in place quality standards for secondary materials to ease scaling and investment.
6	The EU Innovation Fund, InvestEU, the European Investment Bank (EIB) and national state aid should provide similar Capex and Opex support to recycling and circularity projects as cleantech, focusing on commercialisation and technology gaps (e.g. hydrometallurgical recovery of lithium, graphite and other elements).



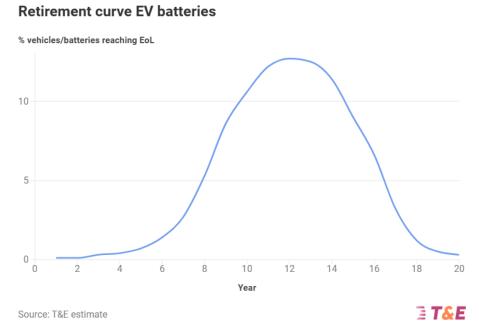


Annex 1: Methodology

1.1 Recycling model assumptions

The feedstock availability from battery recycling in Europe (defined as EU, UK, Norway and Switzerland) has been estimated based on multiple assumptions:

- End-of-life batteries from electric vehicles: 100% collection rate (as required by the Battery Regulation), assuming maximum potential; battery lifespan up to 20 years and 12 years on average, with a retirement curve where 82% of vehicles reach end-of-life between years 8 and 15; it was assumed that 70% of LFP batteries and 40% of NMC batteries are used in second life applications for around 5 years longer.
- End-of-life energy storage system batteries: 100% collection rate; average lifespan of around 10 years.
- Production scrap: volumes were estimated as part of T&E's gigafactory supply analysis, considering the ramp-up of announced projects in Europe. Given the announced battery cell production capacities so far, it has also been assumed that the demand would be largely covered by local supply. Scrap availability would be negatively affected if Europe would import batteries and/or the local production would be lower than estimated.
- Recovery rates are based on the EU battery regulation: 80% lithium recovery rate from 2030, 95% recovery rate for nickel, cobalt and manganese from 2030. Assumptions per year are presented in table 9 of a <u>T&E previous report</u>.
- Data sources include T&E expert opinion, BloombergNEF and Circular Energy Storage.



In order to assess Europe's full potential, the analysis assumes that intermediate products, such as black mass, stay within the region.

Feedstock volumes were compared against battery and raw materials demand in the Regulatory scenario developed by T&E, in line with EU CO₂ emissions standards for light and heavy-duty vehicles. The recent EV stagnation shows that most carmakers sell the minimum required by

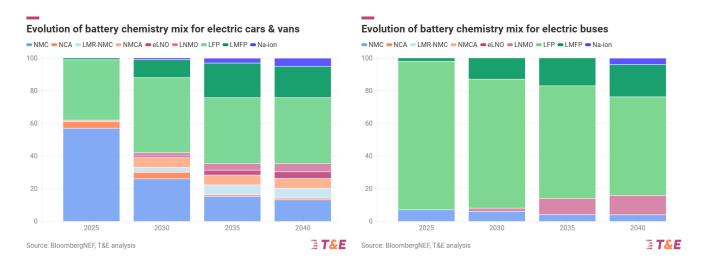


the regulation. There is no additional regulation in place to boost EV sales beyond this for now (e.g. no regulation for company cars).

Since the publication of the T&E report <u>"An industrial blueprint for batteries in Europe"</u>, the current recycling model now assumes an updated battery lifespan, with a retirement curve of 12 years on average instead of 14 years on average previously, based on the regulatory and typical industry EV warranty period. In theory, the life of the battery and EV could be extended much further. However, in practice EV batteries would probably not be used up to their maximum theoretical potential (accidents, technical defects, etc). In addition, this change reflects moving into the mass market with more affordable EV models entering the market (with lower price likely to have other trade-offs). Moveover, significant value can be extracted from the battery and vehicle materials through recycling, making recycling more financially attractive for the owner of an old electric car than selling it at a low price, as is the case with old ICEs today. This has implications on the timeline for the feedstock availability, resulting in a slight increase in the amount of batteries reaching end-of-life earlier, which in turn impacts the availability of recycled materials.

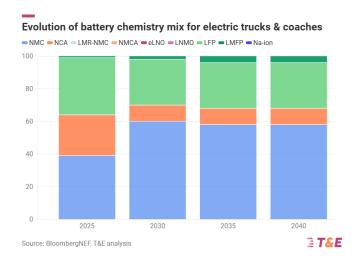
1.2 Battery chemistry mix

The following chemistry mixes for cars, vans, buses and trucks in Europe are based on data from BloombergNEF and assumptions by T&E regarding the evolution of battery chemistries.



T&E anticipates that European gigafactories will align with the market demand, increasing production of LFP batteries compared to current levels.





1.3 Recycling potential

To estimate the number of battery electric vehicles (BEVs) that could be produced with available recycled metal in 2030, 2035 and 2040, T&E assumed a medium sized electric car with a battery capacity of 74 kWh and the average chemistry mix for each respective year (as shown in Annex 1.2). This generated a range of BEV production estimates, reflecting variations in metal content across different battery chemistries.

Average metal content in battery electric cars

Weighted average metal content per car (in kg)	2030	2035	2040
Lithium	6.5	6.2	б
Nickel	19.1	14.3	14.4
Cobalt	2.1	1.2	1.2
Manganese	6.1	9.5	10.3

Source: T&E analysis • Assuming a medium sized electric car with a battery capacity of 74 kWh \exists **T** & **E** and the average car chemistry mix for the respective year.

1.4 Impacts on primary ore extraction

To assess the potential savings in primary metal extraction through recycling, T&E calculated the amount of ore - along with its metal content - that could be conserved by recycling batteries. Using global data on metal production from Wood Mackenzie, categorised by source type (i.e. hard rock or brine for lithium; laterites and sulphides for nickel and cobalt) and by country (i.e. for manganese), T&E determined the average global metal content in lithium, nickel, cobalt and manganese ores. This global average metal content was then applied to projected recycling outputs to estimate the tonnage of ore that could be saved through recycling in Europe.



Estimated average metal content in ores, weighted by global production

Metal content in ore/brine	2020	2025	2030	2035	2040
Lithium in ore	3.4%	3.2%	3%	2.8%	2.8%
Lithium in brine	0.1%	0.1%	0.1%	0.1%	0.1%
Nickel ore	2%	2%	1.9%	1.9%	1.9%
Cobalt ore	0.2%	0.2%	0.2%	0.2%	0.1%
Manganese ore	35.9%	36%	36.2%	36.3%	36.9%

Source: T&E analysis incorporating data from British Geological Survey, Geoscience Australia, 📑 T&E

