Electric vehicle batteries:

Second life applications and recycling in Belgium

GreenImpact
Decrease organisations' CO2 footprint

Federale Overheidsdienst Mobiliteit en Vervoer
Service public fédéral Mobilité et Transports

D-CARBONIZE

AISIN

bpost

LAB A O BOX

Table of contents

List of abreviations

Abbreviation	Definition
ACC	Automotive Cells Company
AKEF	Amsterdam Climate and Energy Fund
ATF	Authorized Treatment Facility
BESS	Battery Energy Storage Solution
BMI	Benchmark Mineral Intelligence
BMS	Battery management system
CES	Circular Energy Storage
C-rate	Rate of charge and discharge
EOL	End of Life
ESS	Energy Storage System
EV	Electric Vehicle
ICE	Internal Combustion Engine
IEA	International Energy Agency
LCO	Lithium Cobalt Oxide
LFP	Lithium-iron-phosphate
LIBs	Lithium-ion batteries
Li-ion	Lithium-ion
LMNO	Lithium Manganese Nickel Oxide
MOU	Memorandum of Understanding
NCA	Lithium-nickel-cobalt-aluminium-oxide
Ni-Cd	Nickel-Cadmium
Ni-MH	Nickel metal hybride
NMC	Lithium-nickel-manganese-cobalt-oxide
ONE	Our Next Energy
ROI	Return on Investment
SMC	Sheet Mould Compound
US DOE	US Department of Energy

List of figures

List of tables

Introduction

What happens to lithium-ion (Li-ion) electric vehicle (EV) batteries once they reach the end of their useful lives in electric vehicles? And what role does a country such as Belgium play in the EV battery value chain?

This report explores the re-use and recycling of Li-ion EV batteries, and seeks to bring together the depth of knowledge available at each stage of a value chain that appears to operate in loosely connected silos. Based on exclusive and highly qualitative expert insights, the report's authors set out to make as many connections as possible between the various stages of the value chain in order to present a big picture while delivering dense, technical, and detailed insights to push the boundaries of expertise. Like the automotive industry, the Li-ion battery industry is global, so the role of a country such as Belgium is to identify and play to its strengths in the value chain; this report illustrates the global battery supply chain, and Belgium's place in two major new and burgeoning areas of industry, namely EV battery second life and recycling.

The surge in adoption of rechargeable electric and electronic devices—from smartphones and other portable devices to electric cars, vans, and even heavy commercial vehicles—has been made possible by Li-ion batteries, which store energy for longer than the nickel-cadmium (Ni-Cd) and nickel metal hydride (Ni-MH) rechargeable batteries that preceded them.

To meet the demands of the low and zero emission targets and legislation being introduced at city and national level in countries and regions around the world, the automotive industry is going electric, transitioning away from the internal combustion engine (ICE) in favour of technology that produces zero emissions at the point of use.

But the use phase of electric vehicles is preceded by a lengthy and well-developed upstream supply chain involving the mining and refining of raw materials, and followed by a downstream post-use phase of reuse and recycling that is still in relative infancy. And both require an intricate supporting infrastructure that can collect used batteries and deploy them into a second life application, or directly into recycling.

The rush to electrification is accompanied by a major ramp up in demand for batteries.

Lithium-ion batteries (LIBs) are considered to have reached end of life (EOL) when they degrade to around 80 percent of their initial capacity to store and supply energy.

An EV battery that has reached EOL is not automatically a battery to recycle, and indeed it may still be useable in a second life application such as an energy storage system (ESS), as will be explored in this report.

So where does Belgium fit in? How should it position itself in the EV battery value chain?

The answer could lie in EV battery recycling and second life applications. Belgium may not have raw materials in the form of natural resources, but it has expertise in waste management, and as this report will outline, what some see as waste, others see as a valuable source of materials. The concept of circular economy is gaining considerable interest across the automotive industry in particular, as is the concept of second life for products such as batteries that have partially degraded; in each of these areas, Belgium has much to offer, and opportunities to explore and exploit.

This is a key moment in the transition to zero emission mobility. The need to handle used EV batteries is clear, and there is a unique opportunity to develop the infrastructure in advance of the inevitable arrival of high volumes of used EV batteries.

With sales of plug-in hybrid and battery electric vehicles rising sharply, governments find themselves in the unusual position of facing a major challenge, but still with sufficient time to act now and install the required infrastructure to tackle it.

What happens to a used EV battery, whether it is reused or recycled – and where – depends on the infrastructure and policies of the country in which that battery ends its life.

Methodology and scope

The report was proposed by non-profit organisation GreenImpact, a public and private consortium supported by Georges Gilkinet, the Belgian federal minister for mobility and vice prime minister, Aisin, Bpost, and Lab Box.

The ambition was to outline key issues in used lithium-ion (Li-ion) electric vehicle (EV) battery handling, notably second life and recycling, with a focus on the role Belgium can play in these areas.

The EV battery value chain is global. In order to illustrate Belgium's place within this value chain, this report presents the "funnel" that makes up the material and product flow, starting with the vast collection, processing, and refining of resources, and progressing through the use phase to illustrate what happens to the batteries at end of life.

This report is based on extensive desk research, and in-depth interviews with over 30 experts and organisations (Fig 1), including:

Aertssen Group	**Febelauto**	**SABIC**
Aurubis	**FIPRA International**	**Solvay**
Benchmark Mineral Intelligence	**IPCEI Batteries**	**Umicore**
Avesta Battery and Energy (ABEE)	**Global Battery Alliance (GBA)**	**Urbix**
Bebat PRO	**Volvo Cars**	**Zenobé**
CLEPA, European Association of Automotive Suppliers	**Neckermann Strategic Advisors**	**Vrije Universiteit Brussel, Brussels (VUB)**
Denuo	**Octave Energy**	**Watt4Ever**
Everledger	**ProLogium**	
FEAD	**RENEOS**	

Sectors represented in this report include:

Materials	**Energy storage system suppliers (second life battery makers)**
Battery makers	**Second life battery users (customers)**
Recyclers	**Automakers**
Used battery collection companies	**Automotive suppliers**

Fig 1. List of companies working in the battery sector that were interviewed for this report.

Around half of the interviewees are based in Belgium. Those who do not operate in Belgium represent international organisations and shared insight relevant to this report.

However, the LIB value chain is lengthy, spanning every continent and reaching around the world—from open cast raw material mines in South America and Australia, via battery refining and cell manufacturing in China, South Korea, and Japan, to battery and vehicle assembly plants around the world, and eventually to used battery collection organisations, which decide whether battery modules are suitable for reuse or recycling.

The automakers are expected to assume responsibility and remain responsible for the batteries until they are recycled; the automakers rely on the battery makers; and the battery industry relies on mining and refining. There is little vertical integration, and the value chain is lengthy and highly fragmented, with key stages appearing to operate in silos.

This lack of homogeneity complicates the industry's attempts to develop a circular economy, in which materials are used and reused within a closed loop.

This is further complicated by a lack of design for recycling, an industry that is only now adopting the closed loop concept, a nascent infrastructure for monitoring and handling used EV batteries, public and corporate concern over the safety and legal status of batteries in second life applications, and a lack of recycling capacity for used EV batteries.

We also discovered there is a similar lack of fluency in terms of published material. We hope this report provides a complete picture of the industry, from raw material to second life and recycling.

Executive summary

Lithium-ion (Li-ion) batteries are the technology of choice for rechargeable products. As well as small batteries for portable electronics, Li-ion batteries are used to power electric vehicles and large renewable energy storage systems (ESS).

There were over 16.5 million electric cars on the road globally in 2021, a tripling in just three years according to the International Energy Agency (IEA); and by 2030, the IEA expects to see between 148 million and 230 million battery powered vehicles on the road, accounting for seven to 12 percent of the global automotive fleet.[1]

The transition to renewable energy brings with it the need for energy storage. Boston Consulting Group notes that Li-ion batteries are used for 90 percent of grid energy storage around the world, especially for wind and solar energy, and that demand for battery storage will only increase in the coming years.[2]

Li-ion batteries meet both sectors' needs; they charge quickly and hold their charge better than other commercially available energy storage technologies—and they provide clean energy at the point of use.

But Li-ion batteries do not last forever. Over time, and with use, their capacity to hold a charge slowly declines; when they deplete to around 80 percent of their initial capacity to store and discharge energy, they are considered to have reached end of life (EOL), although this is a guide rather than an absolute.

Typically, EV batteries are warrantied for eight years or 100,000 km, although batteries are lasting longer than initially expected.[3]

While Li-ion is far from perfect, it is—and will for many years remain—the dominant EV battery technology; it has a relatively high-power density, can be charged quickly, supports a high number of charge cycles, holds its charge well, self-discharges at a low rate, and provides relatively good durability.

For safety and environmental reasons, Li-ion batteries cannot be disposed of in landfill, as they contain hazardous chemicals and present a potential fire risk; they also contain valuable materials, which can be recovered to a high percentage through recycling.

However, prior to recycling, many used EV batteries can still be deployed in less demanding second life applications, such as Energy Storage System (ESS). Ultimately, even the second life batteries will need to be recycled.

Li-ion batteries contain valuable metals and minerals, referred to throughout the report as battery raw materials—and those materials, such as nickel and cobalt, can be recovered and refined to battery grade quality, with recovery rates and material prices high enough to make it a financially viable pursuit. Add to that the introduction of regulations mandating the use of recycled content, such as the proposed European Union Battery Regulation, and it is clear that EV battery recycling will play a key role in the future of mobility.

This report explores what happens to EV batteries when they reach the end of their use in an EV, and either go into second life applications or into recycling, and the opportunities and implications for Belgium.

Like many western European countries, Belgium lacks sources of raw materials for Li-ion batteries.

But as a country physically and metaphorically at the centre of Europe, Belgium has an important role to play in the race to zero emission mobility, and a desire to seek out and add value—and where possible, ensure it can maintain a degree of independence in a global value chain.

The report is based on desk research and high-level industry interviews with stakeholders from across the EV battery value chain. Organised into three main sections, the report reflects the sequence of the EV battery value chain before and after the use phase:

- Chapter 1 looks at the material sourcing and production of EV batteries;
- Chapter 2 explores recycling; and
- Chapter 3 looks at the use of depleted EV batteries in second life applications.

The report features exclusive interviews with an automaker in Belgium (Volvo Car), a battery manufacturer (ProLogium Technology), and a user of second life batteries (Aertssen Group).

1 https://www.iea.org/reports/global-ev-outlook-2022/trends-in-electric-light-duty-vehicles
2 https://www.bcg.com/publications/2022/the-lithium-supply-crunch-doesnt-have-to-stall-electric-cars
3 https://chargedevs.com/newswire/nissan-exec-ev-batteries-lasting-longer-than-predicted/

Key findings

- When a lithium-ion (Li-ion) electric vehicle (EV) battery reaches the end of its useful life in an EV, it can be deployed in a second life application, or sent directly into recycling. Both second life and recycling are in their infancy, but as the market for EVs grows, so too does the number of EV batteries that will eventually reach end of life (EOL).
- Li-ion EV batteries degrade over time and with use, and are considered to have reached the end of their useful life when they fall to around 80% of their initially intended capacity to store and deliver energy – although EOL is a guide rather than an absolute.
- After it has finished its useful life as an EV battery, the used battery is sent either to a recycling facility, or for reuse in a second life application. Ultimately, of course, the second life battery will be recycled.
- There is little cohesion between the various stages of the EV battery value chain. There is little vertical integration, and the value chain is lengthy, highly fragmented, and key stages appear to operate in silos.
- There is currently no fit-for-purpose battery regulation in Europe. The proposed EU Battery Regulation will play a key role in the future of the EV battery value chain in Europe when it is implemented (likely in 2023); the proposed Regulation mandates minimum levels of EV battery recycling, minimum content of recycled materials in new batteries, and a "battery passport."
- Reuse in a second life application aims to extend the life of the battery in a less demanding application where battery cells that have degraded still have much to offer, such as a battery energy storage solution (BESS).
- Producing second life batteries involves the dismantling of used batteries and the assembly of all-new battery products; it is highly skilled and labour-intensive.
- The first electric vehicles using Li-ion batteries hit the market in 2010. Little regard was given to design for recycling of the battery packs, or the recyclability of the raw materials; although design for recycling is starting to be addressed, it will take many years before such batteries are ready for second life or recycling.
- The EV battery value chain begins with the mining of valuable raw materials, notably lithium, and others such as nickel and cobalt, for the cathode, and graphite for the anode.
- Battery development and recycling R&D continues to improve recycling processes globally. However, in terms of capacity, Europe is currently significantly underprepared for Li-ion battery recycling at scale.
- As a result, there are significant opportunities to establish a competitive recycling network of battery collection, pre-treatment facilities, and full recycling facilities.
- Uncertainty over the prevailing battery chemistries of the future makes it difficult to forecast recycling volumes and build business cases.
- Securing permits from regulators to establish recycling facilities and conduct the various operations in the recycling process is difficult and time-consuming, and a major bottleneck to the overall process.
- Governments should support and promote the full Li-ion EV battery value chain, from battery production at one end to used EV battery handling at the other, positioning logistics, second life, and recycling as critical parts of the value chain. Support for the sector includes establishing clear rules and monitoring transfer of battery ownership and liability.
- Governments should promote efficient recycling—that is, support clean energy and clean emission recycling processes, and discourage low recovery rates.
- As the concept of circular economy evolves from a noble ambition into a viable business opportunity, governments should seek to promote and support a circular battery economy; the success of circularity depends on legal frameworks and governmental support.
- Recycling faces a challenge of basic economics; currently, the process of recycling LIBs is more expensive than mining for new ore. At the same time, manufacturers are under pressure to adopt circular economy business models, which suits recycling and second life applications.
- Belgium has one major Li-ion battery recycler operating commercially in Belgium: Umicore has a 7,000t facility at Hoboken, and plans to build a 150,000t recycling facility in Europe.
- A second company, ABEE, is building a small R&D recycling facility at Ninove. In October 2022, ABEE announced plans for a battery pack Gigafactory in Belgium, and is preparing to announce the location of a 50,000t recycling facility in Europe. ABEE also plans a second future facility, which will take its total installed capacity to 100,000t. It has not confirmed where this second facility will be built.

Key challenges and opportunities for the EV battery value chain

Upstream: The EV battery supply chain

1. Long EV battery fragile supply chain with limited visibility over working practices, net zero, CSR and ESG at the mining stage
2. Over-reliance/dependence on dominant sources of raw materials, notably DRC and China
3. Over-reliance/dependence on small number of countries for material processing and cell manufacturing, namely China, South Korea, and Japan
4. Changing EV battery chemistries: the automotive industry uses lithium-nickel-manganese-cobalt-oxide (NMC), lithium-nickel-cobalt-aluminium-oxide (NCA), and lithium-iron-phosphate (LFP) batteries, with differing proportions of battery raw materials—this influences battery pack sourcing, and later which cathode materials can be recycled
5. Rising and volatile raw material prices impact manufacturing costs, battery prices, and therefore electric vehicle prices—and this impacts EV adoption

Downstream: Recycling

1. There is a severe lack of recycling capacity in Europe in general—and in Belgium in particular
2. The permit bottleneck: The securing of permits is laborious and time-consuming, and has been cited on several occasions in our interviews as a major bottleneck
3. The recycling business model is not yet established
4. Recycling is capital-intensive, and depending on the technology used, it is also energy-intensive or chemical-intensive
5. Recycling is (currently) part of the waste industry, and used EV batteries are classified as waste, rather than a valuable source of materials

Downstream: Second life

1. Automakers are reluctant to allow batteries out "into the wild" due to concerns over liability

2. There is customer and corporate hesitancy over safety and durability of second life battery applications

3. There are two schools of thought on second life: one is that batteries should be recycled straight away to keep the raw materials moving through the value chain; the other is that second life applications ensure the battery is kept in circulation for as long as possible, maximising the initial CO_2 and financial investments made in the raw material mining phase

4. Battery chemistries and battery prices influence viability of second life applications; chemistries are changing, and battery-related prices are volatile and rising

5. There is little in the way of standards and regulation for second life, something which the EU Battery Regulation is expected to address

EU Battery Regulation

The proposed EU Battery Regulation was published in December 2020, and is still in trilogue at the time of writing, during which time amendments can be made. It is likely to come into effect in 2023. It will set out minimum recycling targets, mandate the use of minimum percentages of recycled materials in new batteries, set a framework for second life batteries, and call for a battery passport.

Battery Passport

The EU Battery Regulation will call for the use of a battery passport. This is likely to be a QR-code/RFID-based system with Blockchain or other form of distributed ledger technology that shows the history of the battery, from raw materials, manufacturing, and ownership, to repairs and modifications.

An unique opportunity

There is an enormous challenge ahead. Talk of a tsunami of used batteries heading our way in a few years' time may be premature, or an exaggeration, but there is a challenge ahead nonetheless, and one that needs addressing head-on. This is a key moment in the development of zero emission mobility, and the industry finds itself with a unique opportunity to address it in advance, with—currently—sufficient time to plan and instal the necessary infrastructure.

Chapter 1.

Lithium-ion electric vehicle batteries

To understand the handling of used EV batteries, it is essential to understand what is inside them. This section looks at rising battery demand, the battery supply chain, and the battery technologies used in EVs and energy storage systems.

Chapter key takeaways

1. Battery production is a global business, with lengthy supply chains dominated by China, which controls the majority of raw materials refining and cell production.

2. Raw materials represent about 65 percent of the final cost of a battery—and the market for raw materials is highly volatile, with raw material prices rising due to demand for EVs and other rechargeable devices.

3. EV price parity with internal combustion engine vehicles has long been seen as $100/kWh (€97.6 / kWh); this is likely to be achieved around 2030, almost a decade later than experts previously expected.

4. Lithium is the common material in all EV battery cathodes, but it is mixed with other materials such as nickel, manganese, and cobalt—and all cathode materials can be recycled.

5. The most significant material in a Li-ion battery, by weight, is graphite. But graphite is very difficult to recycle.

6. The Li-ion battery lies at the heart of the transition to net zero; Li-ion dominates the EV market; and EVs dominate the Li-ion market.

7. A fast-growing EV market does not equate to an equally rapid growth in used EV batteries. The timelines do not correlate, as some batteries last longer than others.

8. October 2022 saw the first battery Gigafactory announcement for Belgium. The new ABEE plant in Wallonia will have a production capacity of 3GWh/year.

9. Some automakers in Belgium are assembling battery packs at their factories, including Volvo Cars and Volvo Trucks at their Ghent factories[4,5], and Audi at its Brussels (Forest) factory.[6]

10. However, although Belgium does not have natural resources at the production end of the chain, or planned investment in gigafactories, it can leverage its expertise in second life and recycling.

4 https://www.media.volvocars.com/global/en-gb/media/pressreleases/263660/volvo-cars-inaugurates-new-battery-assembly-line-at-ghent-manufacturing-plant
5 https://www.volvotrucks.com/en-en/news-stories/press-releases/2022/may/volvo-trucks-opens-battery-plant-in-belgium.html
6 https://www.audi-mediacenter.com/en/audi-in-brussels-5526/profile-of-location-5527

Demand for batteries is rising fast

This section explores the EV battery in the phases that lead up to the use phase, outlining the materials, supply chains, and cell chemistries

The demand for energy storage is rising fast as the world transitions from fossil fuel to electrification. By 2040, two-thirds of the world's new passenger vehicle sales will be electric says, BloombergNEF.[7]

But the rising demand for batteries is coming not only from EVs—over the next decade, McKinsey forecasts the continued growth of Li-ion batteries at an annual compound rate of approximately 30 percent, and by 2030, EVs, energy storage systems, e-bikes, electric tools, and other battery-intensive applications, could account for 4,000-4,500 gigawatt-hours (GWh) of Li-ion demand.[8]

According to research and consulting company Wood Mackenzie, global cumulative lithium-ion battery capacity could rise over five-fold to 5,500 Gwh between 2021 and 2030. The consultancy notes that electric vehicles account for almost 80 percent of Li-ion battery demand, and that high oil prices and zero-emission transportation policies will cause a sharp rise in demand for lithium-ion batteries, which will exceed 3,000 GWh by 2030 (Fig 2).[10] The remainder includes batteries for smaller products such as portable electronic devices, micromobility vehicles such as e-bikes and e-scooters, and power tools.

In its report, "Net Zero by 2050 - A Roadmap for the Global Energy Sector,"[11] the International Energy Agency (IEA) notes that around 2 billion EVs need to be on the road by 2050 for the world to hit net zero – a steep increase from EV sales in 2021 of 6.6 million units.

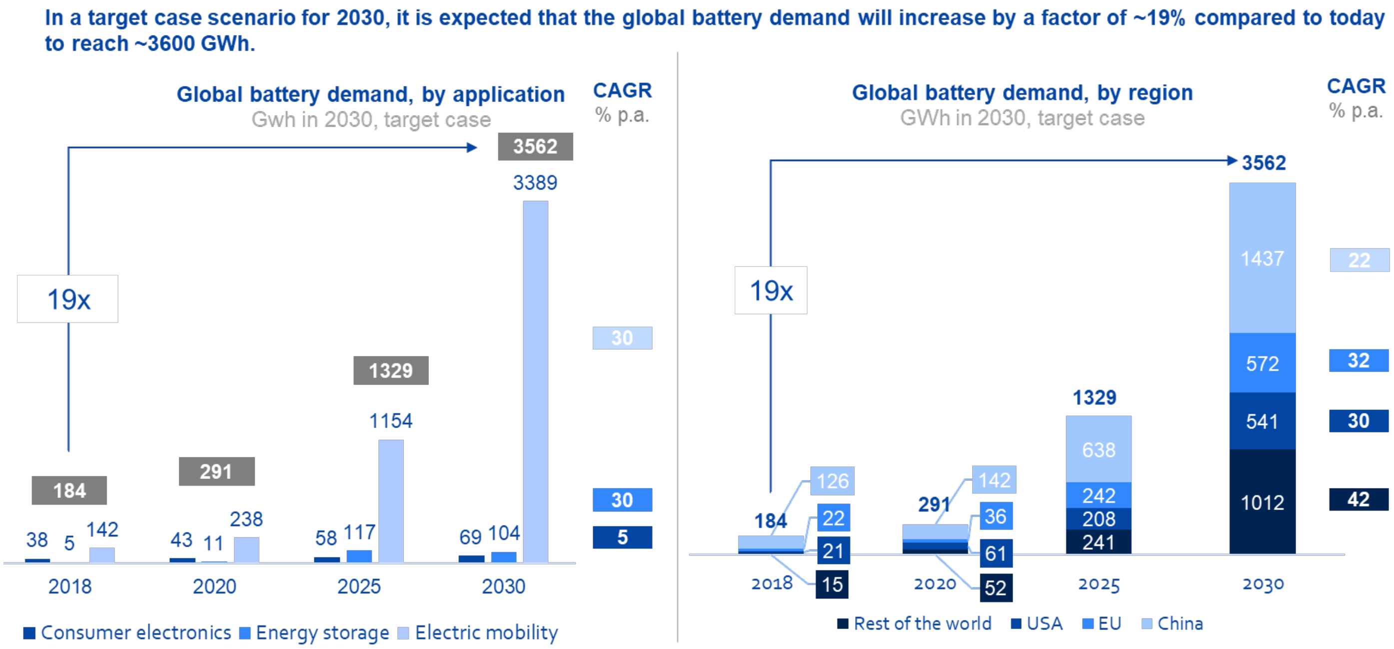

Fig 2. Battery demand in the target state by 2030, by region and application[9]

7 https://www.bloomberg.com/news/articles/2021-08-09/at-least-two-thirds-of-global-car-sales-will-be-electric-by-2040
8 https://www.mckinsey.com/industries/metals-and-mining/our-insights/lithium-mining-how-new-production-technologies-could-fuel-the-global-ev-revolution
9 Adapted from World Economic Forum, Global Battery Alliance; McKinsey analysis
10 https://www.woodmac.com/press-releases/global-lithium-ion-battery-capacity-to-rise-five-fold-by-2030/
11 https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf

What's inside an electric vehicle battery?

An electric vehicle battery is a highly complex machine. The battery pack contains typically hundreds of battery cells, grouped into modules, as well as other high value components, including wiring, a computer known as a battery management system (BMS), a thermal management system to regulate the battery's temperature, separators to isolate the modules, and a conductive liquid that transports the ions between the negative and positive poles known as electrolyte. All of this is housed in a protective enclosure. As a result, an EV battery pack can account for 30 to 50 percent of the value of the vehicle, and around 40 percent of the vehicle's weight.

With raw materials accounting for so much of the battery's value, and the battery accounting for so much of the vehicle's value, almost a third of the value of the car can be recycled in one place; the same cannot be said for recycling the rest of the vehicle, which is more fragmented.

The battery enclosure

Used EV battery recycling assumes recovery of the metals contained within the battery pack, but this overlooks a crucial part of the battery pack: the protective enclosure (also known as the housing, or casing).

The enclosure (Fig 3, Fig 4.) is a critical part of the battery pack – often a structural part, it must be capable of withstanding the impact of a crash, including being pierced; it must also be fireproof, waterproof, and tamper-proof; and it must be able to hold the weight of the battery modules and other parts which make up the battery pack. As a result, the enclosure itself is often very heavy.

Fig 3. SABIC prototype EV battery pack tray

Most battery pack enclosures are made of steel, aluminium, or an unrecyclable sheet mould compound (SMC) – a high-strength glass reinforced thermoset moulding material, typically compression-moulded. A typical aluminium enclosure can weigh 60 to 160 kg, although this depends on the size of the car and the battery pack, and could weigh more. Using a 100 percent composite enclosure rather than aluminium can reduce a battery enclosure weight by 40 percent.

Fig 4. SABIC Honda CR-V PHEV battery pack cover

Some enclosures are made of plastic, but here the plastic matters: a thermoset enclosure cannot be recycled, but thermoplastic can. SABIC, a chemical manufacturing company and major materials supplier to the automotive industry, has developed what it claims is a fully recyclable fireproof thermoplastic enclosure that can, "potentially realize 30 to 50 percent weight savings per component, improve energy density, simplify the assembly process, reduce costs, improve thermal control and safety and enhance crashworthiness."[12] While the thermoplastic enclosure is of no interest to the recyclers discussed in this report—they receive the contents of the pack once it has been dismantled, but not the enclosure—it is worth remembering the wide range of parts that make up an EV battery pack, and the necessary material considerations when discussing recyclability.

The battery enclosure is a key area for design for recycling. As well as the materials used for the enclosure, consideration should be given to the closure mechanisms used to seal the battery pack housing; the enclosure must be sealed for safety and security reasons, but the first challenge faced by battery dismantlers is opening and removing

12 https://www.sabic.com/en/news/29554-sabic-advances-thermoplastic-solutions-for-critical-ev-battery-technologies

the enclosure, which is too frequently sealed specifically with the intention of not being opened.

Estimating battery weight

Across the global automotive industry, there is a wide range of EV battery weights and sizes, which vary according to vehicle size and application. A selection is presented in Table 1. This makes it difficult to assign an average battery weight (Fig 5), but for the purposes of this report, we have taken the battery pack weights and capacities of selected EVs, and calculated battery weight per kWh. For this report, we assume an average weight of 6 kg per kWh.

Table 1. EV battery weight per kWh[13]

Model	Pack weight (kg)	Pack capacity (kWh)	Weight per kWh (kg)
Chevrolet Bolt	435	65 kWh	6.7
Ford F-150 Lightning	726	131 kWh	5.5
Hummer	1329	214 kWh	6.2
Hyundai Ioniq 5	450	72.6 kWh	6.2
Kia Niro	457	64kWh	7.1
Renault Zoe	326	55kWh	5.9
Tesla Model 3	481	75 kWh	6.4
VW e-up!	248	36.8kWh	6.7
VW ID.4	493	82kWh	6.0

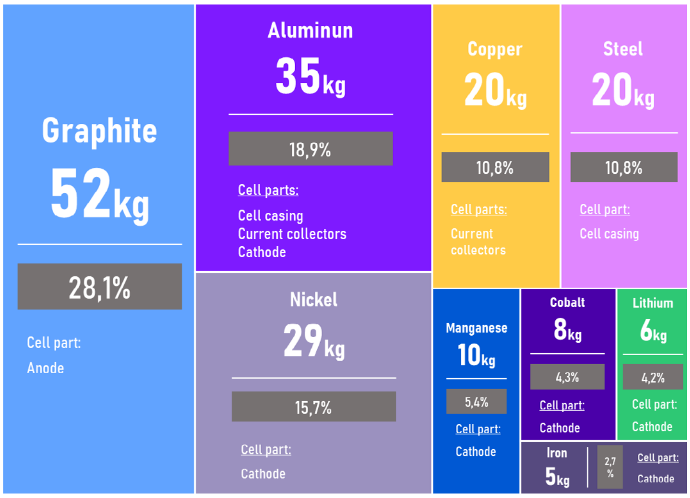

Fig 5. The key minerals contained in an average EV battery. Approximately 185 kg of minerals are contained in the cells of an average lithium-ion battery with a 60 kWh capacity.[14]

At the heart of the battery: The cell

The power in a battery comes from the cells, which are arranged into modules. Not dissimilar in appearance to the "AA" cells required for portable non-rechargeable devices, each cell contains a cathode (the positive pole), electrolyte, separators, and an anode (the negative pole). The Volkswagen ID.4 (Fig 6), for example, has an 82 kWh battery pack made up of 288 cells grouped into 12 modules.[15]

Fig 6. Volkswagen ID.4, credit: Volkswagen, taken from newsroom on 3/12/22.

Lithium-ion battery technology dominates the EV market; Li-ion refers to the lithium-based cathode chemistries, of which there are several. Common to all current Li-ion batteries are lithium and graphite; depending on the cathode chemistry, other materials might include copper, manganese, nickel, and cobalt. As will be seen, acquiring these raw materials is the first stage in the EV battery value chain.

13 Various, Kovetic
14 Adapted from "Transport and Environment"
15 https://www.sae.org/news/2020/11/vw-id.4-launch--u.s.-electrification-overview

The automotive industry has settled—for now—on Li-ion for almost all plug-in vehicles. According to the Atlantic Council, "Given its high conductivity and light weight, the Li-ion battery's namesake mineral is incredibly difficult to substitute."[16]

A lithium-ion battery cell cathode collects electrons during the electrochemical reaction. There are three cell types: cylindrical, prismatic, and pouch.

The cathode contains a lithium-based chemical mix that, depending on the chemistry chosen, may include cobalt, manganese, and iron. The chemistry used for the cathode is crucial to the cell's—and therefore the battery's—performance. The chemistry also influences how the battery is handled at EOL, with the materials' values influencing the return on investment (ROI) of the recycling process, and the process itself influencing which materials can be recovered.

The anode, for which Li-ion batteries almost exclusively use graphite, delivers the electrons via the electrolyte to the cathode. EV batteries tend to range from around 30kWh to 100kWh and around 1kg of graphite is required per kWh of battery energy. Based on this approximation, the VW ID.4's 82kWh battery pack would contain 82kg of graphite – roughly equivalent to the average weight of an adult man.

A cost breakdown of lithium-ion cell is represented in Table 2. BloombergNEF notes that the cathode cost includes mining and refining, adding: "If you take away the processing costs, the raw materials in the cathode still account for about a third of the total cell cost."

Table 2. Breakdown of the costs of a lithium-ion battery's cell components.[17]
Note: Due to rounding, totals add up to more than 100.

Cell cost component	%
Cathode (containing lithium, nickel, cobalt, manganese, etc)	51
Labour, manufacturing, depreciation	24
Anode (graphite)	12
Separator	7
Electrolyte	4
Housing/enclosure	3

The long tail of the EV battery supply chain

There are six key stages in the EV battery value chain (Fig 7):

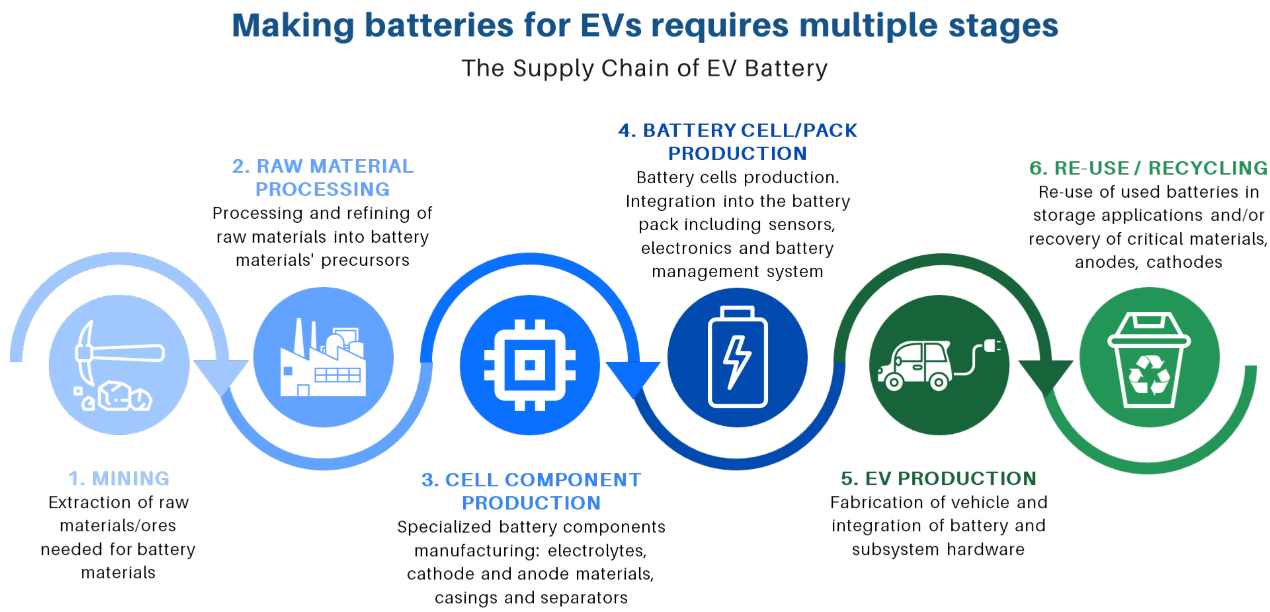

Fig 7. The six key stages in the supply chain of EV batteries.[18]

16 https://www.atlanticcouncil.org/wp-content/uploads/2022/09/Alternative-Battery-Chemistries-and-Diversifying-Clean-Energy-Supply-Chains.pdf
17 https://www.bloomberg.com/news/newsletters/2021-09-14/ev-battery-prices-risk-reversing-downward-trend-as-metals-surge
18 Adapted from IEA, 2021.

The lithium-ion battery: a global effort, dominated by China

Battery production is a global business, with lengthy supply chains dominated by China, which controls the majority of raw materials refining and cell production.

Battery raw materials: The Big Five

The five main battery materials are lithium, nickel, cobalt, manganese, and graphite. These, and other materials, are mined in countries as far apart as Australia and Chile, shipped around the world (mostly to China, which controls the majority of raw materials refining and cell production) for refining, and then sent to cell makers, then module assemblers, and finally to battery pack assemblers, before being sent to the vehicle assembly plant to be built into an electric vehicle. That vehicle may, of course, make a long journey before it reaches the market where it will be used.

Note that the European Commission considers cobalt, graphite, and lithium to be critical raw materials.[19]

- **Lithium:** Australia, Argentina, and Chile are the major sources of high-grade lithium. Global lithium reserves stand at about 20 million tons, and global lithium production in 2021 totalled 90,700 tons; this represents approximately 0.5 percent of total global reserves, according to the US Geological Survey[20]. Argentina, Bolivia, and Chile make up the so-called "lithium triangle," collectively accounting for 58 percent of the world's identified lithium resources;[21] Australia produces around 60 percent of the world's lithium[22] and is the world's fifth largest nickel producer.[23]

- **Nickel:** Available in many countries worldwide, but primary sources are Australia, Brazil, Canada, Indonesia, New Caledonia, the Philippines, and Russia (prior to the invasion of Ukraine, Russia held 11 percent of global nickel production and 15 percent of world nickel exports[24]).

- **Cobalt:** A by-product of nickel and copper production, only a small percentage of cobalt comes from dedicated cobalt mines. Around 70 percent of the world's cobalt comes from the DRC, according to cobalt trade association, the Cobalt Institute, citing the United States Geological Survey; China controls 80 percent of global cobalt processing capacity.[25]

- **Manganese:** South Africa is the largest single source of manganese, accounting for 37 percent of the world's manganese mining in 2021, and 43 percent of the world's manganese reserves.[26] Gabon and Australia make up the top three sources of manganese.

- **Graphite:** China, Brazil, and Mozambique are the three leading producers of graphite.[27] China is responsible for 80 percent of the global refining capacity for battery raw materials and 60 percent of the world's graphite production.

According to research by Greenpeace East Asia, battery production between 2021 and 2030 will spend 30 percent of the world's proven cobalt resources. During that same period, 10.35 million tons of nickel, cobalt, lithium, and manganese will be mined.[28] Fig 9. shows main countries providing these raw materials together with a forecast for 2030.

To put some perspective on the world's dependence on these countries' role in the global battery value chain, a typical NMC battery cathode might contain 60 percent nickel, 20 percent cobalt and 20 percent manganese; there are now efforts to increase the nickel content in NMC cathodes up to as much as 80 percent and reduce the other metals to 10 percent each.[29] And as outlined elsewhere in this report, the automotive industry is transitioning away from NMC in favour of lithium iron phosphate (LFP).

19 https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en
20 https://pubs.usgs.gov/periodicals/mcs2022/mcs2022.pdf
21 https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-lithium.pdf
22 https://www.ansto.gov.au/news/australia-charges-ahead-new-lithium-technology
23 https://www.nrcan.gc.ca/our-natural-resources/minerals-mining/minerals-metals-facts/nickel-facts/20519
24 https://www.oecd.org/ukraine-hub/policy-responses/the-supply-of-critical-raw-materials-endangered-by-russia-s-war-on-ukraine-e01ac7be/
25 https://www.atlanticcouncil.org/in-depth-research-reports/issue-brief/alternative-battery-chemistries-and-diversifying-clean-energy-supply-chains/
26 https://pubs.usgs.gov/periodicals/mcs2022/mcs2022.pdf
27 https://investingnews.com/daily/resource-investing/battery-metals-investing/graphite-investing/top-graphite-producing-countries/
28 https://www.greenpeace.org/eastasia/press/6175/greenpeace-report-troubleshoots-chinas-electric-vehicles-boom-highlights-critical-supply-risks-for-lithium-ion-batteries/
29 https://cen.acs.org/energy/energy-storage-/Lithium-ion-batteries-cobalt-free/98/i29

Despite the lengthy supply chains, rechargeable batteries lie at the heart of the transition to net zero. And Li-ion is the dominant technology for anything with a rechargeable battery.

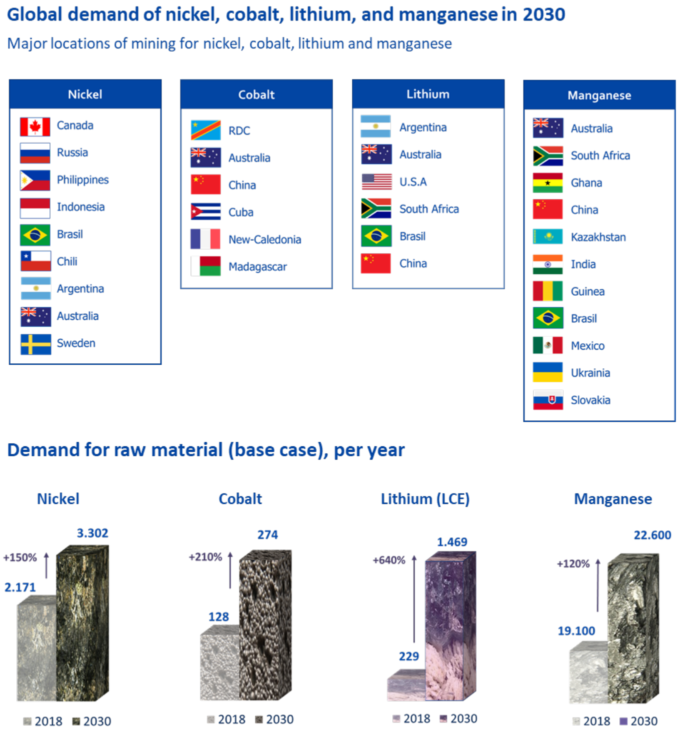

Fig 8. Major nickel, cobalt, lithium, and manganese mining sites. Expected global demand in k tonnes of raw materials in 2030 compared to 2018.[30]

Cobalt is "the highest material supply chain risk for electric vehicles"

The US Department of Energy (US DOE) considers cobalt to be "the highest material supply chain risk for EVs in the short and medium term."[31] The US DOE notes that a 100 kWh EV battery pack using a cobalt-based cathode chemistry contains up to 20 kg of cobalt, equating to a cobalt content of up to 20 percent of the weight of the cathode.

The automotive industry is transitioning away from cobalt, with LFP now becoming the dominant cathode chemistry for EV batteries.

The graphite challenge

The most significant material in a Li-ion battery, by weight, is graphite. Approximately 30 percent of every Li-ion battery is graphite, typically in the form of tiny graphite balls about a tenth of the thickness of human hair.

Our research found that:

- **China dominates graphite supply:** Most of the world's natural graphite comes from China, and almost all of the world's graphite refining takes place in China. Synthetic graphite helps reduced reliance on China, but it is made from fossil fuels, and it is becoming more expensive than natural graphite.

- **Graphite is very difficult to recycle:** Graphite is very difficult to recycle, as its chemical structure is usually damaged during battery operation due to factors such as charging and discharging cycles, and ambient operating temperatures.[32]

- **Graphite *can* be recycled, but the level of refining depends on the business case:** Noshin Omar, CEO of ABEE told us this depends on the grade of graphite required. "Ultimately, the quality and purity of the materials is the decider. In principle, everything can be recycled. It is just a matter who is going to pay for it and what is the output material."

- **Battery-grade graphite recycling is not yet commercially viable:** "Based on what the market is paying, and based on the complexities of pulling out graphite out of the black mass that is created in recycling, it is not commercially viable to recycle graphite at this stage. It can be repurposed, but it would need to be sold for a price that makes it viable to even go through that exercise," said our interviewee Nico Cuevas, CEO and co-founder of Urbix, an Arizona, US-headquartered specialist in advanced energy storage cell designs and materials.

- **Graphite recyclability depends on the recycling method:** "Typically, pyrometallurgical recycling burns out the graphite," noted ABEE's Omar, who believes graphite must be recycled. ABEE does not use pyrometallurgy.

- **The graphite in a used EV battery can be used in the battery recycling process:** Umicore uses graphite's chemical characteristics as a reducing agent in its high temperature process. "That is the highest possible value that we can attach to graphite at the end of life of a battery," said Kurt Vandeputte, Sr Vice President Battery Recycling Solutions of Umicore. "I do not see graphite being refined to battery grade in the near future." He added that in terms of circularity, graphite presents a challenge, because of its

30 WEF
31 https://www.energy.gov/eere/vehicles/articles/reducing-reliance-cobalt-lithium-ion-batteries
32 https://pubs.acs.org/doi/10.1021/acssuschemeng.1c04938

low value as a primary product. Separating graphite is very difficult, and it is even more challenging refining it to battery-grade, said Vandeputte. "The costs would be horrendously high. That is the key bottleneck to create the closed loop."

- **Graphite can be extracted and prepared for other companies to recycle:** Graphite can be separated from the black mass during the first stage of hydrometallurgy. Christophe Couesnon, Director of Strategy, Raw Material and Recycling, Battery Platform at Solvay explained that Solvay could separate graphite and prepare it for any company that can fully recycle it.

China dominates the EV battery value chain

The EV battery value chain may be global, but it is controlled by a small number of countries; 85 percent of the world's EV batteries are produced by China, Japan, and South Korea—and China is the dominant of these three countries. As can be seen in Fig 8, Chinese companies occupy around two-thirds of the Li-ion battery supply chain, dominating cobalt refining, and graphite mining and refining. China is also a major source of lithium brine and the fourth largest source of manganese.

CHINA'S ROLE IN...

RAW MATERIAL SOURCING		CHEMICAL REFINING/PRODUCTION		CATHODE & ANODE PRODUCTION		BATTERY CELL PRODUCTION
Lithium	13%	Lithium chemical	44%	Cathode	78%	70%
Cobalt	> 1%	Cobalt refining	75%	Anode	91%	
Nickel (refined)	18%	Nickel sulphate	69%			
Manganese (refined)	8%	Manganese refining	95%			
Graphite (mined)	64%	Spherical graphite	100%			
		Synthetic graphite	69%			

Fig 9. China's dominance of the Li-ion battery value chain.[33]

The quest for EV/ICE price parity

The automotive industry has long expected to achieve price parity between electric vehicles and internal combustion engine (ICE) vehicles by around 2023, based on declining battery prices and advances in battery technology. However, recent price increases and considerable volatility in raw material prices look set to push back the date by which parity can be achieved.

According to CICEnergiGune, a non-profit research centre for electrochemical and thermal energy storage based in the Basque Country (Spain): "raw materials represent about 65 percent of the final cost of a battery"[34]—and the market for raw materials is highly volatile. Benchmark Mineral Intelligence (BMI), a consultancy specialising in tracking battery materials performance notes that since January 2020, the cost of raw lithium has risen almost 900 percent, and in the period January to August 2022, Chinese battery-grade lithium carbonate prices have risen by 90 percent, and lithium hydroxide by 127 percent.[35]

Raw material prices influence battery prices; and battery prices influence EV prices, and by extension, EV sales. Raw material prices also influence the business models for recycling and second life applications.

A battery price based on $100 / kWh (€97.6 /kWh) has long been seen as the turning point for EV adoption, as it is expected to enable EVs to reach price parity with internal combustion engine vehicles.

To put this into context, a VW ID.4 battery would have cost not so long ago around €50,000, but today's price of around €15,000 is a more reasonable investment.

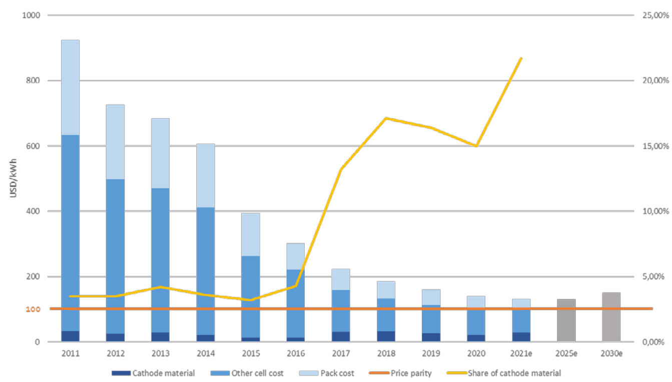

Fig 10. Evolution of the average lithium-ion battery pack price and cathode material cost share between 2011 and 2021, based on IEA analysis of BNEF.[36] Expected battery price for 2025 and 2030.

However, although a steady decline in battery prices (Fig 10) led to projections over the last decade of sub-$100 / kWh battery packs by the early 2020s, recent volatility and considerable rises in raw material prices have pushed back expectations of reaching, let alone breaching, the $100 / kWh barrier.

33 Adapted from https://www.benchmarkminerals.com/membership/chinas-lithium-ion-battery-supply-chain-dominance/
34 https://cicenergigune.com/en/blog/critical-materials-battery-industry
35 https://www.benchmarkminerals.com/membership/what-is-driving-lithium-prices-in-2022-and-beyond/
36 Adapted from https://www.iea.org/data-and-statistics/charts/average-pack-price-of-lithium-ion-batteries-and-share-of-cathode-material-cost-2011-2021

Recent lithium price rises will be passed on to automakers with lithium supply contracts, and ultimately on to consumers.

According to a Fitch Solutions report in October 2022,[37] high and volatile prices of lithium, nickel and other raw materials will prevent battery prices from reaching the $100 / kWh price mark before 2026, with Fitch analysts expecting battery prices to remain around $130 / kWh until 2025. Fitch analysts note that: "A drop in EV prices will be necessary to increase EV adoption amongst middle-to-low-income consumers, particularly in markets where there are no incentives or subsidies to support consumers in purchasing an EV."

E Source, a Colorado, US-based research firm, expects a 22 percent rise in average battery cell costs by 2026. E Source puts current cell prices at $128/kWh, but expects a surge in raw material demand to push the average cell cost to a peak of $138/kWh in 2026, before declining to around $90/kWh by 2031. This could add between $1500-$3000 to the price of an EV in 2026, with Euro values broadly similar thanks to current USD-EUR exchange rates.[38]

Clearly, considerable progress has been made in bringing down battery prices, but high and volatile raw material prices make it difficult to forecast EV:ICE price parity.

Raw material pricing is further impacted by demand for EV batteries outstripping supply. According to Benchmark Mineral Intelligence (BMI), at least 384 new graphite, lithium, nickel, and cobalt mines will need to be built over the next decade to meet demand for electric vehicles and energy storage batteries by 2035.[39] As an indication of the role that recycling could play in supplying material for new batteries, BMI's forecast for new mine demand drops to 336 if recycling is included as a source. BMI also notes that mines take at least five years to build, underlining the urgency in establishing the necessary recycling infrastructure not only to deal with used EV batteries, but also to support mining with the supply of battery raw materials.

As a result of this high demand, raw material prices are soaring.

And the rising and volatile raw materials prices, coupled with demand outstripping supply, has slowed the decline in Li-ion battery prices, pushing back the date by which we can expect to see EV:ICE cost parity.

The business case for recycling is directly linked to the price of raw materials; the higher the price for virgin materials, the more attractive recycling becomes. This also influences the business case for second life applications, as battery owners will seek to recover value from the battery through recycling.

Price parity around 2030 is almost a decade later than experts had previously expected and will delay the adoption of electric vehicles.

Lukas Neckermann, Neckermann Strategic Advisors

Although battery prices have dropped considerably, increased demand for lithium and cobalt have kept EVs from reaching absolute price-parity. As raw material prices stagnate or increase, and the availability of second life and fully-cycled batteries from first-generation vehicles increases, it creates a real opportunity for battery recycling, expected to be a multi-trillion dollar business by 2030.

Recycling will be a lucrative business and an essential link in the battery value chain. Done well and consistently, it is likely to even reach or surpass the volumes from virgin materials. But at the moment, it is still in its infancy, and there are many challenges to overcome, not least the logistics of sourcing and transporting battery packs, as well as the diversity of cathode chemistries and cell technologies.

Hence, we need batteries to be designed for recycling, and ensure that recycling processes are as environmentally friendly as possible, including using renewable energy for the recycling process, and we need to ramp up recycling capacity. This presents a perfect opportunity for companies and countries to take a leading position in the handling of used EV batteries. Now is the time.

37 EV Battery Outlook: Lithium Price Surge Poses Additional Headwind To Automakers
38 https://www.autoevolution.com/news/ev-battery-production-costs-estimated-to-rise-22-in-the-next-four-years-189093.html
39 https://www.benchmarkminerals.com/membership/more-than-300-new-mines-required-to-meet-battery-demand-by-2035/

Europe's rapid battery gigafactory footprint expansion

Although this report is about recycling, it is worth noting the development of Europe's battery Gigafactory footprint. As Kurt Vandeputte of Umicore told us, "Every gigafactory that is built to make batteries will be followed ten or 15 years later by a gigafactory to recycle the batteries."

Fig 11 illustrates the locations of new gigafactories, and *Battery News* has collated information about likely timelines.

Belgium's first battery pack Gigafactory

In October 2022, ABEE's CEO Noshin Omar announced the first Gigafactory for Belgium. Located at Seneffe-Manage in Wallonia, the plant will have a production capacity of 3 GWh/year. This will be the first battery gigafactory in Belgium, and the company expects the factory to be fully operational by mid-2025, producing LFP batteries for automotive and stationary applications. The Seneffe-Manage plant will produce complete battery packs, using outsourced cells.

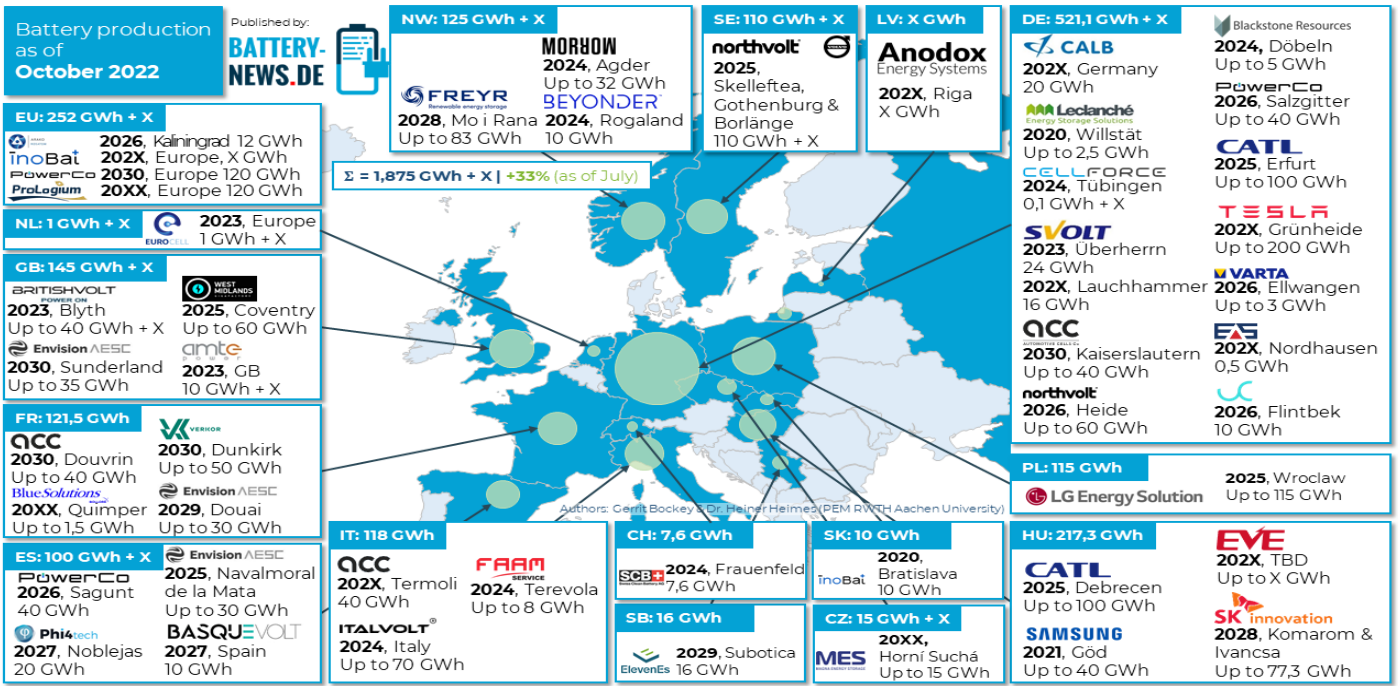

Fig 11. Battery production in Europe as of October 2022.[40]

40 Battery News (with permission)

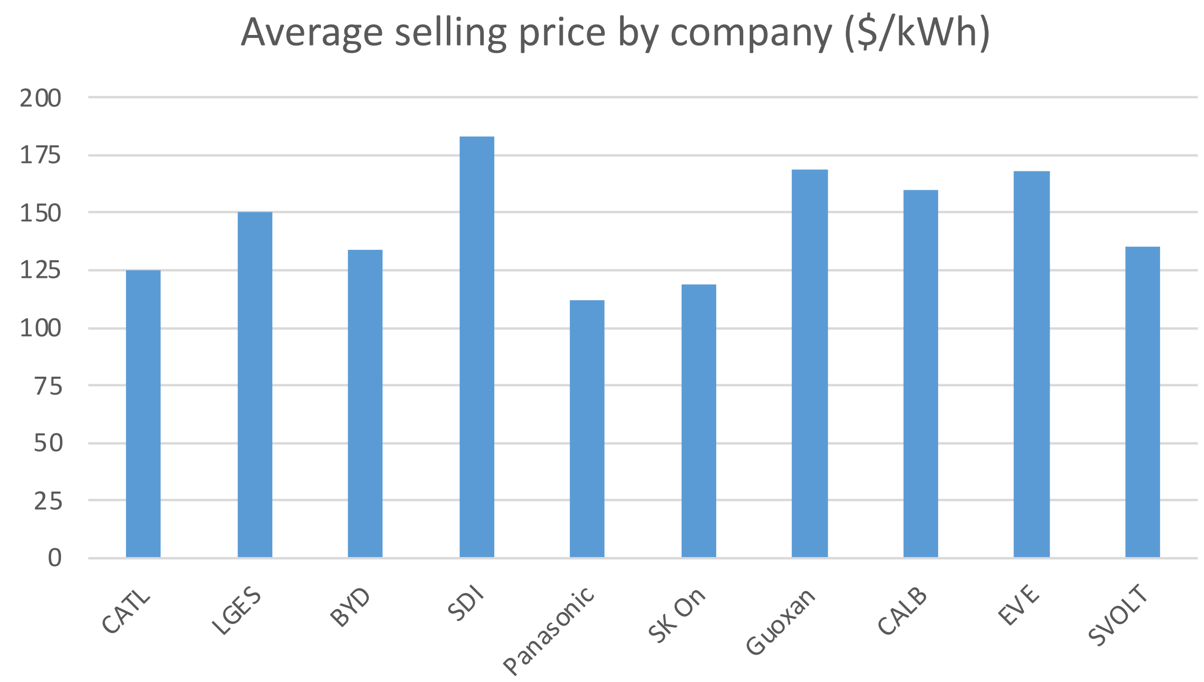

Fig 12. Average selling price of batteries of the 10 largest battery suppliers, by company in $/kWh.[41]

Table 3 shows the world's top ten battery suppliers, and the dominance of Asia in battery manufacturing. The average selling price of battery of these top ten suppliers is illustrated in Fig 12.

Table 3. The 10 largest battery suppliers. Sales and sales volume of batteries per company.[42]

	Sales		Sales volume	
Company	**M$**	**M/S**	**MWh**	**M/S**
CATL	13,000	30%	104,000	39%
LGES	5,840	14%	38,900	14%
BYD	3,836	9%	28,700	11%
SDI	2,980	7%	16,300	6%
Panasonic	2,150	5%	19,200	7%
SK On	2,070	5%	17,400	6%
Guoxuan	1,130	3%	6,700	2%
CALB	1,520	4%	9,500	4%
EVE	520	1%	3,100	1%
SVOLT	420	1%	3,100	1%
Others	9,264	22%	21,800	8%
Market Demand (in terms of pack)	42,730	100%	268,700	100%
Top 10 sales	**33,466**	**78%**	**246,900**	**92%**

41 https://www.sneresearch.com/en/insight/release_view/48/page/0?s_cat=|&s_keyword=#ac_id
42 https://www.sneresearch.com/en/insight/release_view/48/page/0?s_cat=|&s_keyword=#ac_id

What are the key EV battery technologies?

To understand the complexities of handling used Li-ion EV batteries, and Belgium's role in these sectors, it is essential to understand EV battery technology, and the global EV battery industry.

The lithium-ion battery lies at the heart of the transition to net zero

Lithium lies at the heart of the transition to net zero, and lithium-ion is the dominant technology for rechargeable devices.

Although some of the very earliest cars were battery electric vehicles, the modern mainstream EV industry, using Li-ion batteries, began around 2010, when Nissan launched the Leaf, and Peugeot, Citroen, and Mitsubishi jointly launched a vehicle that sold under their own brand names as the Ion, C-Zero, and i-MiEV respectively; these were followed two years later by Tesla with the Model S.

Since then, sales of EVs have evolved slowly, until now; a rapid acceleration in EV sales is expected as ultra-low and zero emission mandates bring to an end the sale of cars with internal combustion engines (ICEs). Indeed, December 2021 marked the first time that Europeans bought more electric cars than diesels. Global EV sales in 2021 were 4.4 million vehicles, up 127 percent year-on-year, and Goldman Sachs forecasts sales growing 56 percent year-on-year in 2022 alone to 6.9 million vehicles.

Nonetheless, although EV sales are rising sharply, and EV technology has developed rapidly, it remains youthful compared to the internal combustion engine (ICE). Cost, range, raw materials sourcing, battery chemistry – all remain under-developed, dynamic areas subject to volatility.

The challenge for all stakeholders is what to do with a Li-ion battery when it reaches EOL.

Li-ion dominates the EV market – for now...

While Li-ion may dominate now, it is expected that longer-term there will be other battery chemistries and technologies. As well as concerns about undersupply of raw materials, geopolitical risks also threaten Li-ion's future; as noted earlier, Russia and China both play key roles in the EV battery value chain.

Longer term, the search is on for viable alternatives that reduce or avoid entirely the need for specific battery raw materials such as lithium, nickel, cobalt, and graphite. While such batteries would not be available for recycling until perhaps 20 years or more from now, it is important for anyone building a long-term recycling business to understand.

The Li-ion battery recycling business has evolved very traditionally around batteries containing nickel and cobalt, but the battery market is evolving fast. "By 2028 or 2030, we will have solid-state technology, but there are no recycling plants for solid-state technology. We (ABEE) are currently setting up at one university a research pilot plant to deal with solid-state technology, because we want to fully understand solid-state recycling," said Noshin Omar, CEO of ABEE. "The recycling industry is very traditional. But electrification is moving fast, and that is creating opportunities for new players."

Here we summarise the key features of Li-ion and other promising technologies:

Lithium-ion

Lithium-ion is the dominant technology used for electric vehicle batteries. There are three designs for Li-ion cells: in cylindrical, prismatic, and pouch formations. And within Li-ion cells, there are three main cathode chemistries of interest to this report:

- NMC: Lithium-nickel-manganese-cobalt-oxide
- NCA: Lithium-nickel-cobalt-aluminium-oxide
- LFP: Lithium-iron-phosphate

All three contain lithium, while NMC and NCA contain nickel and cobalt; LFP is less material-intensive, and currently the automotive industry's preferred cathode chemistry.

The rise of LFP, and what it means for the recycling business model

NMC currently dominates the EV market, but the automotive industry is transitioning from NMC to LFP batteries. The use of LFP is on the rise, and only Tesla uses NCA batteries in some of its vehicles. However, NCA's high nickel content, while capable of delivering high range, requires a more complex and controlled production process than NMC and LFP.

On Belgium: Stefan Wolf, ETIP Batteries Europe & Accompanying Research for the Battery IPCEIs

It is good for a smaller European country (i.e. Belgium) to focus on a specific part of the EV battery value chain. Belgium is well positioned logistically. The country has expertise in recycling, and it can integrate recycling into cathode production. Focusing on recycling is a good industrial policy, but regulatory hurdles could hinder the development of a recycling industry. Belgium should figure out how to make the material inflow as easy as possible.

Lithium-iron-phosphate is a lower cost technology, which requires no nickel or cobalt. It is more stable than NMC and NCA, but has a lower energy density, which equates to a shorter range. As the EV charging infrastructure expands, consumers may accept lower stated ranges; LFP also brings down the cost of the battery, enabling cheaper EVs.

According to Wood Mackenzie, NMC accounted for half of EV and energy storage batteries in 2021. However, thanks to LFP's competitive cost, long lifecycle, and high safety performance, the consultancy expects LFP's market share to surpass NMC in 2028.[43]

Approximately 90% of the world's LFP battery cell manufacturing capacity is based in China,[44] and only Chinese companies are allowed to produce and sell LFP batteries in that country.

However, while the absence of nickel and cobalt in LFP batteries is clearly important for reducing the environmental impact of the battery, it is also the absence of these materials—and as a result, their lower resale value—which makes LFP batteries less attractive to recyclers.

"Lithium batteries in general but LFP in particular have triggered a need to consider corporate responsibility for batteries," said Catherine Lenaerts, Managing Director of Febelauto, a Belgian battery collection company profiled later in this report.

Although there is currently no recycling of LFP in Europe, ultimately, the recycling industry will need to be able to handle LFP and other battery chemistries. Dismantling the pack to cell level is the same regardless of battery chemistry. Only at this point are separate chemistry-specific recycling processes required, which would be aided by tracking and tracing of the battery system such as a battery passport as called for by the proposed EU Battery Regulation.

And the EU Battery Regulation is expected to require recycling of all batteries, including LFP, regardless of business model.

The challenge for the automotive industry is to reduce the cost of batteries; the challenge for recyclers is to profitably recycle lower value batteries, whilst factoring in the long-term decline in cell and pack prices that will see recycled battery prices close to parity with new battery prices on a $/kWh basis.

43 https://www.woodmac.com/press-releases/global-lithium-ion-battery-capacity-to-rise-five-fold-by-2030/
44 https://www.greencarcongress.com/2022/01/20220109-lfp.html

Anode-free batteries

All Li-ion EV batteries currently use a graphite anode, with either natural or synthetic graphite. However, in September 2022, Our Next Energy (ONE), a Michigan-based energy storage company, unveiled a 240-Ah prismatic anode-free cell, which eliminates the need for graphite and anode manufacturing equipment, enabling $50/kWh cell cost at scale.[45]

Cell to pack batteries

In June 2022, CATL detailed its third-generation cell to pack technology. Cell to pack technology bypasses the need for battery modules, with considerable implications for the volume of the pack dedicated to cells, the remaining space taken up by structure, connections, safety features, and cooling. CATL's Qilin technology offers 72 percent volume utilization efficiency.[46] It remains to be seen whether cell to pack technology will facilitate or hinder the recycling process.

Solid-state batteries

Where lithium-ion batteries use a liquid or polymer electrolyte (the medium which enables the ion to travel between the cathode and anode of a battery cell), a solid-state battery uses a solid electrolyte. Solid-state batteries are expected to make a market entry within the next decade or so; the technology is promising, but has yet to be proven. One of the challenges faced by manufacturers is scaling conductive solid material sufficiently for electric vehicle applications.

Benchmark notes that although the solid-state battery market could be worth $2.7 billion annually by the end of the decade, "production will require a substantial increase in the supply of lithium metal by the end of the decade."[48]

We interviewed Gilles Normand, Executive Vice President International Development at solid-state battery manufacturer ProLogium Technology. Solid-state batteries, he told us, address six deficiencies of Li-ion batteries, namely safety, weight, energy density, chargeability, weight, cost, and recyclability (Table 4). He also acknowledged that work still needs to be done on cell chemistry, manufacturing, and charging cycles.

Table 4. Comparison of the advantages and challenges of solid-state batteries.[47]

Advantages of solid-state batteries	Challenges of solid-state batteries
Safety: Solid-state batteries use solid electrolytes. Li-ion batteries use liquid electrolyte, which can be unstable and has been associated with thermal events	**Number of charging cycles:** ProLogium says it has achieved well above 500 cycles, but wants to achieve 1000 cycles to match auto industry requirements
Solid-state batteries have a higher **energy density** than Li-ion batteries	Recycling industry has not yet established how to successfully handle solid-state batteries
Improved charging compared to Li-ion. ProLogium claims its solids state battery can charge to 80% in 12 minutes	Solid-state contains even less valuable recyclable material than LFP batteries, adding further challenges to recycling
The absence of liquid electrolyte **reduces weight** and **increases packaging space for active materials**	
Lower cost than Li-ion batteries: Prologium claims it can reduce cost by 16% at cell level, and 25% at pack level, thanks to simplified technology and lower cost per kilowatt hour manufacturing	**Cell chemistry** (and associated manufacturing process) remains in development
Recyclability: solid-state is easier to **recycle** than Li-ion batteries	

45 https://one.ai/news/anode-free-release
46 https://www.catl.com/en/news/958.html
47 https://www.samsungsdi.com/column/technology/detail/56462.html?listType=gallery
48 https://www.benchmarkminerals.com/membership/solid-state-needs-lithium-metal-production-to-gear-up-to-meet-future-demand/?mc_cid=83ec4c5e5c&mc_eid=bd6fa1c38f

Battery maker deep dive: ProLogium Technology

ProLogium Technology is a Taiwan-headquartered solid-state battery manufacturer. In September 2022, ProLogium shortlisted France, Germany, Poland, and the UK for an $8 billion solid-state lithium battery plant, and in October, it signed a Memorandum of Understanding (MOU) with Automotive Cells Company (ACC) to cooperate on solid-state battery development.

Gilles Normand, EVP International Development at ProLogium Technology shared insight for this report. Normand is an automotive industry veteran, with decades of experience at Nissan and later Renault, where he most recently led Renault's Mobilize brand which focuses on shared mobility and carbon-free energy.

Gilles Normand
EVP International Development at ProLogium Technology

What sets solid-state apart from Li-ion batteries?

Solid-state batteries help to overcome six main deficiencies of the current generation of lithium-ion batteries, namely safety, energy density, chargeability, weight, costs, and recyclability.

What is holding solid-state back?

We believe what really matters for a new technology is mass production capability. As a technology-ready company, ProLogium's next step is to scale up as soon as possible to expand our production footprint worldwide. We are seeking an overseas site for the production of next-generation solid-state batteries in Asia, Europe, or USA in light of the exponential growth in demand for electric vehicles over the next decade.

When will solid-state make it to market?

We will start our gigafactory for mass production in Taiwan at the beginning of next year, with production starting much earlier than initially expected. It was expected that solid-state would not happen before next decade. We think we can start much earlier than that.

How long will a solid-state battery last before it enters second life or recycling?

Current Li-ion technology is good for automotive application up to 15 years, followed by another ten years in a second life application. So current generation batteries can last up to 25 years before being recycled. For automotive applications, we think solid-state will be very similar. We have not tested solid-state for second life, so we do not yet know the total life. But I expect there to be a trade-off between charging rates and utilisation.

How important is recycling, and design for recycling?

For the first generation of batteries, nobody was looking for automotive applications, so we took what was available off the shelf. We did not know about recyclability, so recyclability was the end result. At ProLogium, we said we want this technology to be highly recyclable, to more than 90%. We are in discussions with recyclers, because recycling seems to be directly linked with where we will have production. Our plan is to have a gigafactory in the US and in Europe, so we need the capability to recycle there. Recycling has two fundamental objectives. First, we do not want any of our batteries dumped without control, and second, when you recycle, you reduce demand on mining.

On Belgium: Gilles Normand, ProLogium

Belgium is ideally located between three rapidly developing electric vehicle ecosystems. On one side, in northern France, there is a rapidly developing battery valley starting from Dunkirk, and going towards Lille and Douai, with Envision, ACC, and Verkor, and potentially a fourth Gigafactory in this part of France. There is an electric vehicle assembly plant, and a strong university ecosystem is being developed in order to address these future developments.

On another side, there is the Netherlands battery valley, around Arnhem city and the University of Twente. Near Arnhem there is a number of development centres related to batteries and studies on recyclability and testing batteries.

The third ecosystem, on the German side, involves all German carmakers, German universities, and gigafactories. All of these are developing raw material optimization, recycling capabilities, and need universities, and laboratories.

Belgium is perfectly situated between all of these ecosystems.

It would be very good for Belgian authorities and Belgian stakeholders to leverage Belgium's location and engage with these rapidly developing ecosystems.

ProLogium has talked about closed loops for batteries. What will that look like?

First, no battery will be lost, because there are three very interested parties: the automakers, the recyclers, and the battery makers. And each would like to capture the recycled material.

Most probably OEMs will take the lion's share, because they control the car. And increasingly, cars will not be sold, but leased, so at the end of the vehicle's life, their network will secure the battery pack. The recyclers will want a contract for recycling, but also the ability to profit from the sale of the recovered materials. And the cell makers will need access to recycled materials, so I anticipate joint ventures and partnerships being established.

Will the high cost of raw materials affect interest in allowing the batteries to go into second life?

It is a question of economics. Regulation that limits mining promotes recycling to recover raw materials from current batteries as soon as possible. The cost of those used batteries will go up, because of the scarcity of raw material, making them more attractive for recycling. But it would be disappointing to prevent batteries going into second life and then recycling, because we want batteries to reach full maturity, over a 25- or 30-year cycle.

What is your view of second life EV battery applications?

There are two kinds of second life applications, which we could call pre-life and post-life.

In terms of pre-life, when I was at Renault, I was involved in running battery farms in Germany and France. We purchased additional LG batteries up front for the Renault Zoe for future needs and after sales purposes. These batteries were new, and we put them in containers. In order to keep those batteries working, we charged them, and fed power back to the grid when it was needed. This kept the batteries in good health, generated revenue, and stabilised the grid when required. When a battery is needed, it can be taken from the battery farm and offered to the customer at a favourable price. By doing this, we secured batteries at production costs; if we had not done this, buying a battery would be an outrageous cost for the customer.

For post-life applications, we collected end of life battery packs, disassembled the packs, and used the modules in other applications. One of the key applications was to store renewable energy. Other second life applications include use in small river boats, and battery packs to replace diesel power generators for industry and events.

Used EV batteries: Handle with care

The need to handle EOL batteries is inevitable

What happens to an EV battery after it has reached the end of its life is currently highly complex.

End of life "defined"

An EV battery only becomes EOL once the decision has been made to remove it from the vehicle.

There are three main reasons why Li-ion batteries degrade (Table 5): environmental conditions and temperature, rate of charge and discharge (known as the C-rate), and time (known as calendar degradation).[49]

Table 5. Main causes of battery degradation and how they influence the degradation.

Cause of battery degradation	Level of influence on degradation
Calendar degradation	+++
C-rate	++
Weather and environment	+

Unless a battery has been damaged in a collision or suffered some other failure, degradation in this sense refers to Li-ion batteries gradually losing their capacity to store energy. As capacity decreases, range reduces. At around 80 percent of its initial intended storage capacity, it is considered to reach EOL.

Unlike vehicles with ICEs, which can run for decades if properly maintained, shorter life expectancy of the battery translates into a shorter lifetime for the EV itself.

There is no technical cut-off point, which adds to the challenge of forecasting EOL volumes—the length of time a battery takes to deplete to 80 percent of its originally intended capacity depends also on use and operating temperatures. Calendar degradation is inevitable; usage degradation is variable, dependent upon charging rates, driving styles, and operating temperatures. And of course, the vehicle owner can keep using the vehicle even below 80 percent. As a result, EOL is determined by the user, not a clearly defined list of values.

The first Li-ion vehicles only hit the market in 2010, and the first EV batteries were expected to reach EOL after 160,000 km and were typically warrantied for eight years. Table 6 shows the manufacturer warranties for selected mainstream EVs, with model launch dates to indicate the earliest that each model's batteries would be out of warranty.

However, EV batteries are lasting longer than initially expected, anecdotally ten to 12 years.

Table 6. Type of warranty for several vehicles.[50]
*5 years / 96,560 km for 24kWh vehicles

Vehicle	Warranty	Model launch
Renault Zoe	Eight years/160,000 km	2012
BMW i3	Eight years/160,000 km	2013
Nissan Leaf*	Eight years/160,000 km	2017 (2nd generation)
Hyundai Kona Electric	Eight years/160,000 km	2018
Jaguar i-Pace	Eight years/160,000 km	2018
Kia e-Niro	Seven years/160,000 km	2018
VW iD.4	Eight years/160,000 km	2020

49 https://blog.ucsusa.org/hanjiro-ambrose/how-long-will-my-ev-battery-last-and-3-tips-to-help-it-last-longer/
50 CAR magazine, automaker websites

Handle with care

Careful and correct handling of EOL battery material is essential for a successful transition to EV, for several reasons:

- **Safety:** For safety reasons, Li-ion batteries cannot be thrown into landfill. They contain hazardous substances, and they can be a fire risk.
- **Valuable raw materials:** Recycling turns waste into wealth, and used EV batteries contain valuable materials.
- **Recycling complements mining,** making potentially endless use of materials that have already been mined. Used EV batteries contain several endlessly reusable materials, which, correctly recycled, can be returned to battery grade and used in new battery production.
- **Raw material independence:** Material prices are highly volatile. Europe is urging member states to identify and leverage their mining capabilities to ensure self-sufficiency in the future. Some countries do not have natural battery material resources, but they can play a role in offering recycling capabilities, and promoting second life applications.
- **Economic benefits:** Industrial scale used EV battery handling, second life battery production, and battery recycling create jobs, shorten supply chains and reduce dependence on other nations.
- **Cost:** Using recycled materials optimise bill of materials, and thereby the cost of the end product.
- **Use:** Ideally, batteries should be used for as long as possible before recycling. Ultimately, they will need to be recycled, whether they come directly from end-of-life vehicles, or from a second life application, such as a battery energy storage solution.
- **Circular economy:** The concept of circular economy is gaining ground in the automotive industry in particular, and the development of a closed loop for EV batteries offers an easy point of entry.
- **Regulation:** The proposed EU Battery Regulation aims to codify the parameters for recycling and second life applications, and will mandate the use of minimum levels of recycled material content in new batteries.

EU Battery Regulation will clarify recycling and second life

At the time of writing, Europe's most recent regulation covering batteries dates from 2006, well before the beginning of the modern era of EVs.

The absence of a fit-for-purpose battery regulation in Europe underlines the gulf between this rapidly evolving technology and the slow speed of regulatory reform.

A new proposed EU Battery Regulation[51] was published in December 2020, and is currently in trilogue, the period during which the Council of the EU and the European Parliament can suggest amendments. It is widely expected to be implemented in 2023. When implemented, the Regulation is expected to create clarity and commercial opportunities for the battery recycling industry and second life applications.

Part of the European Green Deal, the EU Battery Regulation addresses the reuse, recycling, and remanufacturing of used batteries, and subjects manufacturers to new legal and technical obligations.

The draft Regulation calls for specific actions throughout a battery's life, from conformity assessment, labelling and tracking using a so-called Battery Passport, to collection and treatment, with specific provisions for second life applications, recycling, and the use of recycled materials (Table 7 and Table 8).

Table 7. Paragraphs of the article 1 of the EU Battery draft Regulation.

Art. 1 Para. 1	This Regulation establishes requirements on sustainability, safety, labelling and information to allow the placing on the market or putting into service of batteries, as well as requirements for the collection, treatment and recycling of waste batteries.
Art. 1 Para. 2	This Regulation shall apply to all batteries, namely portable batteries, automotive batteries, electric vehicle batteries and industrial batteries, regardless of their shape, volume, weight, design, material composition, use or purpose. It shall also apply to batteries incorporated in or added to other products.

51 https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020PC0798&rid=1

Table 8. The proposed EU Battery Regulation includes specific obligations for manufacturers of rechargeable industrial and electric vehicle batteries with internal storage and a capacity above 2 kWh

New EV battery category	The draft EU Battery Regulation calls for a new classification of EV battery
CE-marking obligation	The implementation of CE conformity for batteries, "affixed visibly, legibly and indelibly to the battery"
Carbon footprint declaration	From 1 July 2024, batteries must "comply with maximum lifecycle carbon footprint requirements"
Mandatory levels of recycled content in new batteries	Specific minimum percentage of recycled materials recovered from waste required for batteries from 1 January 2030, expected to increase over time: 12% cobalt, 85% lead, 4% lithium, and 4% nickel
Battery passport	An electronic exchange system for battery information, to be in place by 1 January 2026
Battery management system (BMS)	Calls for access to data including battery state of health and expected lifetime stored on the BMS of industrial and EV batteries >2 kWh
Provision for reuse / second life	Further use of the battery involving repurposing or remanufacturing must be documented by means of an invoice or a contract for the sale or transfer of ownership of the battery

Mandatory levels of recycled content in new batteries

The proposed EU Battery Regulation includes a recycled content declaration requirement, mandating the inclusion of minimum levels of recycled content in new EV batteries from 2030 and 2035 (Table 9).

Table 9. Evolution of the percentages of mandatory levels of recycled content in new batteries increases over time in the proposed EU Battery Regulation.

	Proposed minimum recycled content requirement for new batteries			
Year	**Cobalt**	**Lead**	**Lithium**	**Nickel**
2030	12%	85%	4%	4%
2035	20%	85%	10%	12%

Battery Passport

The proposed EU Battery Regulation calls for a battery passport to monitor a battery's ESG and lifecycle information, and provides transparency on a battery's history, contents, and whereabouts.

There are several battery passport initiatives; one is being developed by Everledger, a London-headquartered digital transparency company that uses an "asset agnostic" blockchain-based platform to establish the provenance of a wide range of valuable materials.

Everledger advises the Global Battery Alliance (GBA)—a program of the World Economic Forum—which in 2020 released a battery value chain roadmap. The Everledger Battery Passport provides a digital identity that connects the battery and its critical parts to the internet and supports an exchange of data among authorized lifecycle stakeholders, enabling the support of a sustainable value chain for EV batteries and stationary storage batteries.

Lauren Roman, Business Development Director, Metals & Minerals Ecosystem at Everledger, explained that as an EV battery moves through the supply chain, information about what goes into that battery, manufacturing, bill of materials, chemistry, and more, risks being lost, with no record of any alterations to that battery on its journey. Everledger proposes using a permissioned blockchain platform, which enables only qualified stakeholders to share and access permissioned data on the blockchain in real time. Furthermore, proprietary information can be hidden through the blockchain. The data is immutable and secure; it cannot be changed, and due to the nature of a permissioned blockchain – as opposed to a public blockchain such as Bitcoin – the users are known.

Everledger explains that its Battery Passport can support three pillars of an electric vehicle battery circular economy:

- **Provenance from the mine:** Responsible sourcing of critical battery minerals from the mine;
- **EV battery lifecycle management:** Optimum battery lifecycle management, life extension and assurance of responsible recycling;
- **Greenhouse gas accounting:** Traceability and accounting of greenhouse gas footprint throughout the battery's entire lifecycle.

Successful battery passport implementation requires ensuring participation by all relevant stakeholders, with a viable business model and incentives to ensure full transparency.

Benedikt Sobotka, Co-Chair of the Global Battery Alliance and CEO of Eurasian Resources Group told us: “One of the most important features of the Battery Passport is that it will collect data throughout the entirety of a battery’s lifecycle, from mining and refining, to cell and pack production, to its assembly and utilisation in an EV. As such, the Passport can provide essential information about a battery’s material composition, provenance, and history, all of which will support the recycling, re-use and the closed-loop management of the battery. Currently, there are limited systems in place to enable the re-use and recycling of over 11 million tons of spent lithium-ion batteries which are forecast to be discarded by 2030.[52] The data collected will make it easier to assess opportunities to lower repurposing and re-use costs for batteries. For example, the data could potentially be used to establish a framework to help address regulatory and liability challenges.”

Everledger and Ford battery passport pilot

In October 2022, Everledger launched a battery passport pilot with Ford to ensure responsible recycling of EV batteries. This will give the automaker visibility on out-of-warranty batteries, validate responsible end of life recycling, and gain access to data such as recycled critical minerals produced and associated CO_2 savings.

Everledger’s battery passport solution will track batteries in various EV models for six months; the pilot is being run in partnership with lithium-ion battery recyclers Cirba Solutions and Li-Cycle.

The Ford batteries and their inner modules are tagged during production with 2-D data matrix codes; they can be scanned using a cell phone by each organization as the battery changes hands, providing information such as a battery’s location and chemistry, as well as details about transportation, disassembly, and recycling.[53]

Currently, used batteries and production scrap can be sold in Europe or exported, and London-based consultancy Circular Energy Storage (CES) notes that “today, both batteries and production scrap [move] from Europe and North America to India and South Korea.”[54] The EU Battery Regulation aims to ensure critical battery raw materials remain in circulation in Europe.

End of Life Vehicle Directive

In Europe, the handling of end-of-life vehicles is regulated by the End of Life Vehicles Directive.

This first came into force over 20 years ago, and although it has evolved with vehicle technology, it was written before the widespread use of lithium-ion batteries, and before current calls for a switch to zero emission vehicles and the inevitable transition to electric vehicles.

In the European Union, the producer – that is, the vehicle manufacturer, also known as the automaker, or the original equipment manufacturer (OEM) - is responsible for compliance with the ELV Directive, which requires any vehicle to be 95 percent recyclable based on its material content, and calls for the takeback of ELVs, storage and treatment of ELVs, the removal of hazardous liquids and components from ELVs (depollution), and the reuse, recycling or disposal of parts.

A new EU End of Life Vehicle directive is anticipated. In 2021, the European Commission (EC) held a public consultation as part of its efforts to address the shortcomings of the 2000 ELV Directive, and propose a new directive.

52 https://www.marketsandmarkets.com/PressReleases/lithium-ion-battery-recycling.asp#:~:text=The%20average%20lifetime%20of%20LIBs,discarded%20by%202030%20 (Kochhar).
53 https://everledger.io/everledger-launches-battery-passport-pilot-with-ford/
54 https://circularenergystorage.com/articles/2022/9/7/a-tsunami-or-a-drop-in-the-ocean-how-to-calculate-the-volumes-of-lithium-ion-batteries-available-for-recycling

Re-use or recycle: What happens to used EV batteries?

Once the battery has been removed from the vehicle, a decision must be made: reuse, or recycle? Factors in the decision include:

Age of battery: Older batteries were more raw material-intensive, and contained a higher concentration of metals, making recycling more attractive than extending use in second life.

Battery chemistry: The business of recycling depends on the recovery of valuable battery raw materials, such as cobalt – but the use of cobalt is being reduced in new cathode chemistries. LFP – now the auto industry's preferred chemistry – contains no cobalt, which changes the business case. LFP has better cycle life and safety performance than NMC; both factors are important for stationary storage.

Battery ownership: Understanding the ownership of an EV battery is essential for understanding the second-life or recycling decision-making process. Batteries are currently generally warrantied for eight years. If the battery is replaced during the warranty period, the automaker retains control of the battery. If it is removed by a dismantler, it remains in the dismantler's possession and may be sold to the highest bidder.

Used batteries: Hazardous waste or valuable raw material?

Recycling is evolving from an environmentally friendly solution into a lucrative and essential commercial opportunity. Properly recycled and refined, the quality of valuable materials recovered from a LIB is equivalent to virgin raw material.

It is hoped that one of the issues the EU Battery Regulation will clarify is the status of used Li-ion batteries, and whether they are classified as hazardous waste. This is currently unclear, and adds to the complexity of the recycling process. Recyclers consider used EV batteries to be a valuable source of raw material. However, used Li-ion batteries are currently considered in the EU "as non-hazardous waste when fully discharged… Yet, an incompletely discharged lithium-ion battery, e.g., from an electric car, constitutes hazardous waste for which there is no category in the EU List of Waste."[55]

"Hazardous waste regulation is a real hurdle," said Charles Stuyck, Business Director for the Battery Recycling Unit at Umicore. "There are two parts of the regulation that increase the complexity of getting a used battery from A to B. One is the UN Dangerous Goods regulation. The first, especially for overseas transports, has become difficult, but it is manageable. The other concerns hazardous waste, and relates to waste classification and the material specification of scrap."

A major challenge comes with the classification of recyclable Li-ion battery material as hazardous waste, and its impact on the transport of this material from one country to another in Europe. Regional and national environmental protection agencies can determine whether a battery is amber-listed (indicating hazardous waste) or green-listed. "As soon as it is amber-listed, the required level of administration increases, adding considerable time and limiting the ability to choose the destination of the recyclable material," noted Stuyck. "Transporting used batteries across a national border involves a very lengthy process, which is hampering the development of this industry."

This, said Kurt Vandeputte of Umicore, illustrates how existing regulation is unsuitable for new industries such as LIB recycling. "Our troubles start when things are labelled as waste. Society and industry are changing, but regulation is not keeping up. We very strongly advocate for a review of regulation to be suitable for a circular economy model. What is waste? Frankly speaking, a battery pack, even no longer usable, is not waste."

On a European level, transferring waste from one country to another, in this case, batteries, requires adherence to European waste shipment regulation, which applies equally in all member states. The rise in electronic

55 https://www.europarl.europa.eu/doceo/document/E-9-2022-002782_EN.html

On Belgium: Kristof Bogaert, Denuo

I think it would be good for Belgium to profile itself as a recycling hub in Europe, and EV batteries certainly fit this profile. And we are seeing increasingly that Flanders and Wallonia are really looking to invest in projects that stimulate recycling, and the circular economy in general.

equipment and electric vehicles means e-waste will need to be shipped within Europe due to the lack of sufficient battery recycling capacity in each country.

In Belgium, Denuo is the waste and recycling association. It is a member of FEAD, the European Waste Management Association.

Both organisations have lobbied for the use of mandatory levels of recycled content in new products. Kristof Bogaert, advisor at Denuo, told us: "This stimulates the market for recycling, creates demand for recycled materials, and stimulates innovation for high quality recycling to produce high value output material."

In Belgium, waste management is handled at a regional level, creating additional challenges. Bogaert told us: "We would like federal level legislation that is the same for everybody. Rules vary in Belgium between Flanders, Wallonia, and Brussels, which makes it very difficult to operate. But product regulation is federal, which makes it even more difficult to operate if you are dealing with products for recycling and sustainability."

Reneos, the Tienen, Belgium-headquartered European battery collection organisation, notes that the limited number of EV battery recyclers in Europe, and absence of any recyclers in some countries, means that lithium-ion battery recycling will be a pan-European industry with batteries needing to be shipped across borders.

Philippe Celis, CEO of Reneos, agreed that subjecting used EV batteries to waste notification and permits presents an additional challenge. "Waste legislation is country-specific, and lithium-ion batteries are classified as hazardous waste," he said. "They fall under ADR[56], a European regulation on how to transport hazardous waste, which specifies how to package, and transport used and damaged batteries. Our collection partners in each country have the packaging to transport the battery, and they are not dedicated just to EV batteries – they collect large lithium-ion batteries."

56 https://unece.org/transportdangerous-goods/adr-2021-files

The permit challenge

Securing permits to establish Li-ion battery recycling operations was cited as a key challenge to the development of used EV battery recycling in Europe, and in Belgium in particular. The challenge is such that recycling companies suggested it would be a deciding factor in where to establish a recycling business.

According to Denuo's Kristof Bogaert: "Within Belgium, and especially in Flanders, securing a permit for waste management is a very lengthy process, which is difficult especially if you are investing in a new installation. And usually there is only one competent authority per region that issues such permits."

"The permitting process is number one on our list. It's almost the starting point in our decision to locate a plant," said Kurt Vandeputte of Umicore. "The recycling industry's speed is limited by permit speed. We need a permit for each stage. The market is growing fast, but you cannot meet it because you are hitting all these permitting hurdles."

On Belgium: Benedikt Sobotka, Global Battery Alliance:

All countries have a role to play in the collection of, and transboundary movement of EOL EV batteries. For the creation of a circular EV battery value chain, it is essential that all relevant stakeholders, including policy makers from countries like Belgium, work together to address current friction points that prevent the effective handling of, repurposing, and recycling of EOL EV batteries.

The rise of the circular economy

Batteries will play a significant role within a circular economy. More than just a buzz term, circularity is becoming a major aspect of industrial strategy, especially in the automotive industry.

FISITA, the international network for automotive engineers, defines circular economy as: "the ultimate closed loop production system, in which companies reduce waste throughout the supply chain and in manufacturing; and when those products reach EOL, they are recovered, and then disassembled, repurposed, renovated, reconditioned, or recycled, as appropriate."[57]

The concept is being rapidly adopted by automotive industry stakeholders, notably Groupe Renault, which is working with the Ellen MacArthur Foundation,[58] and Ford Motor Company, which has been working with University of Michigan researchers.[59]

In 2019, Audi and Umicore started a closed loop for cobalt and nickel, stating that more than 90 percent of the cobalt and nickel in Audi e-tron high-voltage batteries can be recycled.[60] And in November 2022, Nevada, US-based recycler Redwood Materials announced a partnership with Volkswagen Group of America to recycle all end-of-life batteries from Volkswagen and Audi electric vehicles, and to operate a consumer-facing battery collection programme enabling consumers to recycle old devices and rechargeable batteries at Audi dealerships.[61]

57 https://www.fisita.com/library/fisita-output-paper/2022/fop2022-10-01
58 https://ellenmacarthurfoundation.org/circular-examples/groupe-renault
59 https://seas.umich.edu/news/circular-economy-framework-automobiles
60 https://www.umicore.com/en/media/press/battery-recycling-audi-and-umicore-start-closed-loop-for-cobalt-and-nickel
61 https://www.redwoodmaterials.com/news/redwood-audi-consumer-battery-recycling-partnership/

Automaker deep dive: Volvo Cars

Ane Dalum, Cluster Lead for Circular Batteries at Volvo Cars, shares exclusive insight into one automaker's approach to second life battery applications and used EV battery recycling

Ane Dalum
Cluster Lead for Circular Batteries at Volvo Cars

Volvo Cars has a factory at Ghent, where its 7,000-strong workforce produces the Volvo V60, a plug-in hybrid version of the XC40, and two fully electric vehicles, namely the C40 Recharge and the XC40 Recharge, as well as the plug-in hybrid version of the XC40 and the Volvo V60 plug-in hybrid.

In 2021, the factory produced 183,238 vehicles.[62] This included 24,519 units of the XC40 and 3,533 units of the C40, equivalent to 15.3 percent of total production.

In 2022, Volvo Cars completed work to triple its electric car capacity at Ghent; more than 50% of the plant's total production capacity is now dedicated to electric vehicle production.

Ane Dalum is Cluster Lead for Circular Batteries at Volvo Cars, and is responsible for Volvo Cars' circular battery strategy.

Dalum told us that Volvo Cars focuses on ensuring the battery's longevity in the car and on recycling to secure a circular material loop. Volvo Cars does not support the use of EOL EV batteries in second life applications without knowing the battery history, primarily for safety reasons, she said, adding, "and even when you have the history of the ELV battery, it is hard to predict the remaining battery lifetime in such an application after being placed in a car for 15 years or more.''

Volvo Cars' main concern regarding EOL EV batteries is safety, with special training is required to handle high voltage batteries after they have been removed from the cars and put into another application. Unless the EOL vehicle is returned directly to the original vehicle manufacturer, she said, automakers have little to no control over EOL EV batteries once they are no longer suitable for use in an EV. "EOL batteries need to be stored correctly, and safely. But, for now, we cannot say where these batteries end up, as it is the last owner of the ELV that decides the final destiny of the car," she explained.

62 https://www.volvocargent.be/nieuws/volvo-car-gent-schakelt-versnelling-hoger-inzake-elektrificatie-en-zet-laatste-stappen-richting-klimaatneutrale-productie

On Belgium: Ane Dalum, Volvo Cars

Belgium is placed in a sweet spot in the middle of Europe, and it should take advantage of being a logistics centre, because this is where it would typically be ideal to place the hubs.

And Belgium could potentially invest in the needs for a local supply chain to support the volume need, which could count cathode active material production, when you have access to the recovered material from the recycling process. In addition, the long-term need for critical raw materials for the batteries will require huge investments locally and regionally to be able to compete in the long run. By that we would directly be able reduce several of the known ethical and environmental risks we face in today's battery supply chain.

Focus on the opportunities when bi-directional charging capabilities and vehicle to grid are launched with the growing electric fleet and get the energy companies into the game, and open for business opportunities for consumers and for society.

Investments should be made in new and improved recycling methods and technology, not only to be able to handle today's batteries but also future chemistries and new cell and pack design.

From a legislative point of view, we should not standardize too early or be too prescriptive. We need to embrace and allow an arena of innovation and recognize that we are just at the very beginning of the battery technology revolution.

In Belgium, waste and recycling are handled at regional level, so one request to the government is to create a federal environment, to prevent different situations in Flanders, Wallonia, and Brussels.

This is specific to Belgium, but the federal government must play a coordinating role with the regions, because that is not something that can be done just by one actor in Belgium.

Volvo specifies hydrometallurgical recycling…

Volvo Cars specifies hydrometallurgical recycling, Dalum told us. "We have just been through a global sourcing process, and with one exception, we chose battery recyclers using hydrometallurgical recycling. We prefer hydrometallurgical recycling due to the high purity and recovery rates. At the same time, the energy usage is relatively low, which means reduced emissions. From what we have learned in the sourcing process, pyrometallurgy alone is hardly the way forward."

…powered by renewable energy and diversified recycling capabilities

Volvo Cars requires the use of renewable energy by recyclers. "You can reduce the carbon footprint by about two-thirds, if you use recovered material in a hydrometallurgical process with high recovery rates and the use of 100% renewable energy in the process," said Dalum. "And according to industry forecasts, the cost of producing CAM (cathode active material) from recovered material will drop to around one third of the cost compared to primary material production. For now, we have seen the best results from hydrometallurgical recycling. However, we are looking into other recycling technologies as well, such as direct recycling. But as we are at the beginning of cell technology, we are also at the beginning of battery recycling technology, which will evolve with the increased demand for new technologies and the need to handle chemistries other than NMC, such as LFP, LMNO, and sodium-ion."

Ane Dalum, Volvo Cars

"We launched our first pure electric cars in 2020. We will not see these batteries again until well beyond 2030. These batteries will be in use for 15 years, so call me again in 2035!"

Dalum also underlined the importance of minimum recovery rates for new cell production to start the circular transformation of the industry. "Needless to say, the availability of recovered material shall be considered when minimum recycled content targets are set within EU, and as an industry we shall push for high recovery rates to ensure an efficient recycling process. In addition, we need to look for alternative sources of recovered material, as the critical volume of recycled battery material will not be available until beyond 2030." And she emphasized: "We should not send batteries for recycling before time."

Partnerships with recyclers

“Hydrovolt is one of our recycling partners. They receive our battery modules and produce black mass, which is then sent for hydrometallurgical treatment at Northvolt’s recycling division, Revolt. The recovered material will be used for Volvo Cars batteries as of 2025. Until then, we will still contribute to the circular transition of the industry as other OEMs can benefit from the recovered material.”

Second life: “Repurposing”

“In terms of second life, we have chosen to call it repurposing at Volvo Cars,” said Dalum. “Liability, warranty, and ownership are currently unclear, but we expect the EU Battery Regulation to address these topics and that the extended producer responsibility (EPR) is transferred to the second life applicant.”

Second life EOL EV batteries are being used in energy storage solutions (ESS). In-depth knowledge about a battery’s history is essential to use used batteries in ESS for safety reasons, said Dalum, who notes that a company investing in ESS would be unlikely to accept a 15-year-old depleted EV battery with an uncertain history and no warranty or guarantee in terms of durability. “Currently, we have no 15-year-old batteries that could be used in second life applications, since they are still in use in the electric vehicles. However, we are testing diverse batteries, both fully electric and hybrid, in different applications outside the car, but so far only in limited numbers.

“We still need to explore and understand to what extent ESS with used batteries is the right thing to do in a circular economy,” said Dalum. “You might prolong the battery’s life, but you lose control of the batteries as you transfer the extended producer responsibility to the new applicant. Once it enters second life, it leaves our responsibility, so it is not possible to control where it ultimately ends up and a new chain of responsibility starts. The big question: Is it better to put batteries into second life applications or directly back into a circular material flow?”

Industrialised circular loops

“When it comes to recycling, we should establish industrialised circular loops in a European perspective,” said Dalum. “We should not collect batteries specifying which automaker gets which batteries. That is far too narrow-minded. It should not matter who gets the specific batteries, if the batteries enter a circular industrialised loop with a guarantee that all the metals are recovered to the highest level and used in new battery cells.”

However, she emphasized that those batteries should stay in Europe to establish a local circular supply chain for the future. “We should not solely focus on battery cell manufacturing—a regional supply of sustainable raw materials as well as an industry-scale CAM production are equally important for the transition into circular and sustainable electro-mobility.”

Design for recycling

Volvo Cars has initiated an internal transformation programme on circularity, and within this programme, Dalum leads a cross-functional work stream exploring circular battery life cycle.

She notes that in terms of battery chemistries, most batteries being launched in China now are LFP batteries, which are considered less attractive for recyclers than NMC. The LFP batteries do not contain nickel or cobalt, but an increased amount of lithium which still needs to be recovered.

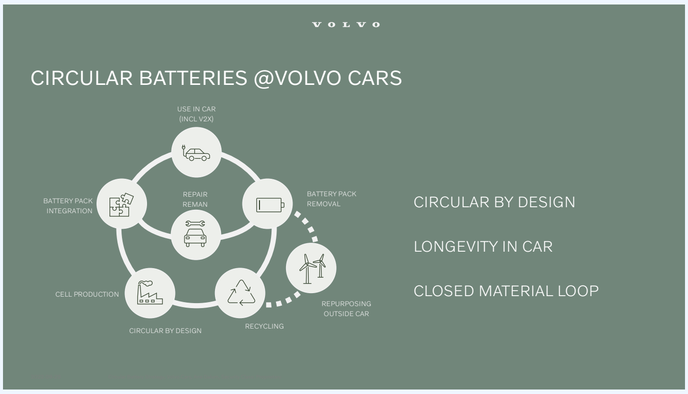

Fig 13. Circular batteries at Volvo Cars[63]

In terms of technologies, the industry is pursuing structural batteries, such as cell-to-body and cell-to-pack, as well as solid-state batteries, and this together with diverse chemistries will raise new challenges for the recycling process, said Dalum. “These are challenges the industry needs to solve together—and as an OEM, we need to start with ourselves. When we design the battery, we shall prioritise design for repair, disassembly, and recyclability.”

63 Volvo Cars

Chapter 2.

EV battery recycling

Once a battery has reached the end of its useful life in a car and is not suitable or required for a second life application, it is recycled, and the valuable battery materials are recovered, refined to battery grade, and resold for use in new EV batteries. This chapter explores the recycling processes, with insight from recyclers operational in Belgium and elsewhere.

Chapter key takeaways

1. The volume of Li-ion battery recyclable is currently the sum of production scrap and end of life batteries. The size of the EV market does not correlate to recycling volumes.

2. Recycling capacity includes pre-treatment capacity and black mass refining capacity. Recyclers define Li-ion "recycling" as recovering used Li-ion materials and refining them to battery grade quality for new battery manufacturing. Pre-treatment to produce black mass is only the first step in the recycling process.

3. For this reason, they define recycling capacity as the sum of pre-treatment capacity and material refining capacity; and they define recycling volumes as production scrap and EOL recyclable material.

4. Production scrap currently accounts for a disproportionate amount of Li-ion battery material recycling. Production scrap rates in cell production are as high as 30 percent, for reasons outlined later in this report, and this scrap material is sent directly to recycling. With low volumes of batteries ready and available for recycling, recyclers depend on the currently high levels of production scrap to fill their recycling capacity. However, this trend is expected to reverse, with scrap rates declining to single digit percentages as cell manufacturing improves, and used batteries becoming available for recycling—but this will not happen before mid- to end-2020s.

5. The proposed EU Battery Regulation calls for minimum percentages of recycled material in new batteries, securing recycling's place in battery manufacturing… so recycling will effectively be mandatory in order to meet the requirements of the EU Battery Regulation.

6. Local and national/regional networks required: Long distances make no sense for recycling. Expect to see local pre-treatment facilities close to battery factories for separation of metals and powders, and black mass production; and national or regional metallurgical facilities for refinement.

7. Recycling requires minimum volumes for economic viability: expect minimum 3-5,000t operations, likely near gigafactories.

8. Permits are a major bottleneck; easing restrictions and accelerating permitting will create a much more efficient operating environment for recycling companies.

9. Recycling complements mining, but it will never be able to replace it. Our interviews revealed recycling eventually accounting for up to 10 percent of material supply to the battery industry.

10. Second life "delays" recycling, but ultimately, all battery material will be recycled.

11. Europe already lacks sufficient EOL EV battery recycling capacity. The current recycling capacity in Europe is around 25-30,000 tons; in 2030, there will be 600,000 tons of end of life batteries for recycling.

Recycling companies featured in this report

For this report, we spoke to five major recycling companies (Table 10). Umicore has a 7,000t Li-ion battery recycling facility in Belgium, and ABEE is building a pilot recycling plant in Belgium; both have plans to build major recycling plants in Europe. Two of the companies we spoke to are European companies active in LIB recycling in Europe (Aurubis and Solvay), and one is a major North American player (Li-Cycle).

Table 10. Description of the five major recycling companies that have been interviewed as part of this report.

ABEE	**Avesta Battery & Energy Engineering (ABEE)** **HQ: Diegem, Belgium** **Sites in Belgium and Macedonia** **20+ employees**	Engineering company with expertise in battery pack manufacturing and recycling. Currently building an R&D recycling facility in Ninove, on the Dorn Noord sustainable business park, approximately 30 kilometres north-west of Brussels October 2022: announced plans to build a battery pack gigafactory in Belgium Preparing to announce location of a 50,000 tons recycling facility in Europe, as part of a plan to increase its total recycling capacity to 100,000 tons
umicore	**Umicore** **HQ: Brussels, Belgium** **11,050 employees and revenue of €3,963m (2021)**	Operates three industrial sites in Belgium: Antwerp, Hoboken, and Bruges. Dedicated 7,000t lithium-ion recycling facility at Hoboken, Belgium uses a proprietary method combining mechanical, pyrometallurgical and hydrometallurgical recycling. Planning to build a €500 million 150,000 tons recycling facility "in Europe." It has not yet confirmed where this will be.[64]
SOLVAY	**Solvay** **HQ: Brussels, Belgium** **21,000+ employees and net sales of €10.1bn (2021)**	Supplies chemicals to recyclers using hydrometallurgy.
Aurubis	**Aurubis** **HQ: Hamburg, Germany** **Around 7,200 employees, with production in Europe and the US**	Operates four multi-metal recycling facilities: Olen and Beerse in Belgium, Lünen in Germany, and Berango in Spain. February 2022: Aurubis Supervisory Board approved a €70m investment at its Olen, Belgium site to increase its nickel-bearing materials processing capacity.[65] Preparing to invest around €200 million in an industrial-scale recycling facility. No location has been confirmed.
Li-Cycle	**Li-Cycle** **HQ: Toronto, Canada**	Operates a Spoke and Hub model; at its Spokes, Li-Cycle carries out battery dismantling and shredding, the output of which is black mass. The Hub operations refine the black mass using hydrometallurgy. Operations at its Spoke in Norway[66] are projected to commence by early-2023, with a processing capacity of 10,000 tons; later, it will open a 10,000 tons capacity Spoke in Germany.[67]

64 https://www.umicore.com/en/files/secure-documents/51e0b8ab-4cff-462c-9338-542e116c91fa.pdf
65 https://www.aurubis.com/en/media/press-releases/press-releases-2022/aurubis-builds-facility-to-recycle-more-nickel-and-copper-in-belgium
66 https://li-cycle.com/norway-spoke/
67 https://investors.li-cycle.com/news/news-details/2022/Li-Cycle-Holdings-Corp.-Reports-Financial-Results-for-Fourth-Quarter-and-Full-Year-2021-Significant-Progress-in-Advancing-Spoke-and-Hub-Network-Strategy/default.aspx

The market for lithium-ion battery recyclables

On Belgium: Noshin Omar, ABEE

I believe Belgium needs large, sustainable recycling plants. But we also need recycling plants that can serve the full industry, including nickel cobalt batteries, and lithium iron phosphate batteries. The demands of the market are very high. And we are glad that the federal government will be supporting ABEE in this regard, and we are going to announce by early 2023 a 50,000 tons recycling plant, which will be the second or third largest recycling plant in Europe.

Critical to the success of any new or growing industry is the ability to size the market and forecast its growth.

Current volumes of recyclable EV battery material are low, and will not hit meaningful numbers for at least a decade.

Sizing the market for Li-ion battery recyclables—essentially the sum of production scrap and end of life batteries—is difficult in any market, let alone for Belgium, for several reasons:

- **No correlation between registrations and EOL volumes:** EOL battery availability does not directly correlate to EV registration data – batteries fail, suffer in collisions, or make their way into second life before being ready for recycling. Similarly, a fast-growing EV market does not equate to an equally rapid growth in EOL batteries.
- **Slowdown in new vehicle sales** due to several factors, including the semiconductor crisis, is keeping vehicles in operation for longer, slowing vehicle scrapping rates.
- **Volume-based, not unit-based:** the range of battery sizes, chemistries, and cell types is such that the industry talks not in terms of units of batteries, but tons of recyclable battery material; this further complicates forecasting models.
- **The disproportionate role of production scrap:** Production scrap currently accounts for a significant portion of EV battery recycling, as outlined later in this section.
- **Time:** The current generation of EVs began appearing on the market in 2010, and the batteries of some of those vehicles have lasted longer than first anticipated.
- **No cut-off points for EOL:** Batteries only become EOL when the battery is removed from the vehicle. There is no cut-off point for EOL; a battery lasts as long as the user wishes it to, and as mentioned previously, the performance of the battery declines according to use and environmental conditions as well as over time.
- **Technology:** The introduction of longer lifecycle batteries will impact volumes of EOL batteries, as will the use of larger batteries with a higher mineral content.
- **Battery chemistry:** A growing trend to lower value batteries (e.g., LFP) disincentivises recycling.
- **Geography:** EVs registered in Belgium do not necessarily end their lives in Belgium. Similarly, vehicles from other countries may end their life in Belgium. And used EV battery modules may end up in second life batteries sold outside Belgium.

A "tsunami" of battery material heading our way?

Many attempts have been made to forecast the market for recyclable Li-ion battery material; the following forecasts indicate the size of the challenge ahead, and illustrate the wide-ranging market forecasts:

- According to Eurometaux, the European non-ferrous metals association, "The first generation [of batteries] will start reaching end-of-life in significant volumes after 2035. By 2050, recycling can give Europe a major supply source if batteries reach EU recyclers and new recovery technologies are commercialised."[68]
- Globally, the International Energy Agency (IEA) sees volumes of batteries reaching the end of their first life rising from less than 2 GWh currently to 100 GWh by 2030, and to between 600 and 1,300 GWh by 2040. It expects the majority of EOL batteries to come from EVs, with 10 percent from two and three-wheelers. Buses and trucks will account for around 5 percent, and energy storage systems will provide just over 1 percent.[69]
- And using an estimated battery lifetime of ten years and a weight of 250 kg per battery pack, the IEA forecast that 23 million EVs sold globally in 2030 could lead to 5,750,000 tons of retired batteries by 2040.[70]
- Arthur D Little estimates[71] that in Europe, less than 4 GWh of used EV batteries will be returned annually by 2025. However, this will rise sharply to more than 200 GWh by 2040. The consultancy estimates that "by 2030, the total annual European Li-ion battery recycling market will reach about 130 GWh, which represents more than 700 kilo tons (ktons) of recycling capacity need. It will then increase threefold by 2040 as more EV batteries reach the end of their usable lives" – putting the forecast total annual recycling capacity market at 390 GWh.
- In terms of how the volume of available Li-ion battery recyclables will grow, management consultancy EY expects: "By 2025, volumes of spent batteries are anticipated to grow to 0.2 million tons per annum (mtpa), driven largely by gigafactory scrap rates as high as 20–30 percent in the early years of production. These volumes will increase to 1.4 mtpa by 2035, as batteries start to reach the end of their working lives and warranty returns become more prevalent by masse."[72]
- A Greenpeace study in 2020 forecast 12.85 million tons of electric vehicle lithium-ion batteries "will go off-line" (i.e. become end of life) between 2021 and 2030.[73]
- Circular Energy Storage (CES) expects 916,000 tons of LIB material available for recycling in 2025 and 1.6 million tons in 2030; note that this is a global total, and that it expects China to account for 60 percent of this total.[74]

Given the lack of European EV battery recycling capacity raised in this report, research by the World Economic Forum (WEF) and the Global Battery Alliance (GBA) found that recycling capacities globally would need to be increased by a factor of more than 25 in 2030 compared to current levels to meet recycling needs.[75]

Tom Welton, president of the London-based Royal Society of Chemistry, said in 2021 that he foresaw a tsunami of batteries ready to be replaced, and urged government and private investment in the reuse or recycling of those batteries.[76]

However, the notion that we might be facing a "tsunami" of recyclable material has been questioned by London-based battery recycling consultancy CES.[77] CES sees recycling pre-processing capacity far outstripping LIB recyclable volumes, attributing this to a high number of players in the market which has increased capacity, improvements in production processes which have reduced production scrap volumes, a slowing new vehicle market, and delays in scrapping vehicles as the semiconductor crisis inflates used vehicle values.[78]

Regardless of whether we face a tsunami, or a large wave, the time to prepare the infrastructure required for handling used EV batteries, is now.

The projected surge in spent battery volumes suggests immense scope for recycling, as illustrated in Fig.14.

68 https://eurometaux.eu/metals-clean-energy/
69 https://li-cycle.com/in-the-news/europes-start-ups-dig-into-battery-recycling/
70 https://www.sciencedirect.com/science/article/pii/S2589004221007550#bib27
71 https://www.adlittle.com/mx-en/insights/viewpoints/european-battery-recycling-emerging-cross-industry-convergence
72 https://www.ey.com/en_uk/strategy/10-ways-to-help-build-a-thriving-battery-recycling-industry-in-europe
73 https://www.greenpeace.org/eastasia/press/6175/greenpeace-report-troubleshoots-chinas-electric-vehicles-boom-highlights-critical-supply-risks-for-lithium-ion-batteries/
74 https://circularenergystorage.com/articles/2022/6/16/the-good-news-about-battery-production-scrap
75 https://www3.weforum.org/docs/WEF_A_Vision_for_a_Sustainable_Battery_Value_Chain_in_2030_Report.pdf
76 https://www.forbes.com/sites/carltonreid/2021/12/29/governments-need-to-prepare-for-tsunami-of-electric-car-batteries-warns-royal-society-of-chemistry-president/
77 https://circularenergystorage.com/articles/2022/9/7/a-tsunami-or-a-drop-in-the-ocean-how-to-calculate-the-volumes-of-lithium-ion-batteries-available-for-recycling
78 https://circularenergystorage.com/articles/2022/8/8/hc4y95jcp1fvlcimsorbw5t2s461hy

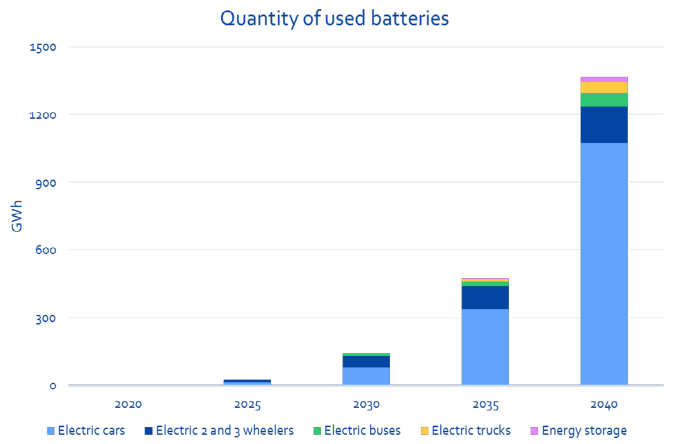

Fig 14. Evolution of the quantity of used batteries 2020-2040, by type of vehicle.[79]

Li-ion battery recyclables: tons, not units

There are several sources of recyclable Li-ion battery material: used EV batteries, production scrap, and batteries used in R&D.

However, production scrap—outlined below—currently accounts for the highest proportion of recycling capacity.

Battery recycling capacity is measured in tons, rather than units because of the variety of sources of recyclable material, and the wide variety of shapes, sizes, and weights of EV batteries.

Long term, EOL batteries will provide the majority of feedstock for the recycling industry, but the market for EVs remains in its infancy, with the surge to electrification only just beginning. These vehicles—and therefore the batteries within them—will be in use for many years to come. That there is no cut off point for an EOL battery, makes it difficult to forecast when any one battery will be ready for recycling. This is further complicated first by the fact that EV batteries are lasting longer than predicted,[80] and second, the redirecting of EOL batteries into second life applications, delaying their availability for recycling.

Production scrap

Production scrap currently accounts for a disproportionate amount of LIB material recycling. This is likely to remain the case for the next decade at least, until production efficiencies increase, and EOL EV battery volumes increase.

EV battery manufacturing is a nascent and fast evolving area of technology, and unlike most other highly efficient areas of vehicle manufacturing, production scrap rates in cell manufacturing of up to 30 percent are not uncommon; here, scrap includes excess foil cuttings, electrode trimmings, by-products from cathode active material production, and parts which fail to meet quality control. Some batteries are used in testing and R&D, and never intended for use in production vehicles, such as pre-production and destruction testing.

In the near term, recyclers will rely on production scrap. Umicore's Kurt Vandeputte told us: "There is currently almost no market yet for EOL battery recycling, because there is nothing available. Battery production generates considerable scrap, which is also recycled. But this is occupying used battery recycling capacity, and will continue for the next five to seven years. Over time, production scrap capacity will be used for EOL batteries, and towards the end of the decade, all models predict there will be more EOL batteries than production. Over the next decade, we need to be ready to accept quite a bit of production scrap. But from around 2030, 2031, we expect EOL volumes to take the majority of the volume."

Production scrap and used R&D batteries are sent directly to recyclers, typically through supply agreements. According to Benchmark: "Scrap material from the ever-increasing number of gigafactories coming online ... will account for 78 percent of the pool of recyclable materials in 2025."[81]

Management consultants Arthur D. Little expect around 70 GWh of European scrap to require recycling annually by 2025.[82]

However, manufacturing processes are improving, and as they do, scrap rates will reduce. Benchmark expects EOL batteries to overtake production scrap as the primary source of recyclable material from the mid-2030s, with increased levels of automation resulting in higher quality and higher yield production.[83]

Circular Energy Storage (CES) also expects a sharp decrease in production scrap, to well below 10 percent as manufacturing processes improve and efficiency in-

79 Adapt from IEA
80 https://chargedevs.com/newswire/nissan-exec-ev-batteries-lasting-longer-than-predicted/
81 https://www.benchmarkminerals.com/membership/battery-production-scrap-to-be-main-source-of-recyclable-material-this-decade/
82 https://www.adlittle.com/mx-en/insights/viewpoints/european-battery-recycling-emerging-cross-industry-convergence
83 https://www.benchmarkminerals.com/membership/battery-production-scrap-to-be-main-source-of-recyclable-material-this-decade/

creases. CES says initial yield rates at major cell manufacturers of less than 80 percent have already improved to "well above 90 percent and in several cases the rejects are under one percent."[84] CES expects "the scrap rates will decrease significantly and approach 4 percent and even 3 percent, with both rejects and naturally generated waste included."[85]

Changes in battery chemistries will impact recycling. Batteries going into products now will become EOL batteries in ten to 15 years, and may be available for recycling then, or even further out if they are used in second life; but the scrap from the production of those batteries is available for recycling now.

Umicore's Kurt Vandeputte noted, "Proportionally, the amount of scrap to be recycled is huge compared to EOL batteries. But the battery industry is preparing now for future electromobility. And I am getting the batteries at end of life that were put on the market ten years ago."

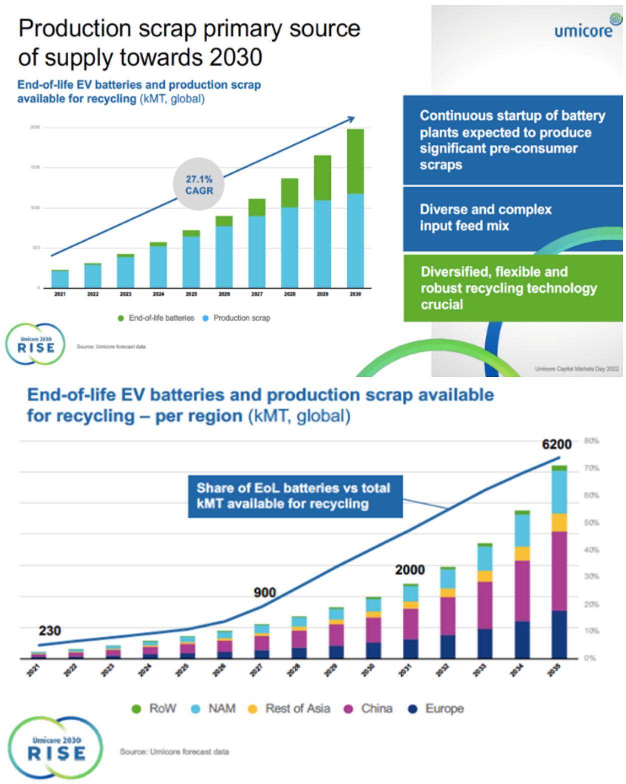

Fig 15. Rise in end-of-life EV batteries and production scrap available for recycling, 2021-2030, and per region.

Recycling capacity

Defining "recycling" is key to defining recycling capacity. Recycling companies may be involved in either the pre-treatment of Li-ion battery material, or the refining of the recyclable materials in battery-grade materials that can go back into the battery value chain.

Pre-treatment—that is, the dismantling of the battery to module level, and the shredding of modules into black mass—is only part of the recycling process.

"For us, black mass is an intermediate stage in recycling, and full recycling is the end goal," said Christophe Couesnon, Director of Strategy, Raw Material and Recycling, Battery Platform at Solvay.

"Black mass is where the value lies. Black mass is impure, and by no means ready to re-enter the value chain. It needs to be refined into pure metals that can go back in that value chain," explained Kurt Vandeputte of Umicore.

Europe already lacks sufficient EOL EV battery recycling capacity. The current recycling capacity in Europe is around 25-30,000 tons, and every recycler is operating at full capacity, said Philippe Celis, Business Unit Consultant at Bebat PRO and Chief Executive at Reneos. "But what is more worrying is that in 2030, there will be 600,000 tons of EOL batteries," he added. "And then the question is, how will we be able to expand capacity, in seven years, from 30,000 tons to 600,000 tons? It is not so much about building the facilities, but about the time it takes to secure the relevant permits."

We asked Benedikt Sobotka of the Global Battery Alliance whether he thought Europe had sufficient recycling capacity to cope with inevitable volumes of recyclable battery material. He told us: "In short, the answer is no. At present, only around five percent of Li-ion batteries are recycled globally – and with Greenpeace predicting that over 12 million metric tons of batteries will retire by 2030, it would be very optimistic to think we will soon have the capacity to recycle on that scale. However, what is important is ensuring that we develop enough recycling capability to effectively support the supply of materials needed for the clean energy transition, to ensure a lack of supply does not hinder the rapid rollout of EVs. There has been promising progress in this area, with companies such as Veolia, Volkswagen, and Renault all having announced major recycling projects in 2022."

84 https://circularenergystorage.com/articles/2022/6/16/the-good-news-about-battery-production-scrap
85 https://circularenergystorage.com/articles/2022/6/16/the-good-news-about-battery-production-scrap

Europe's over-reliance on NMC recycling

Europe is slowly developing an EV battery recycling culture. Asia dominates LIB recycling,[86,87] with around two-thirds of global EV battery recycling capacity, between 208,000 and 220,000 tons. Europe currently has the second-largest recycling capacity, at between 92,000 and 106,000 tons. North America lies in third place, with around 60,500 tons of recycling capacity. China not only dominates in Asia; its recycling capacity is greater than Europe and North America combined.

Globally, major lithium-ion battery recyclers include Accurec (Germany), Aurubis (Germany), CATL (China), Duesenfeld (Germany), Fortum (Finland), Li-Cycle (Canada), Lithion (Canada), and Umicore (Belgium).

Current recycling capacity in Europe is focused almost entirely on nickel manganese cobalt (NMC) batteries. These offer good return on investment (ROI), but the trend in the automotive industry is towards lithium iron phosphate (LFP) which does not contain nickel or cobalt. The ROI on LFP recycling cost is therefore lower than NMC and NCA due to the absence of those materials in the batteries.

LFP alters the recycling business model; until recently, LFP recycling, the result of which is primarily lithium, was unattractive for recyclers, who derived greater value from the various materials recovered from NMC batteries.

However, the rise in lithium pricing in 2022 to a point where it is becoming as important as cobalt in terms of recovery has increased interest in LFP recycling.

For this reason, ABEE told us its decision to focus its recycling efforts on LFP batteries was entirely strategic. "Other recycling plants in Europe are focused on technology which contain nickel and cobalt, simply due to the high prices of the end product," said ABEE CEO Noshin Omar. "It was a strategic decision by ABEE for the recycling plant that we are setting up now in Ninove, added to another recycling plant for a total capacity of 100,000 tons in Europe, to be 90 percent focused on LFP. This is a technology which is mainly used in stationary applications, home storage, renewables, and also in vehicles driving short distances, such as trucks and buses. Those batteries must be recycled, even if the recycling costs are slightly higher than conventional NMC or NCA batteries because the output materials have less value than nickel and cobalt."

Despite the automotive industry's transition to LFP, Solvay has indicated it will not focus on LFP recycling. "Until now, there was little interest in LFP, and we were considering LFP recycling as a cost," said Christophe Couesnon of Solvay.

"When we were first looking at recycling LFP, there was no way the lithium phosphate could go back to the value chain," he explained. "Today the price perspective has changed the economics, and it may be possible, but it is not our priority, for two reasons. First, Europe is dominated by NMC manufacturing. LFP accounts for no more than 20 percent of cell manufacturing in Europe. Second, most of the batteries that we will recycle first are NMC or LMNO (lithium manganese nickel oxide),[88] and most of those batteries are lasting longer than expected."

Canadian recycling company Li-Cycle, however, says its approach enables it to recycle all Li-ion battery types: "All chemistries and formats of lithium-ion batteries are suitable for our [recycling] technology."[89]

86 https://pubs.acs.org/doi/full/10.1021/acsenergylett.1c02602
87 https://www.canarymedia.com/articles/batteries/chart-china-is-trouncing-the-us-on-battery-recycling
88 The original Nissan Leaf used a LMNO battery
89 https://li-cycle.com/services/

How to choose a recycling facility location

When it comes to identifying a potential recycling facility location, our interviews revealed the following requirements from recycling companies, many of which are similar to the requirements for establishing any major manufacturing facility:

- Speed and ease of securing recycling permits: "The permitting process is number one on our list… It is almost the starting point in our decision to locate a plant" – Kurt Vandeputte, Umicore
- Favourable energy costs and availability of low carbon energy
- Land availability
- Good logistics
- Availability of well-developed infrastructure
- A highly qualified workforce
- Subsidies and incentives

Kurt Vandeputte of Umicore told us: "For the battery recycling model that we are applying, it is important that our battery recycling facility is located centrally in the market, because the batteries will have to come from all sides. And that can be with intermediate pre-treatment facilities."

Regional hubs

Recycling facilities are major industrial establishments; highly capital-intensive, they require significant minimum volumes of recyclable material for viability. Long-term, the volumes will be available. In the near term, the recycling industry relies disproportionately on production scrap.

Recycling installations are capital intensive, so they require high volumes to keep them running. According to the University of Warwick's manufacturing research group, WMG, "The break-even point for an automotive lithium-ion battery recycling plant is 2,500 – 3,000 tons per year if the chemistry contains nickel and cobalt."[90]

For Li-ion battery recycling to run efficiently, a network involving local pre-treatment and national or regional refining appears to be a favoured model.

Li-Cycle operates a Spoke and Hub model on North America, and plans to introduce similar operations in Europe. Li-Cycle's regional Spoke facilities receive and process all types of Li-ion batteries, shredding them into black mass; the centralised Hub facilities refine the black mass into battery-grade materials.

ABEE's Noshin Omar indicated his support for such a model in Europe. "We see a trend in Europe for local recycling hubs everywhere in Europe, to ensure durability and sustainability. It does not make sense to send batteries from Spain to Belgium for recycling, for example, due to regulations, transportation costs, and safety reasons. So, we will see hubs popping up everywhere."

Omar said he also sees a trend towards establishing smaller recycling hubs near gigafactories to handle production scrap. "You will be seeing strategic alliances between cell manufacturers and recycling companies for production scrap, with smaller scale hub facilities, typically 3,000 to 5,000 tons. That trend will continue and strengthen. It makes no sense to transport recyclable battery material long distances, as is happening right now."

Ken Nagayama at Aurubis said he too sees potential for mechanical pre-treatment facilities close to battery factories to produce black mass that is then transported to a metallurgical facility with the relevant infrastructure and assets to process it. Given the importance of economies of scale in battery recycling, Aurubis believes black mass refining is not economically viable in small hubs, only high-volume centralized facilities.

90 https://warwick.ac.uk/fac/sci/wmg/business/transportelec/22350m_wmg_battery_recycling_report_v7.pdf

How used EV batteries are collected

How used EV batteries are collected, stored, and transferred through the supply chain from collection to second life or recycling, involves permits and certification, trained staff, specialist equipment, and dedicated storage facilities.

Typically, used EV batteries are collected from dealerships after a crash, when there is an irreparable fault with an electric vehicle or its battery, or if the battery is part of a recall. The dealership arranges collection by an authorised collection company, which has the equipment to handle used EV batteries, as well as the appropriate storage facilities, and is part of a wider used EV battery handling network.

Bebat PRO

Established in 1995, Bebat PRO (producer responsibility organisation) is the battery compliance scheme in Belgium, collecting, sorting, and recycling used batteries.

Bebat members pay an annual flat rate contribution of €60 plus VAT, and an environmental contribution or an administrative contribution per portable, industrial, or automotive battery or accumulator put on the market. Members inform Bebat of their market output of batteries, and for those below 20 kilogrammes, they incur a pay-as-you-sell fee. The participants declare their market output on a regular basis, depending on volumes, and are invoiced accordingly. Bebat collects all battery types, from small consumer cells through to electric vehicle batteries. Bebat has 25,000 battery collection points in Belgium, including supermarkets, and claims its 60 percent collection rate is one of the highest in Europe.

“Today, we collect more portable batteries than EV batteries [in tons], but we know that in 2030 it will be the other way around,” said Philippe Celis of Bebat PRO.

Reneos

For the collection of larger batteries and EV batteries, five European battery compliance schemes founded Reneos: Bebat, Stibat in the Netherlands, Cobat in Italy, GRS Batterien in Germany, and BatteriRetur in Norway. Reneos is a commercial company, fully funded by the five non-profit shareholder organisations.

“Thanks to these five shareholders, we have created a network of battery collectors, and Reneos connects the dots,” explained Philippe Celis, who is also Chief Executive at Reneos. “If a European customer wants a collection scheme in Europe, they have to approach each country individually. But if they contact Reneos, thanks to our network, we coordinate collection through partners in our network of 26 countries. In some countries, where there is no official compliance scheme company, it is a commercial business, such as in the UK, Poland, Switzerland, and France.”

On Belgium: Erik Jonnaert, Chairman FIPRA Public Affairs Consultants and former Secretary General, ACEA

Belgium should continue elaborating an ecosystem which nurtures and enables circularity and recycling, and encourage the creation of viable opportunities for second life applications, such as solar farms and wind farms. Economies of scale are vital. For this reason, Belgium must avoid approaching this in an isolated way—this will create opportunities for companies operating across Europe and must be developed accordingly. Only then will it also open opportunities for Belgian companies, both start-ups and established players.

Febelauto

Febelauto is a Producer Responsibility Organisation (PRO) which operates and manages extended producer responsibility (EPR) as codified by the European ELV Directive. Febelauto manages the monitoring of end-of-life vehicles (ELVs), and EOL batteries of hybrid and electric vehicles, in Belgium.[91] It is operational in all three Belgian regions with valid environmental agreements in each region, and coordinates the collection, treatment, and recycling of ELVs and batteries.

The company is financed by local automakers and importers. It collects for most car brands in Belgium and Luxembourg, usually from dealerships. Febelauto stores the batteries, tests them, and where suitable, sends them for second life applications; if not, they are sent for recycling.

On Belgium: Catherine Lenaerts, Febelauto and Watt4Ever

We have a great potential in Belgium. We have a lot of interesting research institutions, in Brussels, in Flanders, and even in Wallonia. Belgium is really a pioneer. But we need support. We will get of course more competition, but we are not afraid of the competition. We really need a driver for circular batteries.

In 2021, Febelauto collected around 30 tons of EOL recyclable material. In 2022, it expects to collect around 120 tons.

How batteries are collected

The first decision in the EOL EV battery handling process is decided by the automaker's or vehicle importer's strategy; some allow their batteries to go into second life applications, but others do not, primarily for reasons of safety and liability.

For automakers in Europe that are Reneos members, the dealership informs Reneos of the type of battery to be collected, and that information is sent to the local Reneos collection partner, which collects the battery within 15 working days for recycling. Each collection partner has an agreement with a certified recycler, and Reneos only collects the batteries of EVs made by automakers with a Reneos contract.

Febelauto specialises in the collection of used EV batteries, with agreements with most vehicle brands operating in Belgium. The company collects, stores and tests the batteries, and sends them for recycling or second life as appropriate.

The logistics challenge

Logistics is a major part of the recycling process, and accounts for around 40 percent of the overall cost of recycling a battery. Furthermore, specialist equipment is required to transport used EV batteries.

According to Achim Glass, SVP, Head of Global Automotive and New Mobility Vertical at logistics specialists Kuehne + Nagel: "Transport and storage of lithium batteries is not easy and requires particular expertise in logistics management such as trained dangerous goods experts who know about the complex respective packaging and ADR transport legislations. With five years of battery logistics under my own belt I reckon that one percent of all BEV batteries that return from the market are classified as "red listed" and hence are subject to even stricter transport regulations, because of the risk of spontaneous combustion. The latest generation of safety transport boxes for 125 kWh batteries have a net weight of 3.2 tons. That alone is a challenge as standard tail lifts are not capable to handle this weight and makes collecting critical batteries from dealers or road accidents a logistical nightmare. The industry is not really ready for mass adoption yet."

ATF+ certification

European and Belgian legislation stipulates that the dismantling of ELVs must be carried out by authorised treatment facilities (ATFs). In Belgium, an additional certificate was required for ATFs to treat EVs, and Febelauto created ATF+ for those facilities which meet the requirement to enable them to handle hybrids and EVs at their facilities. The ATF+ certification includes stipulations on training, safe storage, administration, handling processes, personal equipment, and auditing. There are 120 ATFs in Belgium. Six have been certified ATF+.

Catherine Lenaerts, Managing Director of Febelauto has said: "We believe all ATFs and auto recyclers will have to add EV sooner or later."

Storage facilities

Once collected, any battery subjected to a recall is sent

91 https://plus.iru-miru.com/en/article/45189

directly to recycling. Otherwise, the battery modules' state of health and other parameters are assessed for second life suitability. Used EV batteries are held in quarantine for a number of days until thermal stability has been confirmed. Trained personnel operates the specialised storage facilities, located outdoors in sun-protected locations and ambient temperatures of 10 to 40 degrees Celsius; the containers are equipped with temperature monitoring, an integrated alarm system, full fire brigade access, and closed loop water circulation. End of life EV battery storage facilities require a permit, and there are very few places with a permit.

The battery collection business model

The portable battery market uses a "pay as you sell" model, where battery makers declare their batteries when they put them on the market, and are invoiced accordingly, with everything paid up front.

The car industry has chosen a "pay as you collect" model, paying for collection at EOL. Unlike a portable battery, which is discarded after four or five years, EV batteries appear to be lasting the lifetime of the car, upwards of 12 years. Some still have 70 to 75 percent capacity, and could be utilised in another application, such as energy storage.

Financially, it would make sense for the automakers if the battery went into a second life application rather than recycling under a pay as you collect recycling business model. However, under current European legislation, the first producer remains responsible for the battery throughout its life. That is being addressed in the proposed EU Battery Regulation, which is expected to come into force in 2023. Until the liability issue is addressed, automakers are likely to prefer to see their batteries going directly into recycling.

Recycling: How to recover valuable battery materials

According to Thierry Breton, EU Internal Market Commissioner, production of the electric cars needed to replace traditional cars by the 2035 zero-emissions sales mandate for new cars and vans would require "15 times more lithium by 2030, four times more cobalt, four times more graphite, three times more nickel."[92]

And Simon Moores, CEO of Benchmark Mineral Intelligence, wrote in a LinkedIn post that to reach the 300TWh of deployed battery storage by 2050, the point at which Tesla Chief Executive Elon Musk believes we can transition the global transportation and energy systems away from fossil fuels, would require an annual increase in battery cell capacity from 0.7 TWh to 20 TWh; a 20-fold increase in lithium and nickel sulphate production; a 25-fold increase in graphite anode output; a 22-fold increase in manganese sulphate output; and a five-fold increase in cobalt supply.[93]

Clearly, battery recycling will play an essential part in electrification and circular economy, both at a corporate level, and at a national level. And the proposed EU Battery Regulation calls for minimum percentages of recycled material in new batteries, securing recycling's place in battery manufacturing; recycling will effectively be mandatory in order to meet the requirements of the EU Battery Regulation.

Lead-acid battery recycling is generally considered "one of the great success stories for the recycling industry with up to 98 percent of the lead-acid battery able to be recycled."[94]

The question is, can LIB recycling match this?

A second mine? Recycling as a new source of lithium and cobalt

The high recovery rates and potentially lucrative business models are why battery recycling is often referred to as an urban mine, or a second mine for EV battery material.

Recycling will complement mining and will ultimately produce a notable percentage of recycled material for use in new batteries. However, our interviews have

92 https://www.politico.eu/article/breton-says-u-turn-on-eus-2035-car-engine-ban-isnt-taboo/
93 https://www.linkedin.com/posts/simon-moores-b0661418_netzero-benchmarkweek2022-cathodes-activity-6998810521890123776-U42B/?utm_source=share&utm_medium=member_desktop
94 https://royalsocietypublishing.org/doi/10.1098/rsos.171368

revealed that recycling is unlikely to account for more than around 10 percent of the material required for battery production.

Consider the impact of mining: It needs 2,273,000 litres of water to mine one ton of lithium. By 2040, the IEA forecasts a 42-fold increase in demand for lithium relative to 2020 levels, and demand for graphite, cobalt, and nickel will rise by 20-25 times over the same period. And Benchmark Mineral Intelligence reports that at least 384 new graphite, lithium, nickel, and cobalt mines will need to be built over the next decade to meet demand for electric vehicles and energy storage batteries by 2035.[95]

To put this into perspective, Swedish Li-ion battery manufacturer Northvolt notes that: "To obtain one ton of battery-grade lithium, for instance, we would need to mine and process 750 tons of brine, 250 tons of ore, or recycle just 55 tons of spent batteries." The company has also stated that: "For every ton of recycled NMC materials we use in cathode production, we avoid approximately 3,800 kg of CO_2."[96]

End-of-life batteries will become a notable source of recycling material from the mid-2030s; electric vehicles sold now will remain in use for at least a decade, and the batteries may then go into second life applications, keeping batteries in circulation and in use—and out of recyclable material calculations.

According to McKinsey, "Battery recycling is expected to increase during the current decade, but not to game-changing levels. Depending on the recycling process employed, it is possible to recover up to 80 percent of the lithium contained in end-of-life batteries. By 2030, such secondary supply is expected to account for slightly more than six percent of total lithium production."[97]

Yann Vincent, Chief Executive, Automotive Cells Company (ACC), noted in an interview with Martin Kahl of Ride: The Urban Mobility Podcast[98] at Reuters Automotive Europe 2022, that, "At some point, raw materials might become very scarce, so recycling might be equivalent to a new mine. From that perspective, it is obviously very interesting for us. We are shooting for 95 percent minimum of all materials to be recyclable. So, we are designing a way for those in charge of recycling to achieve such a number."

As noted earlier, the proposed EU Battery Regulation calls for minimum recycling recovery rates, and for minimum levels of recycled content to be used in new batteries. Northvolt has an ambitious target for recycled materials: "Our target is to source 50 percent of metals for battery cell production from recycling by 2030."[99] It aims to do this via Revolt, its in-house recycling program.

Umicore's Kurt Vandeputte believes recycling can equal mining in terms of quality and output: "Recycling for automotive applications comes ten or 12 years behind the market. We are now recycling cars that were put on the market ten years ago. That is much lower than the market today, so recycling battery materials is never going to be enough to feed the full supply chain in the next ten or 20 years, because we still expect stellar growth. But in terms of absolute size, our industry can be as sizeable as the virgin metal refineries, there is no reason why not."

Metals company Aurubis sees battery recycling reintroducing a notable proportion of raw materials and metals to the production of new batteries. Ken Nagayama, who heads up Business Development Battery Materials at Aurubis explained that once batteries use fewer metals of value, "We might be able to alleviate the pressure on the overall supply and demand balance. But can we be self-sustaining with just recycling? No, because the demand for lithium-ion batteries is only now kicking off."

Recycling recovers a high percentage of valuable raw materials

The LIB recycling industry is in ramp-up and the number of recycling facilities projects is growing as shown in Fig. 16. Demand for electric vehicles is rising, from a relatively low base, and their batteries will be in use for at least ten to 15 years before being sent for recycling. As a result, there is currently little return on investment, making recycling a costly enterprise. It is also energy or chemical-intensive, depending on the recycling method.

However, it is a critical part of the EV battery value chain, recovering a high percentage of valuable materials contained within a LIB. Crucially, raw materials account for about 65 percent of the final cost of a battery[100] - and this is why recycling is such an important aspect of the battery lifecycle.

Electric vehicle battery recycling facilities recycle all types of Li-ion batteries, including depleted electric vehicle batteries, as well as scrap from production, and industrial batteries including BESS.

Umicore claims it has a "Significantly improved metallurgical process with increased extraction efficiency of cobalt, nickel, and copper to now reach over 95 percent yield for a wide variety of battery chemistries."[101]

And Northvolt states, "the metals used in batteries are inherently recyclable. Provided that we recover them in

95 https://www.benchmarkminerals.com/membership/more-than-300-new-mines-required-to-meet-battery-demand-by-2035/
96 https://northvolt.com/articles/revolt/
97 https://www.mckinsey.com/industries/metals-and-mining/our-insights/lithium-mining-how-new-production-technologies-could-fuel-the-global-ev-revolution
98 https://www.ridemobilitypodcast.com/episodes/in-search-of-a-european-ev-battery-champion-feat-yann-vincent-acc
99 https://northvolt.com/articles/revolt/
100 https://cicenergigune.com/en/blog/critical-materials-battery-industry
101 https://www.umicore.com/en/newsroom/news/new-generation-li-ion-battery-recycling-technologies-and-announces-award-with-acc/

the right way, they stand as perfectly suitable materials for use in the production of new batteries."

Lithium can also be recycled, but until recently there has been considerably less commercial interest in lithium than in nickel and cobalt, given lithium's wide availability and it currently still being cheaper to mine than to recycle. Older nickel-based Li-ion batteries such as NMC 1-1-1 ("1-1-1" refers to the equal parts of nickel, cobalt, and manganese) contained a high concentration of cobalt, enough to produce several new batteries using contemporary mixes with a lower concentration of cobalt. As a result, the metals currently of primary commercial interest have been—and remain—nickel and cobalt, but this is changing with the automotive industry's shift from NMC to LFP, and the proposed EU Battery Regulation's mandated recycling targets.

LIB recycling projects in European Union, 2022

NORTHERN EUROPE

NORWAY

- **Glencore & Nikkelverk** – Kristiansand (installed) – **7.000 t/a**
- **Hydrovolt** – Fredrikstad (installed) – **12.000 t/a**
- **Li-Cycle, Ecostor & Morrow** – XXX (for 2023) – **10.000 t/a**

SWEDEN

- **Stena recycling** – Halmstad (for 2023) – **10.000 t/a**
- **Northvolt** – Skelleftea (for 2023) – **125.000 t/a**

FINLAND

- **Akkuser** – Nivala (installed) – **4.000 t/a**
- **Fortum** – Ikaalinen (installed) – **3.000 t/a**; Harjavalta (for 2023) – **XXX t/a**

SOUTHERN EUROPE

SPAIN

- **Endesa** – Cubillos del Sil (installed) – **8.000 t/a**
- **IR Recypilas** – Erandio (installed) – **XXX t/a**
- **ELT InnoEnergy** – XXX (for 202X) – **15.000 t/a**

ITALY

- **ItalVolt** – Scarmagno (for 202X) – **XXX t/a**

EASTERN EUROPE

POLAND

- **SungEel Hitech & Posco** – Bukowice (for 202X) – **20.000 t/a**
- **Royal Bees** – Legnica (2020) – **3.600 t/a**
- **Attero** – XXX (for 202X) – **15.000 t/a**

HUNGARY

- **SungEel Hitech** – Batonyterenye (installed) – **25.000 t/a**

WESTERN EUROPE

GREAT BRITAIN

- **Glencore & Britishvolt** – Northfleet (for 2023) – **10.000 t/a**
- **Veolia** – Minworth (for 2024) – **XXX t/a**
- **Gigamine** – XXX (for 202X) – **XXX t/a**
- **Ecobat** – Darlaston (installed) – **XXX t/a**

SWITZERLAND

- **Batrec** – Wimmis (installed) – **500 t/a**
- **Kyburz** – Freienstein (installed) – **100 t/a**
- **Librec** – XXX (for 2023) – **XXX t/a**

BELGIUM

- **Umicore** – Hoboken (installed) – **7.000 t/a**
- **Aurubis** – Olen (for 2025-26) – **XXX t/a**

GERMANY

- **Accurec** – Krefeld (installed) – **3.250 t/a**
- **Basf** – Schwarzheide (for 2024) – **15.000 t/a**
- **Duesenfeld** – Wendeburg (installed) – **2.900 t/a**
- **Erlos** – Zwickau (installed) – **950 t/a**
- **Walch** – Baudenbach (for 2024) – **1.000 t/a**
- **Primobius** – Hilchenbach (installed) – **20.000 t/a**
- **Redux** – Bremerhaven (installed) – **10.000 t/a**
- **Roth** – Wernberg-Köblitz (202X) – **9.000 t/a**
- **Volkswagen** – Salzgitter (installed) – **1.500 t/a**
- **Mercedes-Benz** – Kuppenheim (for 2023) – **2.500 t/a**
- **Stena** – Wangerland (installed) – **350 t/a**
- **Northvolt** – Heide (for 2025) – **XXX t/a**
- **Aurubis** – Hamburg (for 202X) – **XXX t/a**

FRANCE

- **Snam** – Saint Quentin (for 202X) – **10.000 t/a**
- **Veolia & EDI** – Dieuze (for 2023) – **5.000 t/a**
- **TES** – Grenoble (installed) – **2.200 t/a**
- **Suez** – XXX (for 2024) – **XXX t/a**
- **Veolia & Group Renault** – Amneville (for 2023) – **4.000 t/a**

THE NETHERLANDS

- **TES & BEE** – Rotterdam (installed) – **14.000 t/a**

Fig 16. Lithium-ion battery recycling projects in the European Union as 2022.[102]

Recycling in Belgium

There are two notable LIB recyclers operational in Belgium, namely Umicore and Avesta Battery & Energy Engineering (ABEE).

Umicore has a 7,000 tons facility in Belgium, and plans to build a 150,000 tons recycling facility in Europe.

ABEE is a smaller player, currently building an R&D LIB recycling facility in Ninove. In October 2022, ABEE announced plans for a battery pack Gigafactory in Belgium, and is preparing to announce the location of a 50,000 tons recycling facility in Europe. ABEE also plans a second future facility, which will take its total installed capacity to 100,000 tons. It has not confirmed where this second facility will be built.

102 *Battery-news.be (2022)*

How lithium-ion battery recycling works

LIB recycling is a two-phase process, involving battery pre-treatment, and refining. Here we look at how each phase works and provide insight from companies involved

Pre-treatment

Put simply, pre-treatment involves discharging, dismantling, and shredding the battery.

Before any work commences on a battery, it must first be discharged to protect workers from electric shocks, and prevent the risk of fire during the shredding process. Discharging is typically done using salt-water baths, but other methods include thermal pre-treatment, the use of external circuits, vacuums, or even a liquid nitrogen-based cryogenic process.

Opening and dismantling the battery pack is a complex and dangerous manual process, using force to open sealed battery enclosures. Older packs in particular were sealed for safety and security with little or no design for disassembly.

Dismantlers then remove the battery management system (BMS), copper cables, printed circuit boards, and other parts such as separators; the coolant is drained, and pyrolysis vaporizes the liquid electrolyte.

What happens next depends on the recycling process. There are two main recycling methods: pyrometallurgy and hydrometallurgy.

Pyrometallurgy and hydrometallurgy – the two main recycling methods

Pyrometallurgy involves smelting battery modules in a furnace; this method recovers primarily cobalt and nickel.

If hydrometallurgy is being used, the battery modules and cells are put through a further pre-treatment stage, typically an industrial shredder, to create “black mass”—a powder mix of anode and cathode material, typically lithium, manganese, nickel, cobalt, and graphite. This black mass is then sent to a hydrometallurgy recycler which uses several stages of aqueous chemical treatment to recover the various metals.

These two types of recycling methods are detailed in Table 11.

Table 11. Explanation and comparison of pyro- and hydro-metallurgy recycling methods.

Process	Pyrometallurgy	Hydrometallurgy
Details	Heat-based smelting process Used to refine black mass and built-up battery modules Three stages: Roasting, smelting, refining	Aqueous chemical extraction of metals from black mass containing cathode active materials (CAM) such as nickel, manganese, cobalt, and lithium Metals are dissolved in three aqueous steps: Leaching: aluminium foil is removed and the CAMs are separated Purification Recovery processes known as selective precipitation (separating ions in an aqueous solution) or electrowinning (electrolytic chemical reaction).[103]
Advantages	Pre-processing can be used but is not essential as pyrometallurgy can reduce modules without pre-processing Smelting is a quick way to reduce anything in the furnace	High recovery yield: >90% Can recover lithium Lower temperature processing (lower environmental footprint than pyrometallurgy) High potential for commercial returns of materials Lower safety risks than pyrometallurgy More adaptable to new technologies and different chemistries than pyrometallurgy
Obstacles	Energy intensive, requiring temperatures of 1200°C - 1600°C CO_2 emissions resulting from combustion Requires toxic fume control Cost intensive, due to high energy requirement Lower recovery yields than hydrometallurgy: 50-85% Only certain raw materials recovered, e.g., cobalt and nickel Lithium, aluminium, and manganese are not recovered Results in 'slag'—the remaining residue from built-up battery modules and other non-recyclable materials; the slag needs further handling and disposal	Chemical intensive Capital-intensive process Multiple steps

103 https://www.tes-amm.com/news/the-difference-between-hydrometallurgy-and-pyrometallurgy

Direct recycling: yet to be proven at scale

A third method, known as direct recycling, shows promise but has yet to be proven at scale.

Direct recycling involves the recovery and reuse of battery components directly without breaking down the chemical structure of the cells. Direct recycling keeps cathode crystal structure intact – the process is often referred to as cathode-to-cathode recycling.

RecycLIB

Direct recycling is being explored by an EU project called RecycLIB, which is researching "...a novel process chain of direct recycling of Li-ion batteries with subsequent reintegration of the recovered electrode material into new electrodes via melt manufacturing processes and the performance evaluation in battery cells."

The project's six partners are: Fraunhofer Institute for Silicate Research ISC, Hutchinson SA, Ghent University, ImpulsTec GmbH, Bavarian Research Alliance GmbH, and Carl Padberg Zentrifugenbau GmbH.[104]

Direct recycling avoids energy-intensive and costly metallurgical processing steps, and recovered materials can go directly back into cell manufacturing. This method is labour-intensive as it requires a detailed sorting process to separate battery types; as a result, it is not yet proven at scale.

Globally, pyrometallurgy is understood to be the most common recycling technique.

However, apart from Umicore, which combines pyrometallurgy and hydrometallurgy, the companies we spoke to for this report use hydrometallurgy.

Recyclers discuss pyrometallurgy and hydrometallurgy

Umicore uses a proprietary hybrid recycling model which combines pyrometallurgy and hydrometallurgy (Fig 17). "A very good recycling process will always be a combination of high temperature steps, and chemical metallurgical separation," says Kurt Vandeputte, Senior Vice President Battery Recycling Solutions at Umicore. "As a chemist, I see no other way to go from a very complex, old battery to new cathode material with fairly high-quality requirements if you do not combine these two approaches. And that is Umicore's proprietary process, which we have patented."

Fig 17. Umicore's recycling method (hybrid recycling model combining pyrometallyrgy and hydrometallurgy) compared to others recyclers' method.

High temperature smelting scales well, explained Vandeputte, because it reduces complexity at high temperature, and brings together all the valuable metals in that process.

"We have compared high temperature smelting and hydrometallurgy techniques because we have both in-house, and we prefer for that first step, to go as much as possible with high temperature smelting, because it is robust, it's scalable, and it's doing exactly what we need, reducing the volume and bringing it to the valuable products that are inside."

Note that the Umicore process does not recycle LFP batteries.

ABEE uses hydrometallurgy combined with mechanical treatment, which is much less energy intensive than pyrometallurgy, explained Noshin Omar, CEO of ABEE. "We do not use pyrometallurgy because it is not efficient and not environmentally friendly. That is why we selected the mechanical and hydrometallurgical process to keep the energy consumption down. But customers are now requesting that recycling plants' CO_2 footprint should be a specific level. So, moving towards renewables is very important from that perspective, but of course, if the energy comes from somewhere else, and the prices increase, that will affect the cost of recycling."

104 https://www.era-learn.eu/network-information/networks/era-min3/eu-co-funded-era-min-joint-call-2021/direct-recycling-of-lithium-ion-batteries

Aurubis focuses on hydrometallurgical recycling, but it also sees benefit in pyrometallurgy, said Nagayama: "We acknowledge that our pyrometallurgical flow sheets offer substantial opportunities when it comes to recovering traces of valuable elements. Where it is too costly to use hydrometallurgy, we are willing to consider the idea of combining hydrometallurgical activities with pyrometallurgical flow sheets to optimize the overall recovery of metals."

Solvay supplies chemicals to the mining industry and recyclers using hydrometallurgy. "We favour hydrometallurgy because it does not destroy things, it extracts. Pyrometallurgy destroys the graphite for its energy potential, for example" noted Christophe Couesnon of Solvay. "Hydrometallurgy has a higher recovery rate. We can even separate the graphite, as we believe there will be opportunities to purify all these materials, even graphite, electrolytes, and fluorine, which are considered as by-product or waste today."

Solvay's expertise in chemicals enables it to achieve recycling rates in a way that cannot be achieved with pyrometallurgy, added Couesnon. He added that hydrometallurgy is more adaptable to new battery technologies, but the destructive nature of pyrometallurgy would struggle with solid-state batteries, lithium metal, or manganese-rich mixes. "We believe recycling needs to be able to adapt to the evolution of battery materials."

Li-Cycle uses hydrometallurgy; its recycling outputs include aluminium, copper sulphide, graphite, iron, manganese, sodium sulphate, and battery-grade cobalt sulphate, lithium carbonate, and nickel sulphate. "Right now, the main target is getting scrap over the next three to five years," said Kunal Phalpher, an Advisor to Li-Cycle. "But as we get into the 2030s, we will start seeing big waves of vehicles come off the road, and then you can start to penetrate in the 30, 40, 50 percent range of recycled material. Obviously, this is all dependent on how chemistries and technologies change."

Recycling's CO_2 footprint

The following points were raised in reference to the CO_2 footprint of recycling.

- **Battery production has a CO_2 footprint...:** Kunal Phalpher, Advisor to Li-Cycle, said: "A large portion of the CO_2 footprint of an EV is battery production, and between 30 percent and 60 percent is accounted for by battery materials. Using an increased amount of secondary or recycled materials, and offsetting those primary materials, will help bring down that initial CO_2 "capex" of the vehicle. But we also have to look inward—how do we reduce the CO_2 of our operations?"
- **...but so does recycling:** This can be addressed in part by using renewable energy to power the recycling facility. "You can reduce the carbon footprint by about two-thirds, if you use recovered material in a hydrometallurgical process with high recovery rates and the use of 100% renewable energy in the process," noted Ane Dalum from Volvo Cars.
- **Recycling must be more efficient than mining:** The heavy use of chemicals in hydrometallurgy can be turned to an advantage, noted Christophe Couesnon. The key issue, he said, is to make the recycling process as efficient as possible, and to ensure it is less impactful than a mine, "because otherwise, we will have failed."

The business of recycling

Li-ion battery recycling is an industry with high levels of capital and operational expenditure, highly limited feedstock, and an over-reliance on production scrap. Moreover, the long-term recycling business model remains unclear.

Currently, battery recycling is akin to a disposal business, we were told; recyclers generate revenue from recycling fees and the sale of recycled materials; recycling companies receive payment for the batteries, and they retain the recycled material which they can sell on; and the automakers get battery grade material which enables them to meet minimum recycled content requirements in new batteries.[105]

As recycling capacity increases, such transactions are unlikely to continue. In the future, recyclable battery material is likely to be treated like e-waste, or copper scrap, where the recyclable material has value. At that stage, we can expect owners of EOL batteries to demand payment.

Establishing the infrastructure and capacity for recycling is challenging for several reasons:

- Lack of feedstock
- Difficulties forecasting volumes
- Changing battery chemistries
- Changing battery technologies
- Recycling technology
- Business model

Due to insufficient take-back and recycling capacity, EOL battery handlers pay for batteries to be recycled. Recyclers charge a fee for processing recyclable material – we understand this ranges between €3/kg and €9/kg.

What is a used battery worth?

With recycling currently such a nascent industry, the value and pricing of used batteries, black mass, and refined materials is fluid at best.

According to WMG, the average value in an EOL EV battery pack is €3.8/kg for BEVs and €2.5/kg for PHEVs.[106]

According to EY calculations, high-cobalt batteries could be worth up to $22/kWh, while advanced nickel-heavy batteries could secure up to $18/kWh through recycling service fees, the sale of recovered materials, and other more complex commercial arrangements. However, EY notes the importance of scale: "opex[107] costs per kilogram of converted material begin to reach minimum efficient scale at around 10 ktpa[108] –20 ktpa throughput. At US$1.60/kg opex at 20 ktpa, which some of the larger hydrometallurgical plants are targeting at feasibility stage, this can unlock up to US$11.8/kwh net profit for a NMC811 cell. This is significant considering today's high-nickel cells cost upwards of US$130/kwh to make."[109]

Meanwhile, research by consultancy Circular Energy Storage (CES) found that the average battery pack in Europe and North America is priced two and a half times higher than the value of its recoverable materials, priced as chemical products, and 12 times higher than what a recycler could charge for the black mass they contain.[110]

The recycling business model is entirely dependent upon the resale value of the recovered material, which varies according to battery chemistry, raw material prices, and the cost of recycling process.

105 Automakers rarely produce their own EV batteries, typically operating thorough supply agreements with battery specialists
106 https://warwick.ac.uk/fac/sci/wmg/business/transportelec/22350m_wmg_battery_recycling_report_v7.pdf
107 Operational expenditure
108 Kilo-tons per annum
109 https://www.ey.com/en_uk/strategy/10-ways-to-help-build-a-thriving-battery-recycling-industry-in-europe
110 https://www.linkedin.com/feed/update/urn:li:activity:6998695534236418050/

Supplier deep dive: CLEPA, European Association of Automotive Suppliers

CLEPA
European Association of Automotive Suppliers

CLEPA

CLEPA, the Brussels-headquartered European automotive suppliers association, considers the whole battery value chain, including recycling, remanufacturing, and second life as being vital to the future of road vehicles.

Dr David Storer, Director Research, Innovation and New Mobility at CLEPA, noted a clearly growing relevance of electromobility in Europe and the associated development of battery systems, among other innovation trends.

The continued development of these technologies is possible thanks to a huge effort in R&D, said Storer, who noted that automotive suppliers are the largest private R&D investor in the EU, allocating over €30bn every year to research and innovation.

Several CLEPA members are involved in different parts of the battery system value chain, said Storer, including the thermal management system, and battery pack housings.

Furthermore, CLEPA is involved in Batt4EU, Europe's Research and Innovation partnership, which supports the development of a competitive industrial battery value chain in Europe.

Going forward, Storer noted that CLEPA is keen to develop further activities in this area and to intensify its work with members and interested companies, for example in the design and supply of battery systems and constituent systems and components including cells, and in the recycling process. Although lithium-ion batteries dominate EVs today, battery technologies and chemistries are evolving, and so too will the economics of recycling and reuse, said Storer.

Second life

He also noted that because batteries are optimised for their first-life application, there are some questions over whether the same optimisation is suitable for a second-life application, and whether a second-life application makes viable use of a battery system after its first life.

"Currently there is considerable emphasis on developing and optimising batteries, and developing new chemistries for the first line of application," said Storer. "At the same time, it is crucial to optimise for what will happen after the first application, and how to exploit the intrinsic value of the battery systems to the full."

Circular economy

Storer emphasised the importance of recycling within a circular economy, and the importance of design for recycling, which he said he expects to be a focal point for CLEPA's future activities.

Correspondingly, CLEPA's R&I Working Group has recently launched a Circularity Task Force to define the common R&I priorities of members with respect to circularity in the context of ensuring the sustainability of Europe's automotive industry.

Chapter 3.
Second life battery applications

Chapter key takeaways

1. A second life battery is an all-new product, sold under the second life battery maker's brand, with a warranty and full customer support.
2. Production of second life batteries involves a significant level of manual labour.
3. Automation of battery dismantling would greatly improve the second life battery industry.
4. Volumes of battery feedstock are currently low for a viable second life industry.
5. Production of a second life battery cannot begin until there is a sufficient stock of the same battery. Catherine Lenaerts of Watt4Ever told us the minimum is 3MW.
6. Primary users are early adopters, such as companies driven by environmental goals.
7. For the end user, the battery chemistry is important, for fire and safety reasons.
8. Customer and corporate hesitancy: The concept of second life is not clearly defined, leaving insurers concerned, and customers not understanding why they must pay for what they see as a used battery.

The rise of battery energy storage solutions (BESS)

The cells and modules in depleted EV batteries are still usable in second life applications, generally BESS, typically used for grid balancing, domestic and industrial applications, storage of renewable energy (wind, solar), night-time power supply, and self-consumption—the retention of some stored of energy to provide power required onsite at the wind or solar farms, rather than taking power from the grid.

There is a growing market for energy storage solutions, using a variety of technologies and methods, that include hydrogen, ammonia, compressed gas, liquefied gas, thermal storage, gravitational lifting weights, advanced pumped hydro, redox-flow batteries, and sodium-ion batteries.

Despite this variety, in 2021, Li-ion battery storage contributed 95 percent of new utility-scale capacity globally, according to BloombergNEF. The publication also noted that global energy storage additions will grow to 411 GW/1,194 GWh annually by 2030, with the US and China accounting for over half of all deployments. This, it says, compares with deployments in 2021 of 10 GW/22 GWh, and is 15 times the cumulative installed capacity of 27 GW/56 GWh online at the end of 2021.[111]

And McKinsey notes that by 2030, retired EV batteries could provide 200 GWh of energy storage globally each year.[112] For comparison, this is enough energy to power 30 million homes.[113]

Recycling "should be the last step"

Benedikt Sobotka, Co-chair of the Global Battery Alliance told us: "There are certainly suitable second life applications for EV batteries. One of the most promising options is stationary energy storage, which can support the rollout of renewable energy by increasing energy security and evening out intermittent energy supply. A battery has reached its 'end-of-life' when its value has decreased by around 20 percent. However, at this point it can still have a capacity of over 80 percent.[114] To dispose of the battery at this stage is inefficient and an unsustainable use of resources, which are not being used to their full potential. Especially with the currently limited recycling infrastructure, repurposing is an effective solution which will support low-cost energy storage."

"Recycling should be the last step. Second life should be a priority," said Vanesa Ruiz Ruiz, an independent battery expert and a former Programme Officer at the European Commission's Joint Research Centre (JRC), the EC's science and knowledge service.

Philippe Celis, CEO of Belgian battery collection company Bebat agreed: "From a Bebat perspective, recycling is not the only option," said Celis. "Before a battery goes into recycling, it should be analysed to see if it is suitable for recycling or for second life, and Bebat is investing in this knowledge. You will not avoid recycling, but at least you can postpone recycling, and that will already help."

He added that in terms of a circular economy, it is the duty of a compliance scheme to look at all options available before recycling a battery.

A second life battery is a "new" battery

A common misconception of how a used EV battery makes its way from a vehicle into a second life application is that it is simply removed from the vehicle, and deployed with new external wiring as a power source in a warehouse or garage.

The reality is very different and involves the production of an all-new energy storage system.

Developing a battery for a second life application is a complex process: once collected, the EV battery pack must be dismantled and sorted. Access to the battery management system, if granted, identifies the state of health of the modules, and the useable modules are stored for use in the new ESS. Bebat's Philippe Celis emphasized the need to understand the complexities of second life: "For second life, you need to dismantle a battery, which is a complicated, dangerous, and costly process requiring manual labour. Once dismantled, you need access to the software to read the battery. And only then can you say whether a battery goes into recycling or second life."

Only once there is a sufficient number of useable modules of the same battery type can the assembly process begin. "The development cost and the certification cost of a circular energy storage system are important, so therefore you need at least three megawatts of the same useable modules of the same battery type – and this is dependent on the supply of EOL batteries," said Catherine Lenaerts of Watt4Ever, a Belgian producer of second life batteries.

Once the minimum number of modules has been collected, they are built into a new battery housing, along with an all-new battery management system and thermal management technology. The ESS supplier must transfer liability and ownership of the battery, and offer the end-user maintenance and service for the lifetime of the new battery.

111 https://about.bnef.com/blog/global-energy-storage-market-to-grow-15-fold-by-2030/
112 https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage
113 https://blog.arcadia.com/first-gigawatt-community-solar/
114 https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage

Second life battery suppliers

Second life battery makers represented in this report include two Belgian second life battery suppliers, and a UK supplier which has operations in Belgium

Watt4Ever

Watt4Ever is a Brussels company producing second life EV batteries for energy storage systems (Fig 21). Catherine Lenaerts is Deputy CEO and a board member. Lenaerts is also the MD of Febelauto, a Belgian used EV battery collection company.

Watt4Ever produces second life EV batteries for energy storage systems. It disassembles used EV batteries, and tests the modules' state of health; the good modules are built into a new battery pack, with new battery, energy, and thermal management systems, and new battery pack housing. Where possible, cables and other components are also given a second life. Watt4Ever sells the battery as an all-new product, or as a service under a kWh-based service level agreement, with aftersales service that includes state of health monitoring of the battery modules.

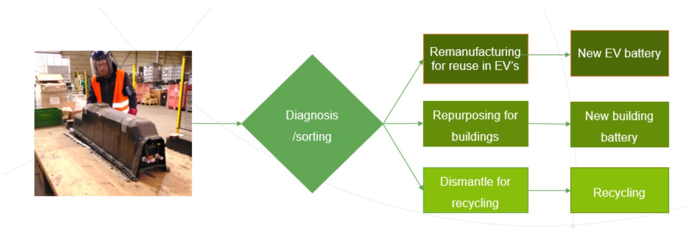

Fig 18. Sorting process of used EV batteries at Watt4Ever.[115]

To date, Watt4Ever has produced around 20 small, medium, and large batteries. Its focus however is now on more valuable medium and large batteries. The market for small batteries is dominated by low-cost products made by Asian companies which Lenaerts fears take no producer responsibility in the European market and have no systems for end of life, take-back, or recycling.

According to Watt4Ever, the BESS market is worth €20 billion, and is expected to grow at a CAGR of 17 percent until 2035.

Watt4Ever says its cost-efficient and sustainable battery storage systems allow customers to stabilize the grid, reduce energy costs, and become energy autonomous.

Octave Energy

Brussels-based second life battery company Octave Energy started in 2020, with a focus on stationary energy storage applications. Maxime Snick is Octave's CEO, and the company targets B2B clients such as SMEs, industrial sites, or large buildings. Its batteries are for peak shaving, and self-consumption for sites with local renewable energy generation, and Octave encourages grid services to increase the profitability of the battery.

Octave Energy designs battery cabinets with a storage capacity of around 100 kWh, and sells them under the Octave brand. Octave buys modules from suppliers which dismantle and test the used EV battery packs, thus bypassing any waste material issues. "This is a big advantage, and it is important for us that we are not buying a damaged battery module."

Octave's commercial partners include Bebat, the local battery collection scheme in Belgium, and Ecaraccu, the battery collection partner in the Netherlands.

On Belgium: Maxime Snick, CEO Octave Energy

I think there is actually a great opportunity in Belgium. We have one of the highest recycling collection rates for batteries, we have a very high collection rate for used cars as well. With Umicore, we have one of the leaders and in terms of recycling. So, we do have an incredible opportunity to build really a thriving second life value chain in Belgium.

The company's expertise, Snick explained, lies in designing the system, using its own patent-pending battery energy management system. Octave gathers detailed and extensive data from the battery cells in operation and learns the behaviour and degradation of these batteries on-the-go. This enables it to perform predictive

115 Source: Watt4Ever

maintenance and swap battery modules if required.

Under a hybrid business model, Octave sells its BESS with assumed liability, and offers a maintenance service which leverages the battery energy management system to monitor battery module performance. Octave offers a battery swapping service to support a warranty on the battery that matches a new battery warranty. "Our warranty is ten years, after which we guarantee that you will have 70 percent of the battery system capacity remaining."

Because Octave cannot guarantee the number of cycles a battery module can do, its battery energy management system and cloud technology identifies modules displaying a lower cycle life and replaces them to ensure the system as a whole stays within the warranty conditions.

At the end of the second life application, the batteries are collected under the Bebat collection and recycling scheme.

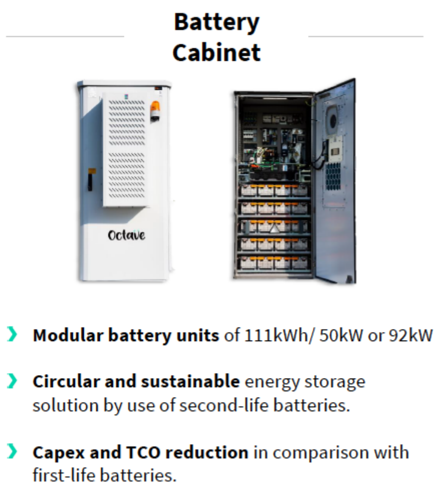

Fig 19. Illustration of Octave's battery cabinet.

Zenobé Energy

Zenobé Energy is a UK owner and operator of battery storage which specializes in battery as a service, charging as a service, and transport as a service, Zenobé also claims a 25 percent share of the UK's e-bus market and has around 540 e-buses contracted globally. One of its customers in the Benelux region is Aertssen Group, which is profiled in this report.

Once the batteries on one of Zenobé Energy's electric buses are no longer capable of supporting a full route, after approximately five to seven years, Zenobé repurposes them as energy storage solutions (Fig 22). "This enables the batteries to go another ten years," explained Peter Pauwels, General Manager, Benelux. Zenobé designs LFP batteries for solar shifting, peak shaving on charging hubs, portable applications in the construction industry, electric vehicles, concerts, and maritime solutions.

Zenobé has second life batteries in service in the UK cities of Birmingham, Coventry, and London to support electric bus charging; it is the Official Energy Storage Supplier for the first season of the new Extreme E race series, and provides a second-life battery to power the race's paddock operations; and in Belgium, Zenobé has installed a second life battery at Aertssen's Verrebroek location to manage energy price volatility and store solar power from 5,500 solar panels.

Zenobé noted that second life batteries are cheaper than new batteries, but perform as well as new batteries in applications where energy density is less critical than in a vehicle. "We own the batteries and manage the charging through our software, we know their exact quality and status, and can provide full performance guarantees over 15 years," said Pauwels.

Zenobé confirms that battery availability currently presents challenges, but its business model means it has a pipeline of future EOL batteries as it operates and finances 771 public transport buses. All of these batteries—the equivalent of several gigawatt hours of energy storage, noted Pauwels—will eventually be available for Zenobé's second life applications in what is essentially its own closed loop.

The business of second life

Although a used EV battery may have lost one quarter to one third of its storage capacity, it still has between two thirds and three quarters of its originally intended capacity, which could deliver five to ten years more in a less demanding second life energy storage application, extending the lifetime of the battery and maximising its potential.

Second life battery users are primarily pioneers and companies driven by environmental and sustainable development goals. Because a second life battery cuts out the need to mine raw materials such as cobalt, lithium, and manganese, second life battery production has a lower CO_2 footprint than new battery production—ideal for an industry in which the concept of circular economy is becoming a leading industry trend that will encourage the use of second life batteries.

Furthermore, the lower value of batteries without nickel and cobalt reduces the urgency to rush LFP batteries into the recycling value chain, and makes these batteries more attractive to second life battery producers.

Catherine Lenaerts was emphatic about the commercial benefits of buying a second life battery, and a Watt4Ever battery in particular: "The CO_2 footprint of our battery is 80 percent lower than a new battery because we do not need to mine new cobalt, lithium, and manganese. There is also a financial advantage, as our medium and large batteries are between ten and 20 percent cheaper than an equivalent new battery. Buying a Watt4Ever battery also supports Belgian production."

As discussed elsewhere in this report, there has long been an expectation that the cost per kilowatt hour of new batteries would eventually fall to below $100/kWh, with $100 widely regarded as the point of cost parity between combustion engine vehicles and EVs. Although the fall in battery prices has slowed, this still seems feasible in the long term.

To this point, Philippe Celis of Bebat asked: "Will that still be competitive with a second life battery? The only way to find out is to do it – and Bebat or the compliance schemes, need to explore second life, to understand and then to adapt."

A second life battery is effectively a new product, he explained, and noted the cost implications. "What will be the cost per kilowatt hour, taking into consideration the dismantling, analysis, and making a new product? And then how does that compare to the cost per kilowatt hour of a new battery?"

Yann Vincent, the CEO of ACC, raised the cost issue in an interview with Martin Kahl of Ride: The Urban Mobility Podcast[116] at Reuters Automotive Europe 2022: "The question is, what could be the usage of a battery at the end of its automotive lifecycle, around ten years? It may be used for energy storage, but the companies operating energy storage will have to ask themselves: Am I better off getting an old battery or buying a new one? And it boils down to the improvement curve over the next ten years. We are all announcing significant savings, thanks to technology, provided those savings are indeed achieved. Is it better buying a new battery whose cost is say $50/kWh, instead of an old one whose initial cost was $100/kWh? The question of usage of a battery at the end of its automotive life is a key question for car manufacturers, because it has an impact on the residual value, and on leasing, etc."

On the point about the $100/kWh benchmark, Maxime Snick of Octave Energy said: "The price for a second life battery module will also be correlated, of course, to the price that you see for first life modules. And in the end, we will always have a cost advantage compared to first life, because we are able to extract value from a product that was already written off. So, the value without second life of that battery module has become zero if you do not have second life, and so this cost delta is always there. And I think we will always be able to exploit that."

Gilles Normand, EVP International Development at solid-state battery manufacturer ProLogium, said the business case for second life applications hinges on a number of factors, and is influenced by regulation, notably the proposed EU Battery Regulation which could affect the value of batteries and the materials they contain. Currently, he said, the attraction of second life battery applications is the use of depreciated batteries, but if a scarcity of raw materials increases the used battery value, batteries will go straight into recycling without being considered for second life applications. Normand is a proponent of second life: "Using raw material for a first life battery, then deploying that battery in a second life application, and then recovering the materials at the end of the second life to feed into a new battery—this is a process we should develop." However, he notes, reaching full maturity of such circularity would take 25 or 30 years. "Shortening this cycle increases the value of the batteries," he noted, "thereby increasing the cost of the vehicles and limiting the sale of new cars. This will encourage people to continue using internal combustion engines. In terms of CO_2 balance, this is not healthy."

Finally, second life is expected to be supported by the incoming EU Battery Regulation.

116 https://www.ridemobilitypodcast.com/episodes/in-search-of-a-european-ev-battery-champion-feat-yann-vincent-acc

Barriers to entry

Despite the compelling arguments in favour of second life EV battery use, several barriers to entry were noted during our research:

- Second life battery production is **labour-intensive.**
- **Difficulties forecasting EOL battery supply** creates uncertainty in second life battery production; minimum batch sizes (Watt4Ever: 3 MW) of the same battery type required before it is viable to use them to begin producing a second life battery.
- **Older batteries contain high valuable material content.** The high concentration of metals in one old battery could produce two or more new batteries, strengthening the case for recycling rather than leaving this valuable material in circulation.
- **Delaying availability of recyclable material:** Sending a battery into a second life application postpones its journey into the recycling value chain.
- **Battery ownership:** Extended producer responsibility (EPR) is defined by the OECD as: "a policy approach under which producers are given a significant responsibility – financial and/or physical – for the treatment or disposal of post-consumer products."[117] McKinsey notes that when second-life markets stabilize, battery residual value will make battery ownership more attractive, leading to a rise in EV-battery leasing enabling automakers or battery makers to control the battery's second revenue stream.[118]

Automaker concern about liability: Automakers note that EV batteries were developed specifically for use in EVs only. Automakers are reluctant to allow batteries into third party second life applications due to liability issues; this could change with provisions in the incoming EU Battery Regulation. However, there are several low volume second life battery trials involving automakers–such as Audi in India, as well as Renault and Nissan on specific BESS trials—in which the automakers have considerable control and oversight (see Appendix).

- **Too much variety:** Large number and variety of battery pack designs, chemistries, and cell formats complicate the collection of modules needed for second life batteries.
- **Insurance:** Thermal runaway and the history of Li-ion battery involvement in fires is a concern for insurers (see Aertssen case study).
- **Limited access to battery information for third parties.** The ESS manufacturer needs deep knowledge of the history and performance of the modules and cells, but proprietary control of the battery management system (BMS) makes it difficult for third parties to gain access to the relevant information.
- **Immature regulatory regime** and nascency of second life battery standards: McKinsey notes a lack of regulation that creates uncertainties for OEMs, second-life battery companies, and potential customers.[119]
- **Confusion over business model:** Catherine Lenaerts of Watt4Ever says a major challenge to the adoption of second life batteries is that people believe batteries in a circular economy should be cheap, or even free, without understanding the amount of engineering and work that is done, the fact that there are new components, such as the inverter, casing, and that a second life battery is sold as a new product with the same warranties as new products.

Recyclers are (unsurprisingly) sceptical of second life

Unsurprisingly, the recyclers are sceptical about sending used EV batteries into second life applications.

Changes in battery chemistries over the last decade mean that a ten-year old battery contains materials that could make two new batteries today, noted Charles Stuyck of Umicore, adding that, "it makes much more sense to recycle them and make new batteries than try to extend the lifetime another five years."

Stuyck also noted that EV batteries are designed for a specific purpose. "A typical ESS does not have the same functional requirements as an automotive application in terms of power, energy density, and heat management. So, you are always compromising by putting an EV battery into another application. It is better to recycle and make it a specific design."

Kurt Vandeputte of Umicore noted the challenge of forecasting how much EOL battery material will go into second life. "It is an economic decision for the owner of the EOL battery. Whether that is an OEM or another party, the question is, what do I get for supplying that battery for a second life application? What is the alternative to buying new materials instead of getting these recycled materials back? That equation will determine the second life market."

Vandeputte also questioned the quality of EOL battery material currently available: "The battery material currently coming back from the market that is usable for second life is very small. What you get back from the car industry right now is damaged batteries, which cannot go into second life. And the material that is suitable

117 https://www.oecd.org/env/tools-evaluation/extendedproducerresponsibility.htm
118 https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage
119 https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage

for second life is very fragmented, with low numbers of different battery packs, that are not sufficient for second life applications."

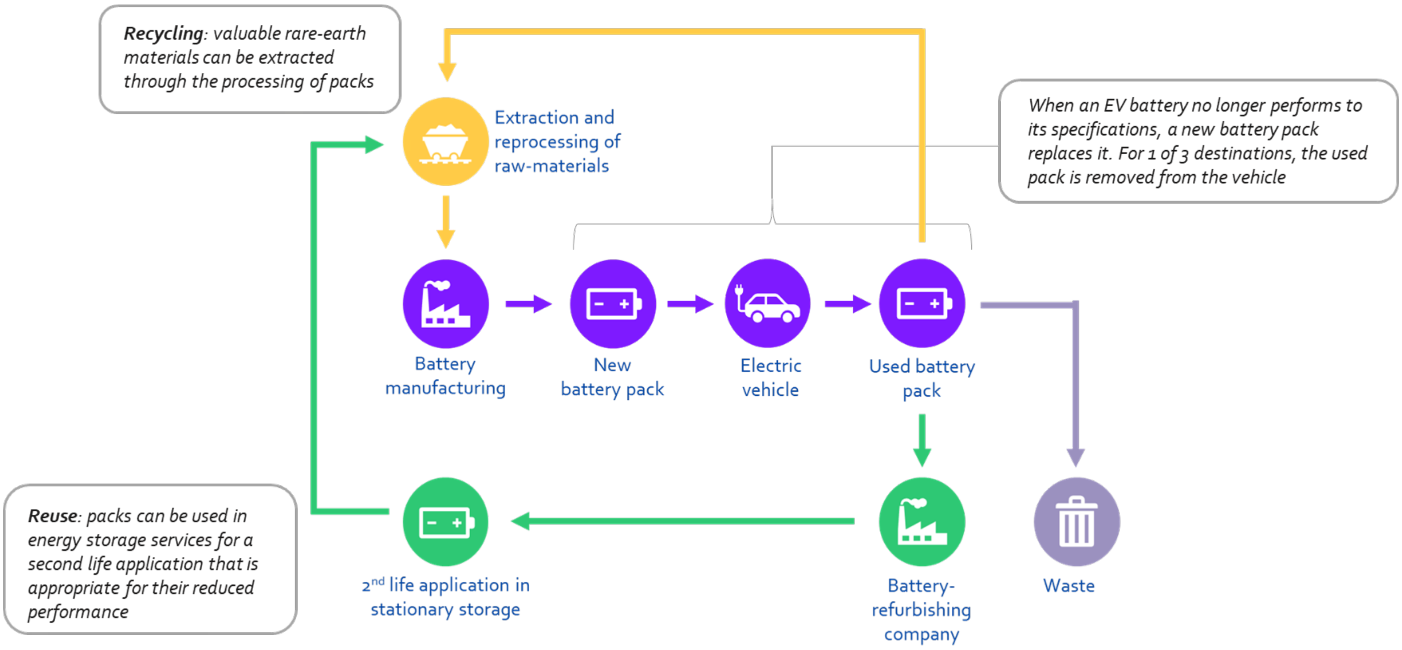

Fig 20. Illustration of the life cycle of an electric vehicle.[120]

Kunal Phalpher, speaking at Reuters Automotive Europe 2022 as an advisor to Li-Cycle, said, "We hear from the OEMs about the risks with reusing the batteries, and liability issues. But the re-used batteries are going to be recycled, so you are pushing out the recycling. There is a supply issue right now, where people are trying to acquire materials, and you are just delaying increasing the percentage of recycled material. So bringing it back into the supply chain earlier rather than reusing the batteries is beneficial on many fronts."

120 Source: Based on McKinsey

Wanted: Second life champions

Although talked about as an option since the current generation of electric vehicles first hit the market in 2010, second life is a relatively new area, due in part to low volumes, and a nascent industry. The low volumes of available second life battery material is caused by batteries still being in use in first application, and automaker reluctance to allow batteries into second life applications.

The proposed EU Battery Regulation seeks to establish an ecosystem for second life, from state of health, transparency, and battery passport to ownership and extended producer responsibility (EPR).

Second life will benefit from second life champions—prominent examples of successful second life battery installations that illustrate such batteries in use. The second life industry needs the support of the automakers to succeed, both in terms of making batteries available and fully accessible to second life producers, and in terms of supporting the conversion of used EV batteries into energy storage systems.

"We really need a driver for circular batteries, such as a major battery energy storage system project from someone leading by example," said Catherine Lenaerts of Watt4Ever.

Catherine Lenaerts, Watt4Ever

We really need a driver for circular batteries, such as a major battery energy storage system project from someone leading by example

By 2030, the supply of second-life lithium-ion batteries could reach 200 gigawatt-hours annually

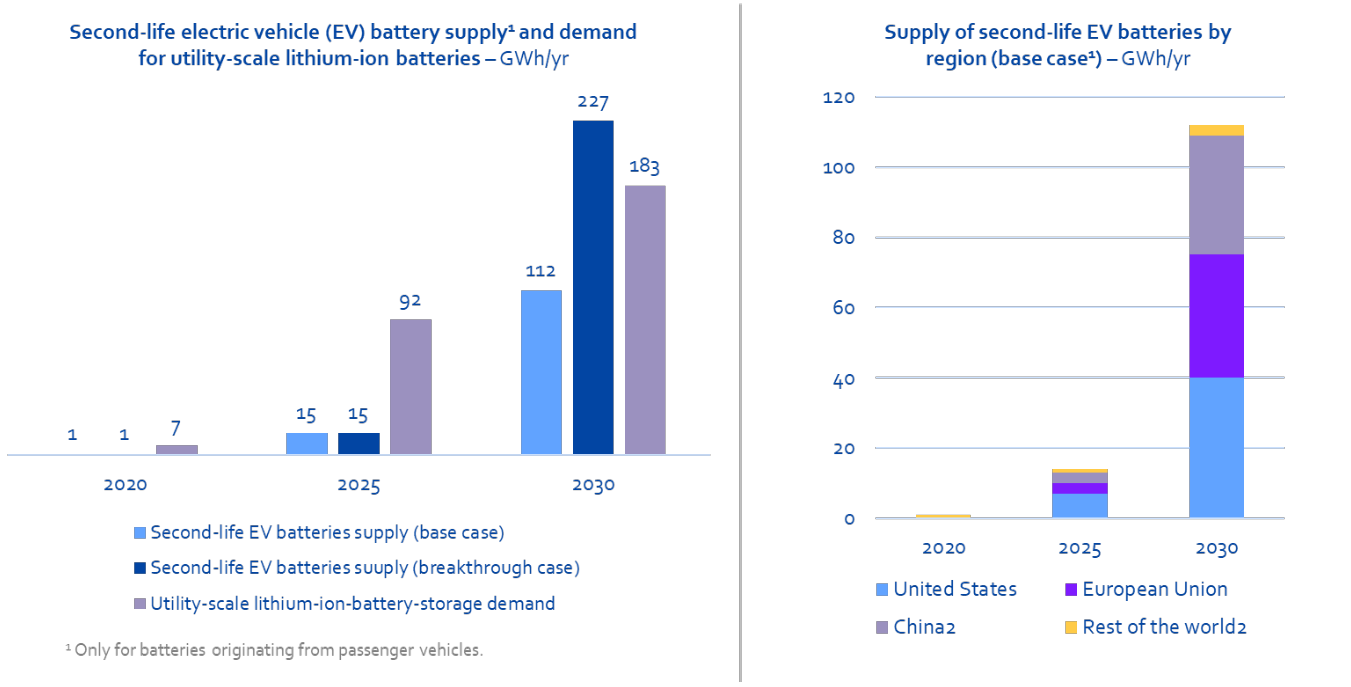

Fig 21. Evolution of supply in second-life electric vehicle battery and demand for utility-scale lithium-ion batteries, global and by region.[121]

121 Source: Based on McKinsey

Second life battery case study: The Aertssen Group

Aertssen Group operates two different second life energy storage systems at its facilities in Belgium: one at its Verrebroek logistics park, and a second on the Terranova Solar Park

Tim Maeyens
Sustainability & Energy Manager at Aertssen Group

Aertssen Group is a family-owned company providing equipment and logistics services for earth-moving, mobile cranes, renewable energy, and transport & logistics. The company has operations across Belgium, at Verrebroek, Kallo, Zeebrugge, Zedelgem, and Westerlo, as well as operations overseas. Headquartered at Stabroek, close to the port of Antwerp, the company employs over 1,500 people.

We spoke to Tim Maeyens, Sustainability & Energy Manager - Aertssen Group, about two different second life battery activities in operation at the company's facilities.

One is at Aertssen's logistics site at Verrebroek[122], where the company has a 1.65 MW solar park. Here it uses a 1.4 MWh second life battery for peak shaving, night consumption, and reactive power correction. The battery operator, Zenobé, takes care of grid balancing services. The battery is a second life battery made from used electric bus batteries.

The second is a smaller battery on the Terranova Solar Park (Fig 20). Terranova Solar is owned by three private companies: Aertssen is the major shareholder of 45 percent, Jan Der Nul and Deme own 45 percent, and 10 percent is in public ownership.

This 16.7 MW solar park is the biggest solar park in Belgium, its 55,000 solar panels supplying energy to 4,000 families.

Fig 22. Terranova solar park[123]

Here, the second life battery is part of a subsidized trial to test the capacity and endurance of second life batteries.

122 https://www.aertssen.be/en/news/aertssen-group-geeft-e-busbatterij-tweede-leven
123 https://www.jandenul.com/projects/zelzate-terranova

Octave Energy designed and installed a battery cabinet with a storage capacity of 75 kWh for self-consumption (some of the power is stored to run other onsite processes such as the 24/7 water treatment plant), night consumption, performing reactive power control and taking advantage of arbitrage opportunities with dynamic market prices. The battery modules were previously used in a Porsche Taycan, and the project involved Bebat, Brussel Leefmilieu, the STEPS programme from Interreg EU with partners Terranova Solar, Flux 50, and POM Oost-Vlaanderen.[124]

Reasons for using second life batteries

"At Aertssen, we believe in recycling, so second life batteries perfectly fit the company philosophy," explained Tim Maeyens.

Aertssen has not invested in the batteries—the cost is being borne for now by the battery operators. For the project in Verrebroek, Aertssen negotiated with several battery energy storage system (BESS) suppliers, and selected Zenobé because it offered second life batteries.

Aertssen only uses second life batteries for BESS, but Maeyens acknowledged that for large solar sites, the company may need to invest in batteries for grid balancing, and at that point, the company will need to decide between new and second life.

Safety

"For us as the end user, the type of battery was quite important for fire safety reasons."

At Verrebroek, the Zenobé second life BESS is a lithium iron phosphate (LFP) battery, previously used in an electric bus. LFP was selected for its relatively low fire risk.

At Terranova Solar, the Octave Energy BESS uses lithium cobalt oxide (LCO), previously used in an electric car.

Maeyens notes Aertssen's insurance provider's concerns over the potential safety risks associated with the use of second life BESS. Opting for LFP, which has lower fire risks than other Li-ion chemistries, made it easier to ease insurance concerns, but the insurance company stipulated that the battery must be placed at least ten metres from Aertssen buildings.

Future use of second life

Aertssen is exploring two possible future second life BESS projects.

One will replace diesel generators with mobile batteries, to save fuel when powering equipment at customer sites.

And at Aertssen's Verrebroek location, the company is exploring the possibility of using 160 kWh batteries instead of diesel generators; currently, it uses the diesel gen-sets to charge aerial platforms ahead of deployment to customer sites.

A viable option?

Asked whether second life has been a viable option, Maeyens said: "It is hard to say, it is too early. The battery has been fully operational for a few months. So, we are still analysing it. But so far, it has been working as it should."

124 https://www.octave.energy/news

Chapter 4.

Closing thoughts: A window of opportunity

Recycling and second life present significant challenges and considerable commercial opportunities:

1. The permit challenge: this is a major bottleneck, the easing of which would accelerate the development of recycling operations, and act as a major incentive to potential recycling companies.

2. The waste challenge: the classification of used Li-ion EV battery material as waste, and hazardous waste, increases the levels of administration required; the relaxation of waste classification for used Li-ion EV battery material could encourage potential recyclers to consider investment in that market.

    a. The handling of waste management at a regional level in Belgium further complicates the situation, with our research identifying this as one of the key challenges for operating in Belgium.

3. Used Li-ion EV battery recycling requires high capital and operational expenditure.

4. There is a severe lack of recycling capacity in Europe, and in Belgium in particular; the current limited feedstock belies an inevitable influx of recyclable batteries, which could be anything from a manageable volume, to a tsunami of used EV batteries—either way, governments should prepare now to handle future recycling volumes.

5. Recycling business models are unclear—unsurprising in this nascent industry, but there is clearly an opportunity for creativity.

6. Used EV battery recycling is currently poorly regulated; the same is true for second life battery applications. Both are expected to be addressed in the new EU Battery Regulation, which is expected to be implemented in 2023.

7. Rising and highly volatile raw material pricing makes this a highly risky and challenging market in which to operate.

8. Belgium may lack natural resources, but it has expertise in waste management and recycling.

9. Belgium is located centrally in Europe, presenting opportunities to handle batteries not only from its own market, but also neighbouring countries.

10. Recycling and second life are both at the start of a path to a trillion-Euro industry. The window of opportunity is wide open.

Acknowledgements

The authors would like to thank the following people and companies for taking the time to share their insight (in alphabetic order by company):

Company	Name	Role
Aertssen Group	Tim Maeyens	Sustainability & Energy Manager - Aertssen Group
Afreecar	Chris Borroni-Bird	Founder
Aurubis	Ken Nagayama	Business Development Battery Materials
Avesta Battery and Energy (ABEE)	Noshin Omar	CEO and Founder
Bebat PRO	Philippe Celis	Business unit consultant
Benchmark Mineral Intelligence	Sarah Colbourn	ESG Research Analyst
CLEPA	David Storer	Director of Research, Innovation and New Mobility
CLEPA	Paolo Alburno	Director, Technical Regulations
Denuo	Kristof Bogaert	Junior Advisor
ETIP Batteries Europe & Accompanying Research for the Battery IPCEIs	Stefan Wolf	Project Manager Accompanying Research Battery Cell Manufacturing
Everledger	Lauren Roman	Business Development Director, Metals & Minerals Ecosystem
FEAD	Paolo Campanella	Technical Officer
Febelauto	Catherine Lenaerts	Managing Director
FIPRA International	Erik Jonnaert	Chairman and Partner
Global Battery Alliance	Benedikt Sobotka	Co-chair
Independent battery expert	Vanesa Ruiz Ruiz	Independent battery expert and former Programme Officer at European Commission Joint Research Centre
Neckermann Strategic Advisors	Lukas Neckermann	Managing Director
Octave Energy	Maxime Snick	CEO and co-founder
ProLogium	Gilles Normand	Executive Vice President, International Development
RENEOS	Philippe Celis	CEO
SABIC	Dhanendra Nagwanshi	Global Automotive Leader - EV Batteries & Electricals
Solvay	Christophe Couesnon	Director of Strategy, Raw Material and Recycling, Battery Platform
Umicore	Charles Stuyck	Director, Battery Recycling Solutions
Umicore	Kurt Vandeputte	Sr Vice President Battery Recycling Solutions
Urbix	Nico Cuevas	CEO and Co-founder
Volvo Cars	Ane Dalum	Cluster Lead for Circular Batteries at Volvo Cars
Vrije Universiteit Brussel, Brussels (VUB)	Maeva Philippot	PHD Graduate Student
Watt4Ever	Catherine Lenaerts	Deputy CEO
Zenobé	Peter Pauwels	General Manager - Benelux
	Lukasz Bednarski	Author: "Lithium - The Global Race for Battery Dominance and the New Energy Revolution"

We are grateful to the following for their support:
CICEnergiGUNE https://cicenergigune.com/en **Battery News** https://battery-news.de/

About the Authors

Martin Kahl

Martin Kahl is an independent writer, researcher, and consultant specialising in automotive and future mobility.

Martin has over 20 years' experience in supply chain research, automaker profiling, consulting, journalism, editing, publishing, conference hosting and moderating.

His career in automotive began as a student at BMW Motorrad in Munich, followed by nearly nine years as a consultant, and 12 years at *AutomotiveWorld.com* where he was Editor in Chief.

Since 2020, Martin has been offering editorial and research consulting services for automotive and mobility stakeholders. He also hosts Ride: The Urban Mobility Podcast which looks at all aspects of the business of getting around.

Frederic John

Frederic graduated from Imperial College London with an MBA and has been researching the sustainable mobility industry through multiple studies and books. He is the Director of Greenimpact, a university professor, and the COO of *D-Carbonize.*

Greenimpact

Greenimpact is a not for profit organisation researching and experiencing innovative and sustainable projects related to mobility and smart city. Greenimpact thanks its partners and sponsors for their support and expertise (in alphabetic order):

GreenImpact
Decrease organisations' CO2 footprint

Aisin

AISIN

Bpost

bpost

D-Carbonize

D-CARBONIZE

Federal Ministry of mobility and transportation

Federale Overheidsdienst Mobiliteit en Vervoer
Service public fédéral Mobilité et Transports

Lab Box

LAB
A O
BOX

Appendix

Second life battery applications - selected examples

The accompanying table details examples of notable second life battery applications deploying used electric vehicle batteries

Project (Location)	Comments
E-STOR (Belgium, Olen)	Collaboration between Connected Energy, Groupe Renault, and Umicore Uses second life Renault Kangoo Z.E. batteries with a combined energy storage capacity of 720 kWh and output of 1.2 MW. The batteries power a quick charge unit that is itself slow-charged by onsite solar PV, micro wind turbines or other low-power generators. The solution enables quick charge units to be installed at locations that cannot use high power connections to the grid.[125]
Second Life (Spain, Melilla)	Enel's "Second Life" project combines 78 Nissan EV batteries (48 EOL batteries and 30 new batteries for performance comparison) at a conventional power plant in Melilla operated by Enel's Spanish subsidiary Endesa.[126]
Hengsteysee reservoir (Germany, Dortmund)	The system is comprised of 60 Li-ion batteries from Audi's e-tron vehicle development programme and is being tested for provision of temporary storage at RWE's pumped hydro plant at the Hengsteysee reservoir, one of the two main reservoirs at Herdecke near Dortmund in west Germany.[127]
Lünen-Daimler – BESS (Germany, Lünen)	This is an equal three-way joint venture between Daimler, Getec Energie (a subsidiary of GETEC Energie Holding) and The Mobility House. Announced in 2015 and commissioned in 2016, this 13 MWh project uses 1000 battery systems from second-generation Smart Fortwo Electric Drive cars for fully automatic energy storage and feed-in from fluctuating, renewable energy sources such as wind farms or solar power stations. The project was developed by Getec Energie and The Mobility House.[128]
Renault Mobilize and Betteries (Flins, France)	In June 2021, Berlin-headquartered Betteries signed an industrial partnership agreement with Renault's Mobilize to establish the first of a series of Betteries' Remanufacturing Centers at Renault Group's Re-Factory in Flins, France. The Re-Factory will handle the entire battery upcycling process including final assembly of Betteries' mobile, modular and multi-purpose energy system made up of 2nd life battery modules from Renault electric vehicles.[129]
Audi and Nunam electric rickshaws (India)	German–Indian start-up Nunam uses used Audi e-tron test fleet EV batteries in three electric rickshaws, to explore reuse of modules from high-voltage batteries in a viable second-life use case.[130]
Renault and The Mobility House (Douai, France)	In summer 2021, tech start-up The Mobility House implemented EV battery storage using a mix of new and second-life Renault Zoe batteries at Renault's Douai plant in northern France.[131]
Nissan and The Mobility House (Johan Cruijff Arena, Amsterdam, Netherlands)	Nissan, Eaton, BAM, The Mobility House, and the Johan Cruijff Arena. Support from the Amsterdam Climate and Energy Fund (AKEF) and Interreg The Johan Cruijff Arena in Amsterdam is home to the largest European energy storage system. This hybrid set-up uses second life and new electric vehicle batteries for a 3 MW storage system with a storage capacity of 2.8 mWh. It stores energy from 4,200 solar panels on the stadium roof and energy from the grid during low demand periods, and provides backup power, peak shaving, and grid stabilization services to the local grid during football matches and concerts when energy consumption peaks. The system is made up of four Eaton bi-directional inverters, 61 racks, 250 second life battery packs, and 340 battery packs made of new battery modules—the equivalent of 63 used and 85 new Nissan Leaf batteries.[132]

125 https://www.renaultgroup.com/en/news-on-air/news/a-second-life-for-batteries-from-energy-usage-to-industrial-storage/
126 https://www.enel.com/media/explore/search-press-releases/press/2022/03/enel-launches-innovative-second-life-storage-system-for-used-electric-car-batteries-in-melilla-spain-
127 https://www.smart-energy.com/storage/rwe-and-audi-create-second-life-ev-battery-energy-storage-system/
128 https://group-media.mercedes-benz.com/marsMediaSite/en/instance/ko/Worlds-largest-2nd-use-battery-storage-is-starting-up.xhtml?oid=13634457
129 https://betteries.com/partnership-with-mobilize/
130 https://www.audi-mediacenter.com/en/press-releases/second-life-use-audi-e-tron-battery-modules-power-electrify-rickshaws-in-india-14745
131 https://alliancernm.com/2022/01/19/the-mobility-house-collaborates-with-renault-to-implement-second-life-car-battery-storage-in-france/
132 https://www.mobilityhouse.com/int_en/magazine/press-releases/johan-cruijff-arena-3mw-energy-storage-system-launch.html

Project (Location)	Comments
GM Milford Proving ground (Michigan, USA)	The Milford Proving ground in Michigan was GM's first real world implementation of secondary battery use. GM is using five used Chevrolet Volt EV batteries to help power the GM enterprise data center at its Milford Proving Ground.[133]
BMW Speicherfarm (Leipzig, Germany)	Opened in 2016 – at its opening, BMW said the farm would connect up to 700 BMW i3 high-capacity batteries "Local energy optimisation at the Leipzig plant with regard to energy costs and CO_2, as well as grid stabilisation, using so-called balancing energy. The large-scale battery storage facility is capable of integrating locally-produced captive energy from four wind turbines more effectively into the plant's energy consumption to lower its CO_2 footprint even further. Using peak shaving – i.e., avoiding costly peak loads – the battery storage farm is also able to help lower energy costs at the Leipzig plant. Beyond the plant, the BMW Battery Storage Farm Leipzig is also able to integrate renewable energies more effectively into the public power grid by stabilising it. The large-scale battery storage facility feeds into the primary balancing power, which relies on the precise responsiveness of our high-capacity batteries." The BMW Battery Storage Farm Leipzig includes up to 700 second-life BMW i3 high voltage batteries. Currently there are 500 new and used high-voltages batteries integrated in the battery storage unit. The BMW Battery Storage Farm Leipzig commands up to 10MW of marketable power and up to 15MWh of marketable capacity.[134]

133 https://eu.detroitnews.com/story/business/autos/general-motors/2015/06/16/gm-ev-batteries/28800549/ / https:/media.chevrolet.com/media/us/en/chevrolet/news.detail.html/content/Pages/news/us/en/2015/jun/0616-volt-battery.html

134 https://www.press.bmwgroup.com/global/article/detail/T0275547EN/bmw-group-underlines-leading-role-in-electro-mobility?language=en

GreenImpact

Decrease organisations' CO_2 footprint

Federale Overheidsdienst Mobiliteit en Vervoer
Service public fédéral Mobilité et Transports

D-CARBONIZE

AISIN

bpost

LAB A O BOX