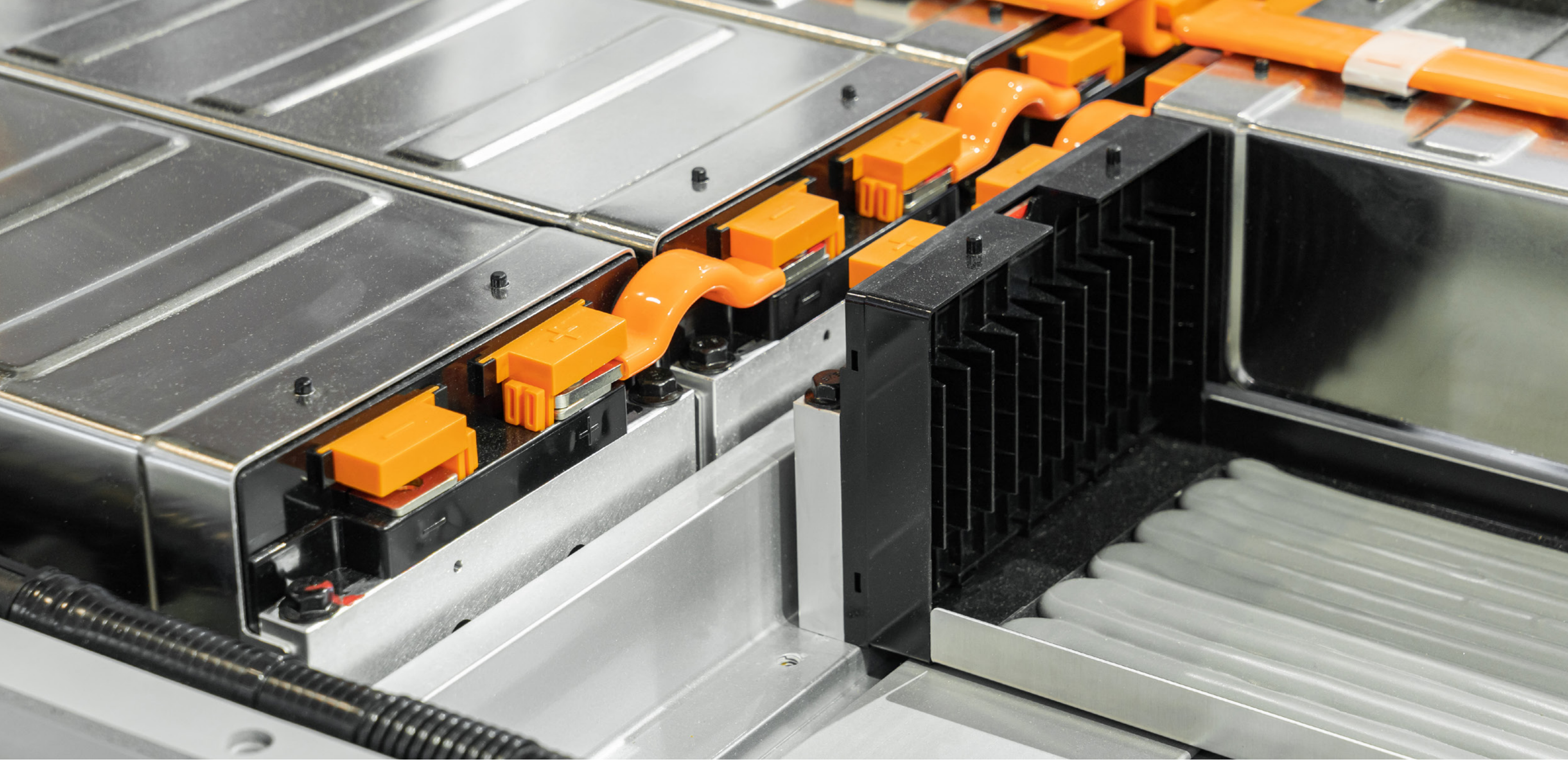
Capgemini invent

POWERING CHANGE

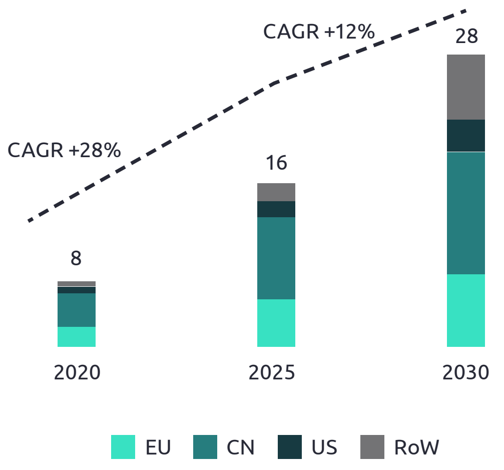
How batteries can foster the electric vehicle revolution



A burgeoning market shaped by major trends

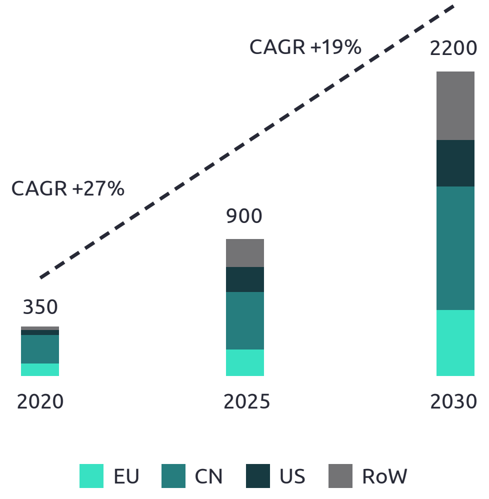
According to the European Environment Agency (EEA) batteries in electric vehicles are a key technology for designing a sustainable transport system and achieving long term climate protection targets in the transport sector.[1]

An increasingly vibrant market for battery-powered electric vehicles will make a tangible contribution to improving the standard of living and air quality, especially in cities.
In addition to improving the quality of life, electromobility also offers important industrial opportunities. After all, the most valuable component of electric vehicles is the battery. Compared to a fuel tank, an electric vehicle battery is much more complex. It also represents a major stake of the total value of an electric vehicle. When looking at the entire battery value chain, including its production and recycling components, it becomes apparent that there is nothing insurmountable preventing a broad market diffusion of batteries, which will likely enter a crucial ramp-up phase in 2020-2030+. Member of the European Parliament (MEPs) are even projecting a 700-fold increase in recyclable lithium batteries from 2020 to 2040.[2]



Global electric vehicles market

(Millions of new vehicles sold)



Battery demand

(in GWh)

Including PHEV and BEV; Summarizing Light-duty Vehicles (i.e., Passenger Cars), Bus and Trucks Sales, assumptions consider growing average battery size per vehicle within the next years; sales are based on the International Energy Agency STEPS Scenario, STEPS is the Stated Policies Scenario.

Global EV market growth drives worldwide battery demand in GWh[3]

[1] EEA (2021) [2] Europäisches Parlament (2020)
[3] WEF (2019), STEPS (2022), International Energy Agency (2022)

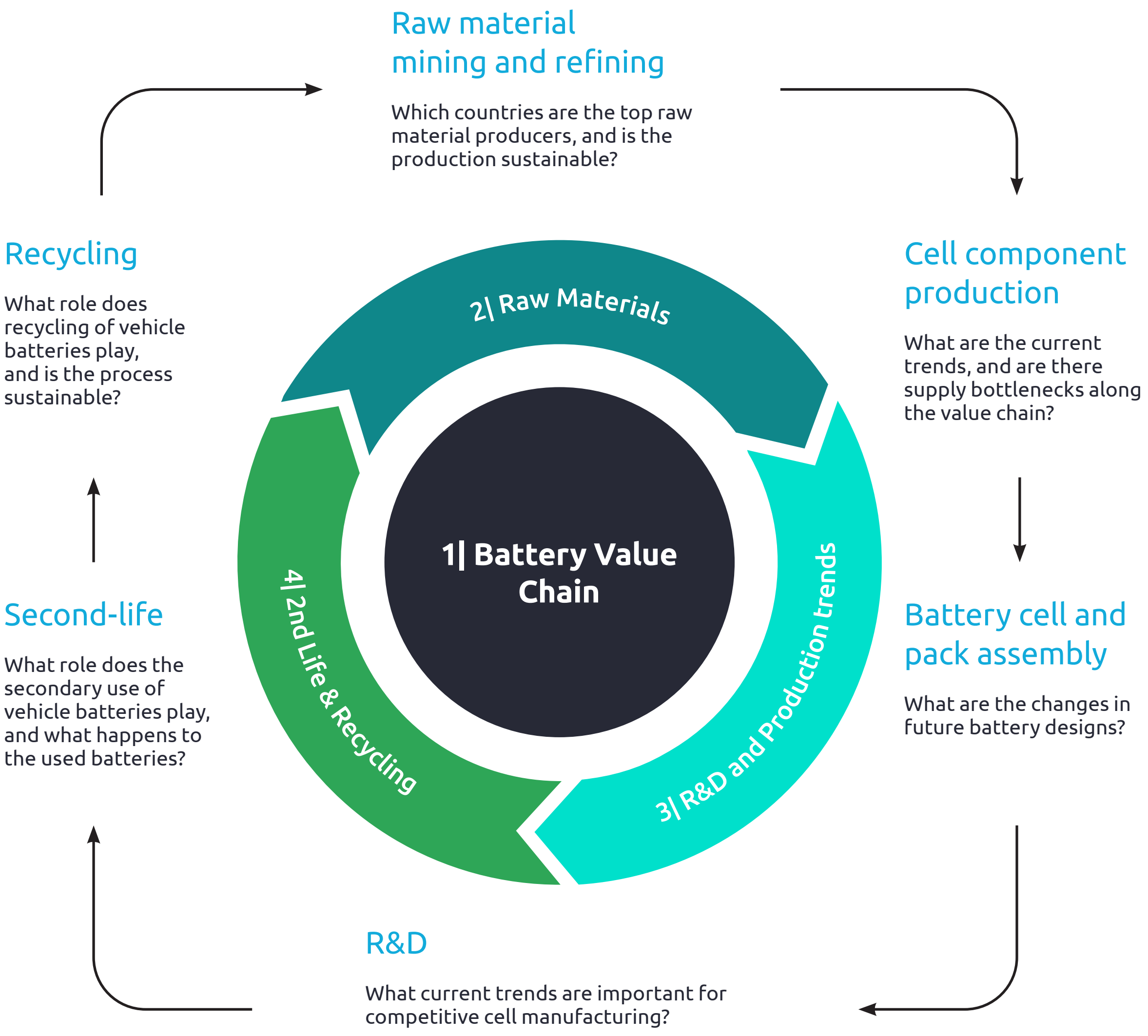
Since a tidal wave of demand for batteries is predicted, companies are getting ready to take advantage, with growing investment in R&D for both product and manufacturing.

Growing demand not only triggers more production, it also kindles technological innovation (e.g., longer-lasting batteries that can be charged faster). This in turn lowers costs and increases the demand for batteries. The adoption of battery electric vehicles (BEVs) will continue to increase as the vehicles become more affordable for the average consumer. This will be facilitated by economies of scale, enabling a higher number of manufactured goods with better quality and lower cost. As a result, it will become necessary to strengthen and diversify the battery supply chain, especially where raw materials are concerned.

According to the IEA (2021), global automotive battery production reached 160 GWh in 2020 (up 33% from 2019) and the average cost declined 13%. The global average for battery packs reached a price of USD 137 per kWh. Battery production continues to be dominated by China, which accounts for over 70% of global cell production capacity. The country also produces about half of all batteries for light-duty vehicles. Many of these vehicles are produced to meet domestic demand. In fact, China accounts for the largest share of demand at almost 80 GWh. But in 2020, Europe had the greatest increase (+110%), reaching 52 GWh.[4]

This point of view explores such key findings and shines a brighter light on the battery value chain, raw materials outlook, battery production trends, second-life use cases, and business models.

In the following section, the most important findings are summarized, followed by a more detailed presentation in the chapters.



Raw material mining and refining

Which countries are the top raw material producers, and is the production sustainable?

Cell component production

What are the current trends, and are there supply bottlenecks along the value chain?

Battery cell and pack assembly

What are the changes in future battery designs?

R&D

What current trends are important for competitive cell manufacturing?

Second-life

What role does the secondary use of vehicle batteries play, and what happens to the used batteries?

Recycling

What role does recycling of vehicle batteries play, and is the process sustainable?

Battery Value Chain

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[4] International Energy Agency (2021)

What are the current trends and are there supply bottlenecks along the value chain?

Even today, temporary supply bottlenecks with various causes exist along the value chain. Such bottlenecks can be found in battery raw materials and cell production. The production and delivery of BEVs have their own hurdles to overcome. A major impediment in the EV supply chain is the lag in battery cell manufacturing.

There is a need to augment and scale the existing supply chain. Many companies are aware of this and are countering the risk through, for example, supplier diversification, strategic industry collaborations along the value chain, research collaborations, joint ventures, and in-house production to secure capacity and favorable pricing.

These examples indicate a trend in which automotive component suppliers are readily investing in eMobility solutions; this trend will continue over the next decade as companies prepare for widespread BEV adoption. These efforts, supported by policymakers, should be maintained in the future to reduce the supply dependencies of the industry. In order to do this, it's essential that the automotive sector develops a flourishing - potentially regional - battery supply chain.

More Information on page 8

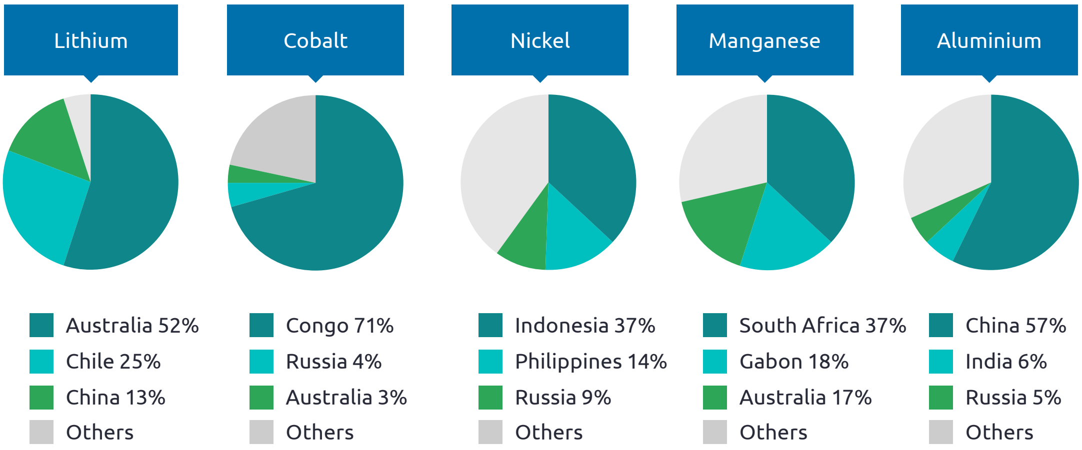
> *"Battery production and raw material extraction are fundamental levers for a sustainable EV value chain."*
>
> *- Sebastian Tschödrich, Executive Vice President, Head of Automotive Global*

Which countries are the top raw materials producers and is the production sustainable?

Raw materials have always represented a large portion of the total costs for batteries both at the cell and the system level. However, recent price increases in many materials such as lithium, nickel, manganese, and cobalt are only exacerbating the challenges that OEMs face. As a result, price reduction at the battery system level has been slow to take effect in the automotive industry.

Irrespective of the cost factor, the extraction of raw materials and the production of technical components are associated with environmental and social risks. These risks grow in severity in countries where weaker state institutions introduce more lenient legislation. In the value chain of e-vehicles, the impacts of battery production and raw material extraction represent environmental flashpoints. Both the high demand for raw materials and the complexity of production processes are to blame. Often, the result is inadequate local environmental, social, and safety standards and the lack of control and regulatory mechanisms worsen the corresponding impacts.

The most often used battery raw materials are lithium, cobalt, nickel, and manganese. They are all theoretically available in sufficient quantities worldwide.



Top three countries in raw materials production[5]

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[5] U.S. Geological Survey (2022)

However, temporary shortages or price increases for individual raw materials cannot be ruled out.For example, there is a possibility that new production sites will need to be developed, raw materials mining will not meet rising demand, and exports from the producing countries will not be sufficient.

In the extraction of lithium from salt lakes in Chile, Argentina, and Bolivia, water usage in a region with water scarcity is one of the main problems. However, research is needed on the specific impact of lithium extraction on the groundwater level and alternative, more water efficient methods. Closely related to this issue are conflicts with local Indigenous populations.[6]

Precarious working conditions can occur in supply chain constellations with missing E2E transparency regarding mining conditions and raw materials extraction. International due diligence initiatives, including their enshrinement in law, are sensible starting points. Better conditions, on the other hand, can be achieved by relocating production. To this end, MEPs call for future factories to be built on abundant brownfield sites so as not to contribute to the irretrievable destruction of farmland, forests, or water protection areas. To be sustainable, we need to think holistically about sustainability.[8]

Companies should be aware of these ethical and environmental challenges.

More information on page 12

[6] U.S. Geological Survey (2022) [7] Tagesspiegel (2022) [8] ÖDP Bundesverband (2022)

What current trends are important for competitive cell manufacturing?

According to the European Commission, Electric car batteries fall into the category of traction batteries. Nowadays, they are subject to many mass-market requirements. In the context of the European Green Deal, one of the European Commission's goals is to minimize the environmental impact of batteries and increase the penetration of electric vehicles.
In addition to the environmental compatibility of the battery value chain, other requirements play a role in the production of batteries, such as price reductions, scalability, performance, energy content, service life, and safety. Gigafactories that are currently being built must be flexible and scalable to meet the requirements of future battery technology and demand.

Batteries should e developed according to a recyclable design for a sustainable circular economy. However, as with the conventional battery manufacturing process to date, Li-ion batteries have a complex structure in which individual cells are assembled into modules, which in turn are assembled into a battery pack. Due to their complicated structure, their disassembly and the associated risks are not only slow and tedious, but the recycling of lithium-ion batteries is also more time-consuming and consequently expensive. This is because battery cells often use adhesives to bond the modules and the package together, which can only be dissolved with molecular organic compounds during the recycling process. This complicates the recovery of used materials. Furthermore, compositions are not labeled, which makes it difficult to identify and classify battery chemistry.
Mandatory legislation or policies are needed to drive recycling efficiency and standardization.

In addition to the policy measures for increasing the efficiency of recycling, there are practical applications. For example, there is much talk about Design for Recycling (DfR). This term is used to refer to a holistic approach to recycling end-of-life (EOL) products, optimizing the consumption of energy and materials. As an aspect of eco-design, it gives manufacturers a roadmap to develop their products with recycling in mind. A strategy that embraces DfR should consider the use of modular design, reduction of disassembly operations, the use of simple and all-purpose tools, and the use of reusable fasteners.

Today, battery design is increasingly moving to a “cell-to-pack” design. Unlike the previous conventional battery manufacturing process, in which battery cells are first combined into modules and these are then combined into a battery pack, cell-to-pack technology (CTP) is used to directly integrate cells in the battery pack. This eliminates the intermediate step of module formation, resulting in significantly higher volume and mass integration efficiency, as well as space and weight savings.

All this is a step in the right direction. However, electric vehicle production and battery assembly is still in its infancy at many traditional automakers. For many, standardization of solutions has not yet been achieved. Additionally, each manufacturer follows its own battery design, which leads to many manual steps in EV battery assembly. As a result, while ramping up production, EV manufacturers often encounter battery production bottlenecks.

To meet future demand, battery manufacturers also need to fully automate their processes and increase process speed. Automation of battery production is key to improving assembly reliability, ensuring quality and traceability, and controlling battery costs. Gigafactories should leverage Internet of Things (IOT) technology to keep pace with the demand for data. Furthermore, the use of digital twins enables second-life and other use cases that facilitate the recycling process.

More information on page 18

What role does the secondary use of vehicle batteries play and what happens to the used batteries?

In the relatively nascent electromobility market, used batteries have not yet played a major role. Electric car batteries contain valuable materials. Their recovery and recycling in the raw materials cycle is essential, especially since some of these materials are finite. Concepts for the secondary use of batteries are currently being tested and expected to reach mass market applications in the near future, followed by a significant increase in the availability of end-of-life EV batteries, approximately from 2025 onwards. These solutions will evolve in step with the recyclable materials market ramping up in the next 10 to 15 years.[9]

Viable business models would require that second-life batteries are available at a low enough cost with sufficient residual performance and can be effectively reintegrated into the value chain. Questions of standardization and warranty (for example, through appropriate operator and owner models) must be taken into account in any viable economic business model. But whether this can be achieved is still the subject of hot debate.

To realize this, it is imperative that second-life batteries hold sufficient power to meet the requirements of most secondary applications and avoid being consigned straight to recycling. However, the recycling of vehicle batteries is now considered technically feasible and is currently being implemented industrially in pilot plants, leading to formal regulation. For instance, the recycling of lithium-ion batteries (Li-Ion) from end-of-life vehicles is regulated within the European Union by Directive 2006/66/EC. Recycling efficiency for lithium-ion batteries will reach 65% in 2025 and could be as high as 70% in 2030. The recycling efficiency of a recycling process is obtained by relating the mass of secondary raw materials recovered (output fractions) to the mass of spent batteries fed into the process (input fractions).[10]
This directive was adopted by the plenary on March 11 and will represent Parliament's negotiating position with EU governments on the final form of the legislation. The European Parliament now agrees that managing the full lifecycle of the battery will enable the EU Green Deal to be achieved.

Furthermore, Simona Bonafè, rapporteur for the EU's Circular Economy Package, pointed out that 700 times more lithium batteries are waiting to be recycled between 2020 and 2040.[11] [12] Currently, three different methods are used to recycle batteries from e-vehicles: pyro-metallurgy (smelt solution), hydrometallurgy (aqueous solution), and direct recycling (recover-functional solution) of raw materials.

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[9] Fraunhofer (2020) [10] Europäisches Parlament (2020) [11] European Commission (2022) [12] Open Access Government (2022)

Advantages of second life and recycling e-car batteries:

Avoiding supply bottlenecks and dependencies and the risk of a shortage of raw materials

In the field of e-batteries, the world market is currently extremely dependent on China. China is the main importer of most raw materials. All manufacturing steps, from the import of minerals to the export of battery cells, are dominated by Chinese companies. At certain times – such as during the COVID-19 pandemic – the impact of such dependencies along the supply chain for the global market is felt more keenly than ever. Improved recycling and a resulting circular economy could provide more stability.[13]

Increasing range and acceleration capability

Previously, batteries that no longer deliver the desired range or acceleration capability in traction applications could still find use in extended, second-life applications such as energy storage systems.

Increasing sustainability

The secondary use of batteries via second-life or recycling is attractive because the carbon footprint associated with battery production could be significantly lower than new batteries. However, the recycling of lithium-ion vehicle batteries creates more challenges for safe and environmentally friendly recycling than regular device batteries. One reason for this is that Li-Ion batteries are much larger and heavier and have much more stored energy than device batteries.[14]

The potential reduction of costs

The growing interest in the reuse of batteries also comes down to, of course, their potentially low costs. But it's worth noting that this is only possible if used batteries meet the requirements for safety, reliability and a minimum residual life for secondary applications.

> *"Second-life solutions are an important step of the transformation towards a circular economy."*
>
> *- Siegfried Adam,*
> *Director, Digital*
> *& Sustainable Mobility*

More information on page 23

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[13] BMZ (2020) [14] Öko-Institut e.V. (2011)

1

ELECTRIC DREAMS: THE BATTERY VALUE CHAIN OF A MORE SUSTAINABLE FUTURE

> *"Global electric car sales indicate a reduction in consumers' range anxiety."*
>
> *- Dr. Philipp Haaf, Director, Head of Electric Mobility*

With growing concerns about climate change and environmental degradation, sustainability has become a strategic priority for automotive organizations. One of the central components of this is electrification: many OEMs decided to switch to electric vehicles within the next years and enable climate neutral passenger transportation. Key to achieving this is improving the internal battery supply; that includes optimizing production, repairing, recycling, and significantly reduced battery costs.[16] The automotive OEMs' strategies are already reflected in global electric vehicle sales, which are beginning to conquer the mobility market at a rapid pace. Even though 2021 was a difficult year for automotive OEMs, who faced challenges such as a global chip shortage, global electric car sales have more than doubled over the past 12 months (6.6 million in 2021 compared to 3.0 million in 2020).[16] Batteries are critical to further the largescale adoption of electric vehicles. They store electrical energy and are the equivalent of a fuel tank in a combustion engine. Compared to a fuel tank, however, an electric vehicle battery is much more complex and represents a major stake of the total value of an electric vehicle. Furthermore, batteries are a key differentiating factor for automotive OEMs due to the so-called "range anxiety" of drivers. Range anxiety refers to concerns about the mileage an electric can provide between charge stops, and the overall fit of an electric vehicle into their daily lives.

[15] Volkswagen (2022) [16] EV-volumes.com

1.1 The battery and its value chain: the heart of the electric vehicle

Today around 99% of the EV batteries used in electric vehicle powertrains are lithium-ion batteries. This is because lithium-ion batteries (Li-Ion) are characterized by a high energy density, the ability to endure many charging cycles, and a high current capability, high power-to-weight ratio to name a few. Within the range of Li-Ion batteries, there are several compositions that differ by the metal dopant that is used. These compositions come in different price points, have different ranges, and are constantly evolving with technological advancements.

More Information on page 12

The production of the li-ion batteries is complex, which is also reflected in the supply chain that consists of four steps that are shown below.The first step is raw material mining and refining. This includes the exploration of raw materials and their production, processing, refining, and conversion into materials that can be used in the development of the cathodes and anodes of batteries. We take a deeper look at the raw material section of the supply chain in chapter two.

Cell component production is the second step and covers the production of the main components of a Li-Ion battery: the cathode, anode, electrolyte, and separator. The cathode serves as the source of lithium-ions and determines the capacity and the average voltage of a battery, whereas the anode stores and releases lithium-ions from the cathode. The separator prevents contact between cathode and anode and electrolytes are the medium that facilitates the movement of the ions.[17]

The third step of the supply chain is battery cell and pack assembly, which starts with the battery cell assembling into group cells that have similar operating parameters in the first place. These batterycell groups are then welded to a module, tested, and later inserted into pack housings. This step is repeated several times until all modules are inserted. These modules are then integrated with other battery management and power components.

The fourth step is system integration with the vehicle. This is the last process step before operational life, in which the battery is integrated into the vehicle. This involves connecting the battery to the vehicle's powertrain and other application verticals, such as energy storage, electronics, and other sub-systems.

Closing the circle of the battery value chain after production and integration are the operational life, recycling, and second-life phases. Learn more about recycling and second-life use cases as a business opportunity in Chapter 4.

More information in chapter 4

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[17] Samsung SDI (2022)

1.2 The battery value chain ecosystem is emerging

The increasing demand for electric vehicles and current supply chain bottlenecks in the semiconductor chip market are forcing OEMs to rethink their strategy on how to source Li-Ion batteries. In general, the spectrum of strategies being considered ranges from low control and completely outsourced battery pack production to a third-party supplier to full control with in-house capabilities to be able to produce a battery. Until recently, most OEMs focused on exclusive agreements with single third-party suppliers that carried all the risks that a partnership with high dependency can come with. In addition to that, outsourcing an element that accounts for a majority of the total vehicle value is another clear risk. To avoid such risks, there are two clear trends emerging. Firstly, OEMs are increasingly diversifying the supply chain by signing agreements with multiple battery suppliers to reduce dependency on a single supplier. OEMs are paying very close attention to the geographical aspects of diversification and are building up strategic near-shore relationships in Europe or US to decrease dependency to Asia, reduce the carbon footprint for raw material extraction and better secure delivery chains in the case of crisis. Even more interesting is the second trend – that OEMs are moving away from low control to total control, as evidenced by the increasing number of partnerships and joint ventures between battery manufacturers and OEMs.

Even between raw materials suppliers and battery manufacturers or OEMs long term supply contracts are more common or even considerations to source own raw materials. One example of such a collaboration between recycling and battery producers is the agreement and strategic investment between Li-Cycle and LG Chem/LG ES to deliver and recycle battery materials for about 300,000 electric vehicles.[18] Such collaboration models make suppliers share investment costs in R&D and provide OEMs important access to battery technology and the battery manufacturing process.

> *“Diversifying, localizing and in-sourcing are key priorities for European OEMs along the battery value chain.”*
>
> *- Sebastian Tschödrich,*
> *Executive Vice President,*
> *Head of Automotive Global*

Key players in each sector

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[18] Electrive 2021

Three examples which underpin this trend:

1. In 2021 Volkswagen intensified its funding of the Swedish cell producer Northvolt AB by investing a further €500 million to hold a stake of 20% in the company. The funds are to be used for capacity expansion in the fields of production, recycling, and R&D. Beside such cooperations, Volkswagen intensified their own efforts and will built 6 Gigafactories in Europe. The new strategic business unit PowerCo will bundle their activities around the battery value chain, with further investments of 20bn until 2030. The first factory built by Volkswagen will be in Salzgitter, and it is expected to go live in 2025.[19]
2. Volvo and Northvolt will build a gigafactory in Sweden with a potential 50 GWh capacity. The battery production is scheduled to be running in 2025, producing batteries for Polestar and Volvo, which are both owned by the Geely Group.
3. Another example for such a partnership is the Verkor initiative joined by Capgemini to built a fully digitalized 16 GWh Gigafactoriy in France. [20]

1.3 Recommendations for action

To state the obvious, there can be no electrified product portfolio without cutting-edge battery technology. In the coming years, the industry will experience a seismic shift in priorities. OEMs that do not optimize and prepare their value chain for a more sustainable future run the risk of becoming obsolete. A successful course correction is not only necessary, it is pressing. Reprioritizing a portfolio entails research and analysis, things that cannot happen overnight. As such, it is imperative businesses take action before the ship sails and opportunity is left on the shore.

A successful supply chain is diversified across the board. For OEMs, it all begins with geography. Delivery capabilities hinge upon maintaining diversified depots. Supply chains that can utilize a multitude of locations have better logistical options during times of crisis. But these facilities are only as useful as the resources they store. As such, OEMs should consider diversifying the location of their resources or even source locally. This helps to mitigate the impact of delivery shortages in certain regions.

To accelerate portfolio restructuring, OEMs can enter into partnerships with companies who have already proven their mettle in the industry. Strategic partnerships in battery production can lead to knowledge sharing for the inexperienced party and cost sharing for the one with expertise. Moreover, the success of project-specific partnerships has the potential to foster future developments and fast-track brand recognition. And since demand for batteries is ever increasing, all of this is necessary once an OEM takes those first steps.

Key considerations

The growing demand for batteries is being driven by new regulations and the cultural zeitgeist. Decarbonization is perhaps the defining feature of modern business and society at large. As such, OEMs should build for the future. When setting up their own production facilities, long-term demand should be at the forefront of their infrastructure plans. In Naypyitaw, Myanmar, local authorities built sixteen-lane-wide highways for a population that barely exceeded 340,000 people. This is because future redevelopment would be both costly and disruptive. OEMs would benefit from the same approach and should design now for long-term success.

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[19]Volkswagen AG (2021) [20]Volvo (2022) [21]Capgemini (2021) [22]EENewseurop (2021)

2

RAW MATERIALS ARE CRUCIAL FOR BATTERY SUPPLY

Raw materials account for a major part of today's battery cost on both a cell and system level. Therefore, the current price increases of many materials (e.g., lithium, nickel, manganese, and cobalt) are leading to a slower price reduction on a battery system level in automotive. Most raw material costs are passed on at the supply chain, i.e., price increases in raw materials lead to higher end-product costs. This makes it more difficult to achieve the often cited $100/kWh cell price, which is needed to reach cost competitiveness with conventional ICE vehicles.

Raw materials account for more than 60% of total BEV battery cost.[22] [23] Stricter regulation and rising customer awareness of ESG criteria in the raw materials supply chain is also playing a key role. However, the meeting of ESG criteria can be difficult because some battery materials can be sourced in only a handful of countries with worrisome political and socioeconomic challenges. To achieve an ethical, secure, and transparent supply chain, new automotive networks and partnerships within the value chain need to be built. Also, new technologies, such as blockchain, may be useful to validate ethical standards through the increased traceability they provide. Some companies, such as RCS Global, have already enhanced functionality to ensure the tracking of raw materials through blockchain supply-chain networks to enable clearer, wider, and more accurate data visibility.[24] [25]

> *"Raw materials account for more than 60% of total BEV battery cost."*
>
> *- Simon Schäfer, Manager, CX E-Mobility*

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[22] This figure assumes cell cost accounts for 82% of total pack cost in cell-to-pack designs and raw materials account for 75% of cell cost.

[23] BNEF (2021) [24] Capgemini (2021) [25] RCS (2021)

2.1 Raw power: the materials used in battery chemistry

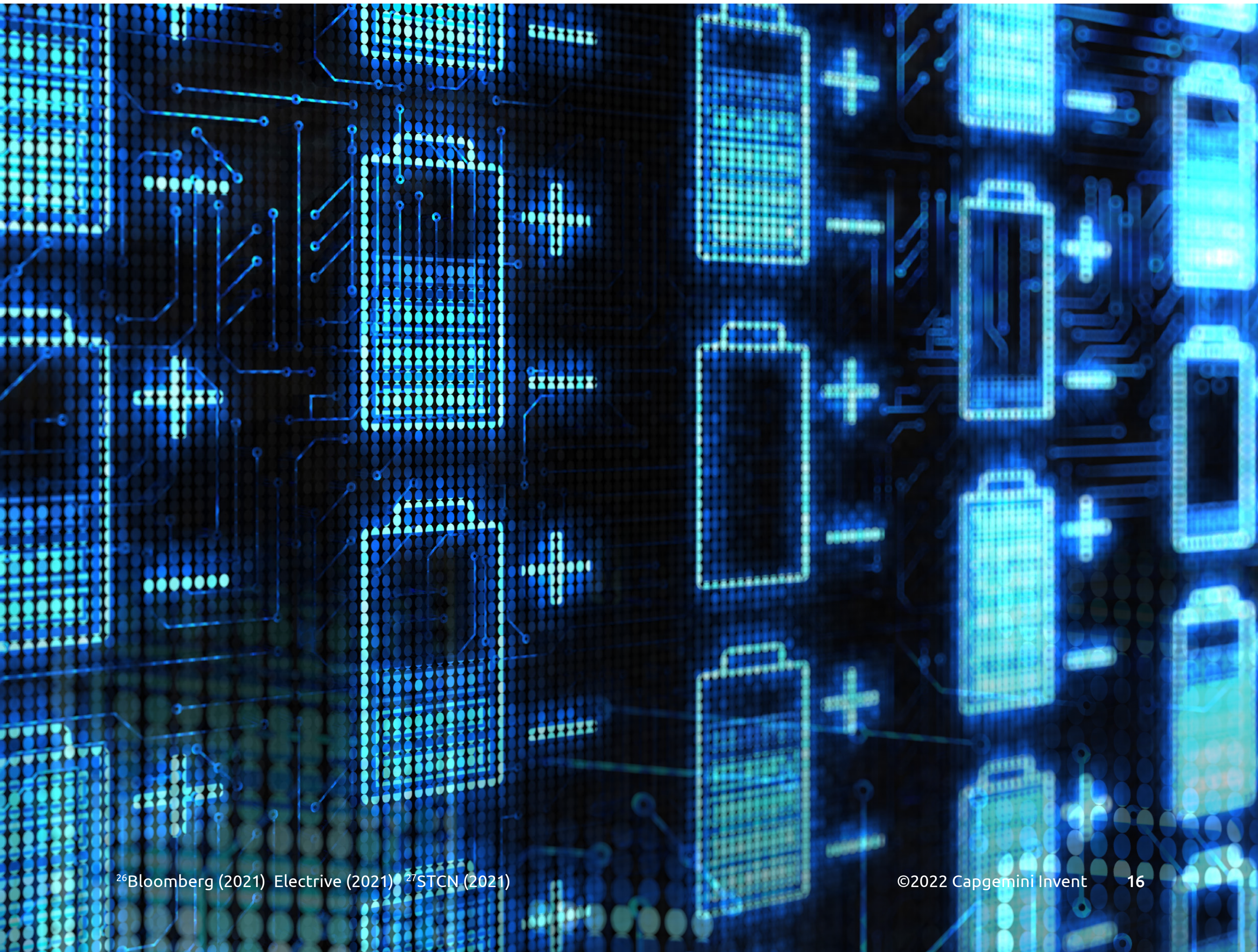
Electric vehicle lithium-ion batteries of the current generation use a wide range of different materials: On the cathode side, a range of materials – like copper, nickel, cobalt and manganese – is used as active material and an aluminum foil as a current collector. The anode consists of graphite, either natural or synthetic, and is based on petroleum coke. Sometimes silicon is added to further improve the overall energy density.

With each battery type there are trade-offs between power, energy, safety, lifespan, cost, and performance. Separator and electrolyte design also influence battery properties. Since the materials used are so important in terms of cost and in terms of vehicle properties such as range or vehicle design, we will have a deep dive in the raw materials market.

Li-Ion Chemistries: Cathode active materials differ between entry and high-end models

The relatively high financial and ESG costs of cobalt are leading to many recent initiatives to avoid or reduce the amount of cobalt used in batteries. From 2023 onwards, for example, Volkswagen plans to have a unified battery cell and will be deploying Lithium Iron Phosphate chemistries (LFP) in its entry models, nickel manganese in its volume models, and nickel-rich NMC in its high-end models. These cell chemistries use little or no cobalt.

Tesla, which presently uses a combination of nickel-cobalt-aluminum and nickel-manganese-cobalt cathodes in its standard range cars, started to shift to LFP worldwide. Although they are less energy dense, LFP-based lithium-ion batteries are lower in cost. Mercedes-Benz will also switch their EQA and EQB models to LFP chemistries to be able to offer price competitive offers in entry-level car segments.[26] While switching to LFP generally leads to price benefits, the higher volatility in the raw materials market led to a price increase for LFP BYD customers in 2021.[27]

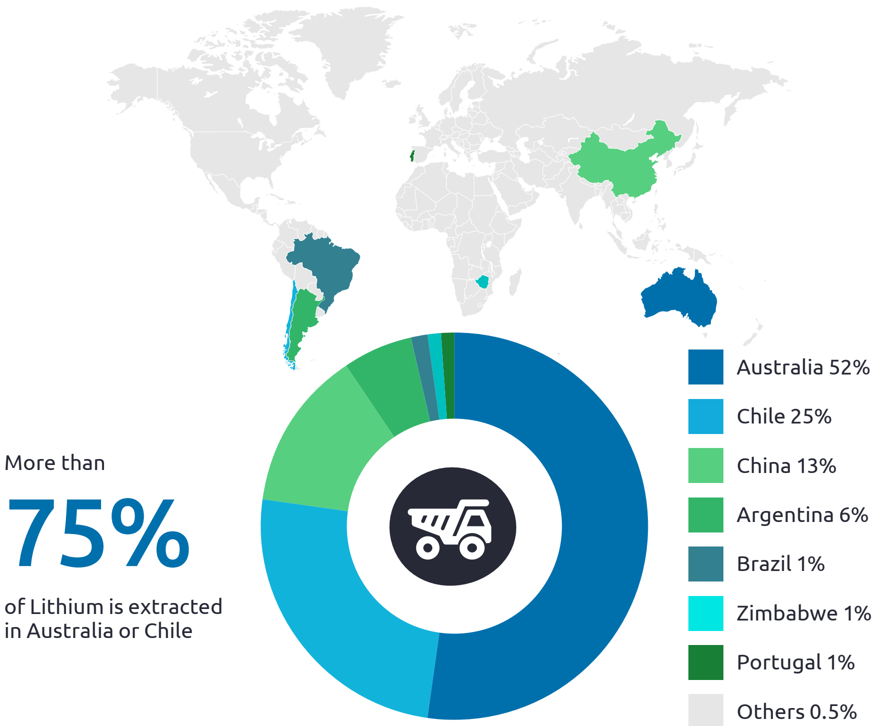


[26] Bloomberg (2021) Electrive (2021) [27] STCN (2021)

2.2 Raw materials sourcing: lithium

Lithium is a key component of automotive batteries, and even if there is a move to other cell chemistries, such as all solid state, lithium will remain a key component. As often cited by eMobility critics, lithium extraction, including the solvent and mining waste produced, presents environmental and health concerns, in addition to being volatile as a commodity.

Currently, lithium mine production is dominated by Australia and Chile, accounting for 75% of all lithium produced in 2021.[28]



More than

75%

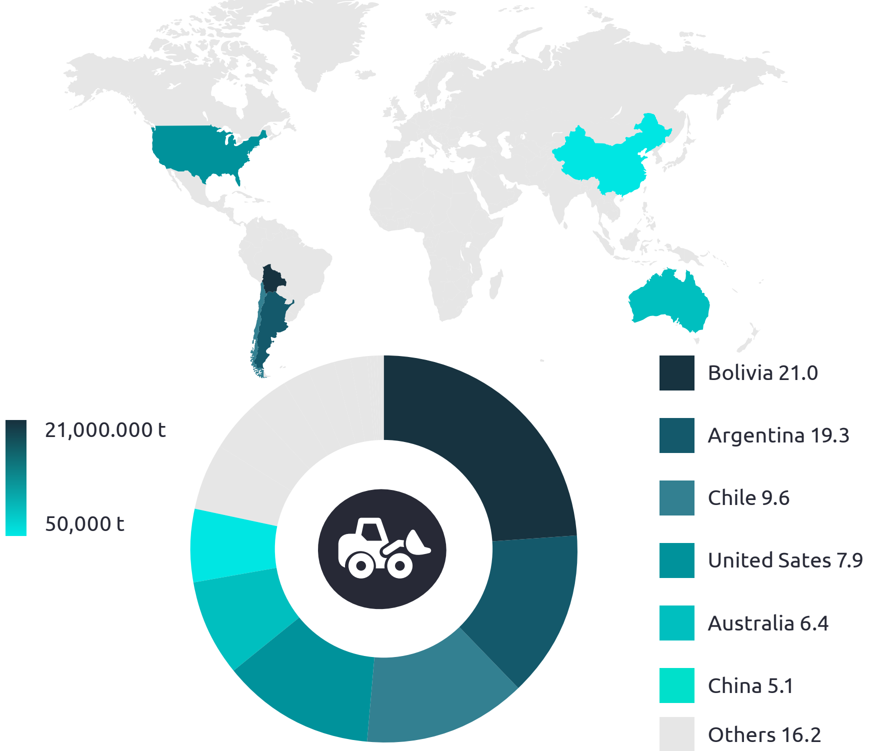
of Lithium is extracted in Australia or Chile

Raw Lithium is currently mostly mined in Australia and China, or extracted via evaporation ponds in Chile and Argentina

While lithium is currently mostly mined in South America, Australia, and China, there are identified resources available in North America and Europe, which could be used to implement a local supply chain.

Local supply chains can improve the security of supply, reduce CO2 transportation effects, and lead to better ESG ratings. Steps are being taken to infuse more responsibility into raw material mining and develop a more sustainable and ethical battery value chain.[29]

Lithium Resources (in megatons)



Identified raw lithium resources have increased to 86 megatons due to continuous exploration and rising lithium prices

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[28] USGS (2022) [29] BASF (2021), Global Mining Review (2021)

A closer look at extraction

In Australia most lithium mining is of the hard rock spodumene variety, whereas in the South American countries, evaporation ponds are used to extract the lithium from saline brines. While hard rock spodumene mining has a higher CO2 footprint, there is less environmental risk due to less water consumption. Evaporation ponds are often criticized for their high levels of salt and sweet water consumption; however, the exact amount is still debated among scientists and much depends on the extraction method or if it is combined with direct lithium extraction (DLE).

DLE can be used, for example, in thermal water brines, where water contains a relatively high amount of lithium, as seen in Germany.
Deep sea mining is currently not in focus for many stakeholders in the battery value chain due to unforeseeable risks, such as noise or light pollution, destruction of marine life habitats, and chemical pollution, when extracting lithium from deep seabeds.

The following methods are used to extract lithium:

1. Hard rock mining and spodumene processing involves producing a lithium sulfate solution from mining and acid leaching the spodumene ores, which is then, using an electrochemical process, converted into lithium carbonate hydroxide.
   Converting lithium carbonate into lithium metal requires an electrochemical process and leads to a high CO2 impact. This method dominates Australian production and accounted for the majority of lithium extracted in 2021.

2. Evaporation ponds use salt-rich waters pumped into evaporation ponds, and when the lithium chloride reaches the desired concentration, it is treated with sodium carbonate, precipitating lithium carbonate. These ponds are in areas in with high evaporation rates, such as the elevated deserts in South America, and the extraction and cleaning is often criticized for its high water consumption.

3. Direct lithium extraction (DLE) has recently gained in popularity and involves the absorption of lithium from saline water using a porous material that enables ion exchange, lithium bonding, and solvent extraction. Lithium is later released by washing it with hydrochloric acid. This method produces dilute lithium chloride, which has impurities. Alternative methods, such as thermal water extraction, are currently only being explored in small scale projects, for example, in Oberrheingraben, Germany.
   If these projects can reach price competitiveness, they will become more attractive due to their more robust sustainability criteria.

4. Deep sea mining can liberate polymetallic nodules that contain minerals like cobalt or lithium. However, in 2021 the WWF and
   a number of major companies, scientists, and political leaders pledged their support for
   a moratorium against deep sea mining due to the risks to ocean health.[30]

Looking at the different players in lithium mining, over the last years there has been a shift away from only a few larger players to a more diverse market, with many smaller initiatives emerging.

	Market Cap	2021 Revenue
Jiangxi Ganfeng Lithium Co. Ltd	38.6B	839M
Albermarle	26.5B	3130M
Tianqi Lithium	11.8B	748M
Sociedad Química y Minera de Chile	24.1B	2868M
Pilbara Minerals	6.8B	176M

Vital statistics for mining companies

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[30] WWF (2021)

2.3 A digital battery passport - possibly built on blockchain technology - could enable transparency across complex value chains

A digital product passport is already being evaluated in the EU, with numerous benefits and use cases for batteries.[31] Blockchain technology can provide irrefutable provenance of more ethically sourced raw materials and interest investors who may have otherwise been deterred. A supply chain infused with data from end to end also provides the flexibility to develop a more pluralistic network. It can respond as batteries evolve and react to geo-political impacts arising from conflict or trade tensions. It also enables strategies of securing raw materials supply, such as the investment in greenfield mining projects to bring new sources of raw materials directly into their supply chains. These strategies are already being implemented by some of the main EV suppliers in Europe or US.

To enable a transition to a circular economy, different actors in the value chain need to share information about products and materials - as well as the usage and charging behavior of the battery - all along the supply chain and to possible second life usage. Several start-ups use blockchain tech to help manufacturers, brands, and OEMs trace raw materials from their source to the end products. This is done by sharing data about their products while retaining information privacy.

Before the advent of blockchain tech, transparency of ethical and sustainable sourcing to interested parties was out of reach.
The sourcing of raw materials posed significant reputational, legal, and commercial risks.

A digital passport – possibly based on blockchain – can overcome this with:

- An incorruptible decentralized control that promotes trust
- An audit trail for irrefutable proof of ethical production of raw materials at every transfer step
- The secure storage of provenance information
- The sharing of data while protecting confidential information

Blockchain not only brings supply chain visibility, security, reduced risk, and flexibility to organizations it can also provide end-consumers with the reassurance that the products they are purchasing are ethically and sustainably sourced.[32] [33]

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[31] EU (2022) [32] Franks (2014) [33] Capgemini (2021)

2.4 The implications of volatile supply in the raw materials market

Currently, with EVs representing a minor stake of total car sales, supplies of nickel, cobalt, and lithium, are sufficient to meet demand. But with Electric vehicles projected to make up 31% of the global fleet by 2050,[34] we anticipate that there is a potential shortfall in the global mining capacity required to extract the minerals needed to manufacture the batteries to meet this projected demand.[35]

Such a shortfall in the raw materials essential for battery production, as EV demand rises, could result in OEMs struggling to fill orders and consumers being deterred from EV ownership by long waiting lists. This would, in turn, mean that the market for EVs is at risk of stalling at very moment it should be accelerating.

We see the following as the main factors that could contribute to a sub-optimal supply to meet demand:

Price volatility

A volatile market impacts everyone, not just the companies extracting raw materials and those considering starting such operations, the OEMs intending the ramp up EV production, and the potential end-users of EVs. For example, battery grade lithium is averaging $76,700 a ton, up 95% since the beginning of 2022. In 2021, the commodity was trading at $13,400 a ton.[36] It also presents significant challenges in financing. Concerns over price volatility, and the nascent character of the sector mean that funders are working out what sort of offtake commitments they are willing to accept from particular projects.

Uncertainty over future battery compositions

As discussed earlier, as the industry moves towards the optimal battery chemistry per use case, the precise make-up of raw materials needed is still indetermined and in flux. For example, the next generation of batteries may result in a decrease in nickel and cobalt demand.

The need for transparency and data and risk management

There is a growing need for transparency and risk management in the raw materials supply chain. With up to US$30-45 billion needing to be invested in mining capacity by 2025[37] in order to meet the demand for EVs and the batteries, it is imperative that as many roadblocks to such large-scale investment are removed as possible. We believe the recent digital advances of data can provide the foundation for more effective tracing and tracking of materials that can assuage the concerns of potential investors. As mentioned earlier, blockchain technology is opening all kinds of doors.

An increase in raw materials mining will need to be supported by an appropriate risk management program that covers such issues as child labor, human rights, and supply chain due diligence and management.

Key considerations

Although Europe and the US do not play a major role in battery raw material production today, theoretically, most of the resources needed are available in Europe and the US. But to build up the necessary mining and raw material industry, long lasting projects are necessary – the building and development of new mines can require over a decade.[38] Therefore, supply security is especially challenging, something that will increase in the near future as the demand for batteries quickly rises.

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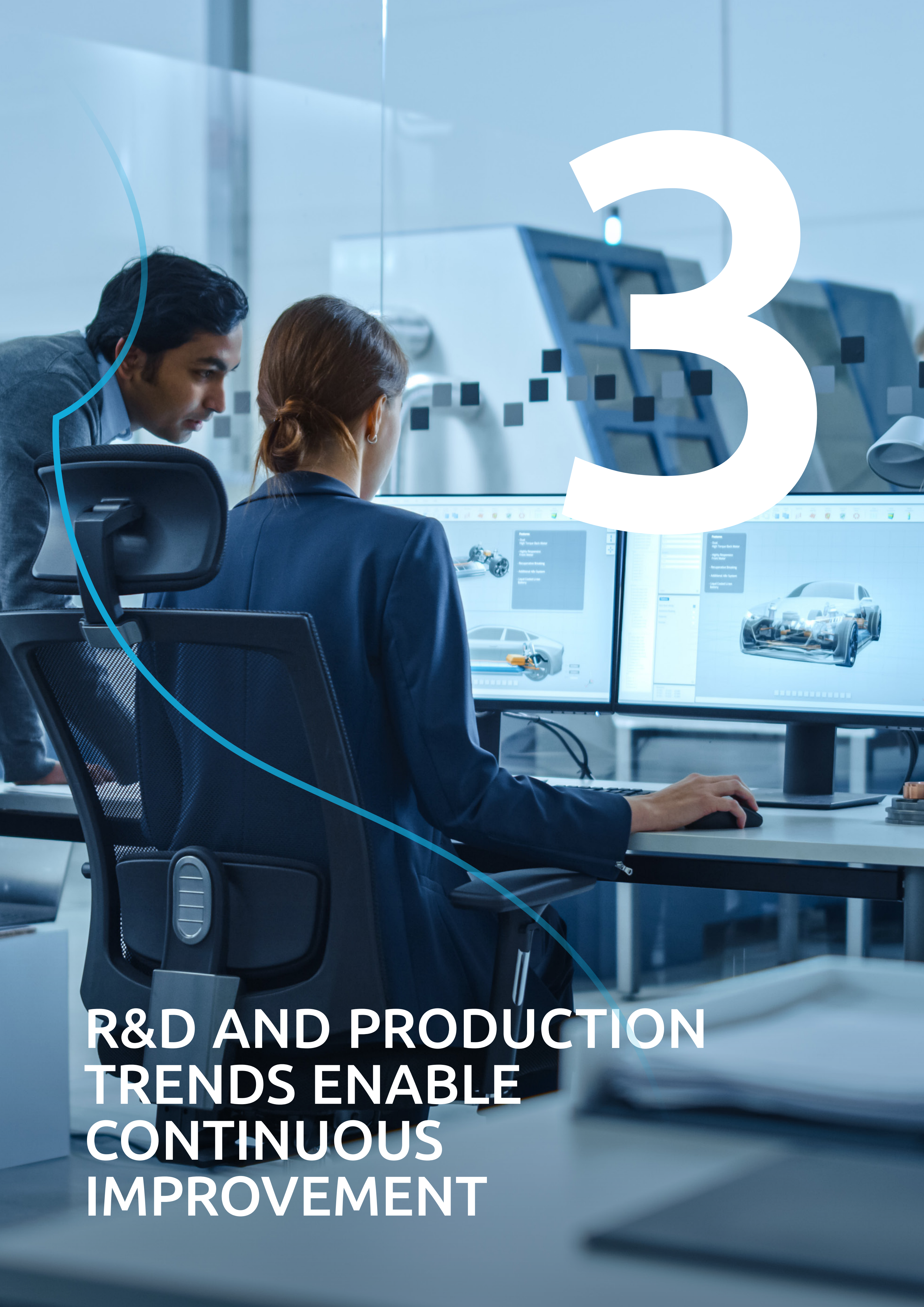
[34] Electrek (2021) [35] Linklaters (2019) [36] Benchmark Minerals (2022)
[37] Horizonte Minerals (2021) [38] CNN (2022)



3

R&D AND PRODUCTION TRENDS ENABLE CONTINUOUS IMPROVEMENT

To fill the projected demand of automotive batteries, there is a need to meet the mass market requirements of affordability and high-volume market processes and standards. And as the trend of consumer awareness on sustainability grows (it's likely that a potential buyer of an EV is both sustainability minded) producers will be forced into designing batteries to fully align with the circular economy model.[39]

This means that future gigafactories, and those currently being built, need to be flexible and scalable to not only meet future demand but to be capable of shifting future battery technology requirements including a likely need to align with circularity.

The requirements of a circular economy mean that batteries need to gain further intelligence, for example, second life applications need to be fully aware of the battery health or meeting sustainability criteria. The need to assess their capacity at different charging rates, the internal resistance or impedance at different life stages, and lifespan and cycle life in different conditions becomes more important in a circular economy.

"Battery producers must now consider the circular economy during the design phase."

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[39] IEA (2021)

3.1 R&D changes due to battery design

In a conventional battery manufacturing process, battery cells are first combined into modules and then the modules are combined to form a battery pack. Each battery module has its own independent battery management and diagnostic system. This allows more controllability and diagnostics at the module level, in addition to some structural support for the battery pack. The trade-off of this design is that the module's terminal plates, side plates, and internal connectors take up more space and weight.

In cell-to-pack technology (CTP), the cells are integrated directly into the battery pack, forgoing the intermediate module formation step, resulting in much higher volume and mass integration efficiencies compared to a conventional battery pack. Battery cell design is increasingly transitioning to a cell-to-pack design, therefore more widely streamlining the module structure, and saving on space and weight. This removes the need for aluminum housing, something that could soon be made viable with the resurgence of solid-state batteries.

> *"Cell-to-pack and cell-to-chassis designs will limit Second Life Use Cases"*
>
> *- Klaus Feldmann, CTO for Automotive Sustainability & e-Mobility, Capgemini Engineering*

R&D trend	Existing R&D initiatives and examples
Cell-to-pack (CTP) and cell-to-chassis (CTC)	Suppliers like BYD and CATL have worked on the development of cell-to-pack (CTP) and cell-to-chassis (CTC) technologies. These batteries have an optimized pack structure, reducing the battery volume by up to 70%. CTP designs may limit Second Life Applications to only use the whole battery pack, since no single BMS is attached to a battery module.
Virtual cell development and design	Cell design can be sped up and facilitated by simulation and digital tools. E.g. Siemens offers a tool to support engineers in the physical and performance cell design.
Security of supply	Several cell manufacturers further integrate into the raw materials value chain. E.g., LG Energy acquired a 4.8% stake in Greatpower Nickel & Cobalt Materials of China, to secure supply of battery materials. LG Energy will receive around 20,000 tons of nickel from 2022 to 2028. This amount is sufficient to power 370,000 EVs that can run at least 500km on a single charge.
High Nickel, Cobalt reduction to improve cost and performance	E.g., Panasonic has worked on reducing the cobalt in automotive cells, which it reduced to less than 5%. Also, LG Energy Solutions is developing next-generation battery products that contain a lower portion of cobalt but attain a higher nickel content.
LFP in entry level models	LG Energy Solutions plans on building a pilot line for the LFP batteries in 2022. Unlike other LFP batteries, these will be of pouch type.

R&D initiatives & targets by major battery manufacturers

3.2 Design for recycling

The pursuit of solutions that result in a circular economy is producing some promising recycling strategies, one of which is Design for Recycling (DfR). As you might expect, DfR makes recycling a priority from the outset of a product's lifecycle. By optimizing the consumption of energy and materials, this eco-design strategy ensures the extended viability of products by facilitating EOL applications.

Li-Ion batteries have a complex assembly structure, where individual cells are assembled in modules which are, in turn, organized together in a battery pack. An EV battery pack comprises up to thousands of battery cells, which not only have to be opened individually but also removed from the ensemble. Moreover, the intricate structure and the associated risks makes the dismantling slow and laborious – the recycling takes more time and is more expensive.

By incorporating the principles of DfR, lithium-ion batteries can increase the overall quantity and quality of materials recovered from EOL products. Naturally, the reusability of these materials results in the product's increased value. Overall standardization of product design and size can be one key to streamline and optimize operations for recycling companies; but at present, this is far from reality.[40]

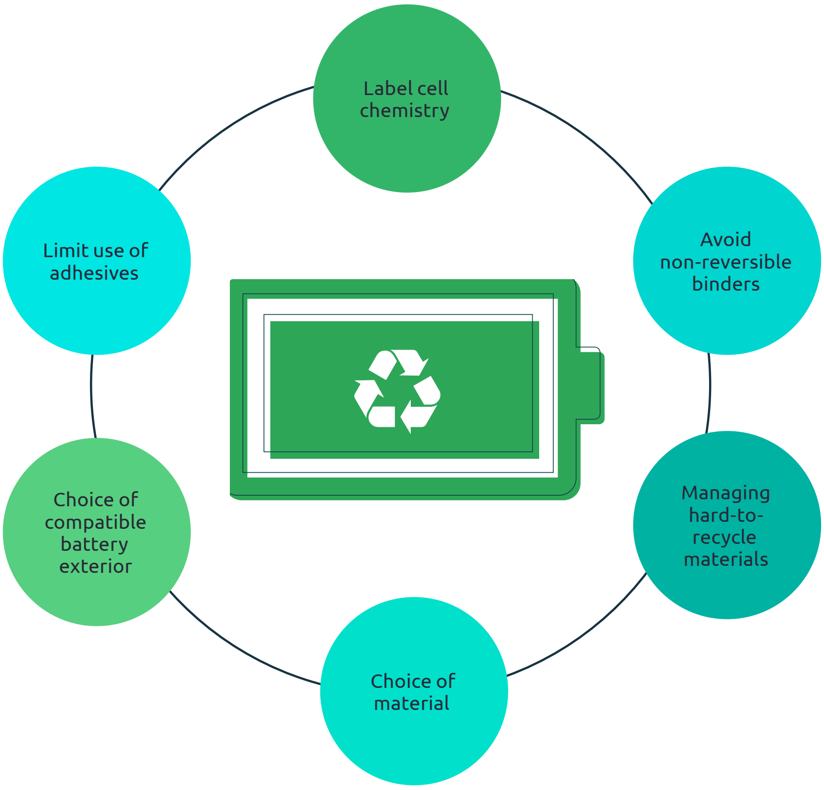
Battery cells are hermetically sealed, and adhesives are often used to join the modules and pack. This provides the pack with rigidity and safety, but these non-reversible and difficult-to-break bonds slow down the material recovery process and make recycling unfeasible. Limited use of adhesives or binders can drive efficiency and standardization in recycling.

Due to technological developments, even the same EV models with different versions may consist of different battery chemistries. When it comes to the recycling process, it is not advisable to mix battery chemistries. At best, it can lead to unwanted results. At worst, it can be a safety hazard. That is why, there are currently only a limited number of acceptable methods of recycling. Improved identification methods can mitigate this problem and help in the segregation of different batteries chemistries via identification methods such as color coding, RFID and ultraviolet, or infrared scanning or blockchain.[41]

The choice of exterior battery materials is important because some exterior materials may be affected by chemical or high-temperature recycling processes. Ensuring compatibility between exterior materials and the recycling process can help skip early physical separation.

The eco-strategy known as Design for Dissassembly (DfD) encourages to avoid rigid exteriors that are durable and cannot be easily removed.

Recycling metrics such as material recovery rate and purity are directly proportional to the choice and the distribution spread of materials in the battery. Use of incompatible materials can result in a comingling of recycling output streams. Also all solid state designs with ceramic electrolytes may limit the ability to recycle, thus making it more difficult to reach overall recycling quotas.



Design for recycling principles

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[40] Norgren (2020) [41] Chen (2020)

It is important to remember that the majority of modern batteries are composed of chemistries that incorporate hazardous materials. The amount varies depending on the battery. But the amount is irrelevant. Whenever hazardous materials are used, proper safety and precautionary measures must be observed during the recycling process. Consequently, the cost of the operation increases and the efficiency decreases. Moreover, hazardous materials may lead to the contamination of other recycled materials.[42] [43]

3.3 Production trends

As described in the introduction, EV demand is predicted to grow tremendously within the next years, especially in China and Europe, but also in the US.

Besides the current challenges of meeting automotive demand with a limited and volatile semiconductor supply and the issues caused by COVID-19 and wire harness supply issues arising from the conflict in Ukraine, future automotive production will face additional challenges due to battery availability – the industry has challenges with producing EVs in sufficient quantities, despite the growing demand.

For many traditional automotive companies EV production and battery assembly is still in the early stages and lacks standardization. Also, each manufacturer follows their unique battery pack design, resulting in many manual steps for EV battery assembly. Therefore, as they ramp up production, EV manufacturers are often encountering battery production bottlenecks. To meet future demand, battery manufacturers must automate their processes completely and improve process speeds. Automation is the key to improving assembly safety, ensuring quality and traceability, and managing battery costs.

The battery supply chain needs to be as efficient, agile, smart, and digitalized as the production floor to be able to evolve in-step with the overall existing EV supply chain. This will also bring a need for gigafactory technologies to be revamped to maximize speed, flexibility, and throughput.

As demand grows and EV production grows to meet the demand, it's essential that partnerships are forged and fostered in the battery production ecosystem, such as between Bosch and Volkswagen, who plan to supply integrated battery production systems and to support battery cell and system manufacturers with ramp-up and on-site maintenance.[44]

For battery manufacturers the meeting of ESG criteria becomes more important. For example, CATL managed to get rewarded as a Global Lighthouse project by the WEF for outstanding sustainability in production. They leveraged artificial intelligence, analytics, and cloud computing to achieve a reduction of energy consumption by 10% per year.[45]

[42] ACS (2021) [43] RSC (2020) [44] Volkswagen (2022) [45] WEF (2021)

Rankings	Automation and IoT platform to increase production flexibility[46]	Digital twin technology plays a major role in battery production[47]	End-to-end automation of gigafactories[48]
Overview	A high-volume production line for battery modules, using the latest technologies following Industry 4.0 principles, for the digitization and automation of the line.	Digitizing and automating production lines at a European battery gigafactory.	A 40+GWh lithium-ion battery manufacturing facility in Northern Europe.
Automated processes and technologies deployed	Deployment of a highly automated line combining industrial robots, vision systems, laser welding, and automated in-line validation of joints via artificial intelligence.	Digitization of an R&D pilot line and production plant, using a variety of solutions and products for the production lines including hardware, HMI screens, light stack, network topology, standardized machine interface, and energy monitoring.	—
Outcome	Production increase to six times its present capacity. Expected time savings and cost reduction by using the IoT and MES platform was 20% in this case, and the line was able to support 50 different product configurations.	The digital twin technology enables the production of premium customized batteries and reduces the time for batteries to go from laboratory to production.	End-to-end automation and digitization of its manufacturing processes at its upcoming facility from the arrival of materials to the output of battery cell products.

These short case studies show possible improvements by major production technologies:

[46] Automation (2021) [47] Siemens (2021) [48] Morrow Batteries (2021)

3.4 R&D and production needs to be flexible, recycling-ready, and fully digitalized

Even though we expect design to pivot around Li-Ion batteries for the next few years, accelerating technology, and the quest to find better and safer batteries, means that R&D and production needs to be flexible, to be able to quickly scale, and easily incorporate future technologies, such as all-solid-state-batteries. In short, it's imperative that research and production facilities are entirely digitalized.

It seems likely too that the sustainability concerns of end-consumers will continue to ramp up and that recycling standards, and regulations will rise in tandem. This will put pressure on a need for even greater flexibility in R&D and production. Such flexibility can be realized though full digitalization, which can be achieved by:

Further automating battery production and battery system integration

It's not only about serving volatile battery demand; it is also about needing to keep pace with the quick evolution of battery technology. As it evolves, battery producers need the ability to evolve along with it and shift in an agile way to produce multiple battery types. To do this you have to adjust production lines rapidly, while still hitting production targets and maintaining quality as well as reducing scrap rates. Automation is the key to achieving this.

Gigafactories leveraging IOT Technology to catch up with demand for data

The rising demand for EVs will require gigafactories for battery manufacturing, which use innovative production processes, ad a paradigm shift in thinking to maximize speed, flexibility, and throughput. Smart manufacturing is vital to scale battery production and feed entire lifecycle optimization. IoT increases the visibility of assets and enables the quick benchmarking of multiple plants, lines, and machines. It provides real-time shop-floor information, and other sources to give a 360-degree view.

> *"Digital twins will improve planning, testing, manufacturing and aging performance prediction."*
>
> *- Christian Michalak,*
> *Executive Vice President,*
> *Head of Intelligent Industry*
> *Germany*

Using digital twins to enable second-life and further use cases

A world awash with data provides an intricate interconnected network of sensors that enables real-time monitoring and measurement. This is the internet of things, and it brings significant potential for developing use cases to supercharge the second life applications and the recycling process.

Key considerations

In R&D, data can be used to construct virtual 'digital twins' digital versions of batteries that can be used in planning and testing as well as in the manufacturing process, and later when in use out there in the real world. Digital twins bring many capabilities such as establishing the validity of a use case and the allowing of fast ramp up of production. But R&D with digital twins need not end there – as batteries are manufactured, sold and used, data is fed in real-time via their battery management system (BMS) to measure performance and to iterate and optimize. This kind of continuous monitoring and measurement will be vital for battery safety, and optimization and the knowledge of the battery history will further enable and foster Second Life usage.

4

RECYCLING AND SECOND-LIFE SOLUTIONS AS SUCCESS FACTORS AND BUSINESS OPPORTUNITIES

The transition to EVs is widely recognized as one vital step towards a more sustainable future. But this progress comes with its own sustainability challenges, such as what to do with used batteries.
At present, EV companies like Tesla and Rimac are proliferating popular culture. The electric vehicle is becoming a must-have commodity. Their rapid uptake is expected to lead to a market for second-hand EVs and their EOL batteries. Though it could change in the near future, many of these used batteries cannot be used in additional EVs. Their second life will need to be the power source for a different device. This is forecasted to lead to an abundance of older-model batteries without any immediate usage.

By definition, the current generation of EV batteries are classified EOL when their capacity is 20% lower than when manufactured. In short, battery regulations mandate a cell capacity of 80%. Any batteries below this 80% benchmark will be ready for EOL solutions.
Therefore, looking at a modest outcome, it is estimated that there will be 95 GWh worth of 'retired' Li-Ion batteries by 2025[49] and between 100 to 200 GWh by 2030 based on current projections of around 10 million EVs on the roads by the end of the decade).[50]

In addition, new, tighter regulations on end-of-life EV batteries will come into force in the near future. The most notable example is Directive 2006/66/EC of the European Parliament and Council.[51] Commonly known as the "Battery Directive," it comes into law in 2022. Consequently, EOL batteries will be regulated differently from 2027 onwards. This will lead to new recycling quotas and mandatory take-back and collection programs, which will affect the entire supply chain for batteries.

> *"The OEMs that act now will define the supply chain according to their needs."*
>
> *- Christian Michalak,*
> *Executive Vice President,*
> *Head of Intelligent Industry*
> *Germany*

All of these changes are opportunities in disguise. Moreover, they present a degree of certainty businesses can utilize to strengthen long-term strategies and projections. The industry should begin preparing for the inevitable.
As the number of used batteries and regulations on how to handle them increase, it will become increasingly important to have a business model that incorporates an EOL strategy. Soon, new regulations will compel everyone to act. But players who delay now may get left behind as the market gathers pace. Being active now instead of reactive later could profoundly alter outcomes. Active players can take the bull by the horns. They can become pioneers as the majority of the market is focused on ramping up primary battery production facilities.

With this in mind, we will analyze the most promising alternatives and solutions that are available today. This will give us a better understanding of their key differences, potential for growth, and practical applications. Such a proactive approach will enable us to identify the next steps for OEMs and other players who are attracted to the increasingly relevant market of EOL batteries.

[49] Capgemini (2019) [50] IEA (2021) [51] European Union: Eur-Lex (2020)

4.1 Different use cases emerging for end-of-life EV batteries

Despite recent advancements in sustainability, EV batteries have a finite lifetime. Automotive requirements for batteries are high compared to micromobility industries (e-bike, scooter applications) and also batteries in vehicles often have a thermomanagement reducing thermal degradation. In general, the end of the lifetime is defined as a 20% fall in cell capacity from the rated value.[52] When they finally reach the end of the road, there are four major management options.

1. Second-life reuse

Batteries running below 80% capacity can, by definition, still be used in less demanding applications, such as energy storage systems (ESS) or smaller mobile applications.

2. Recycling and raw materials recovery

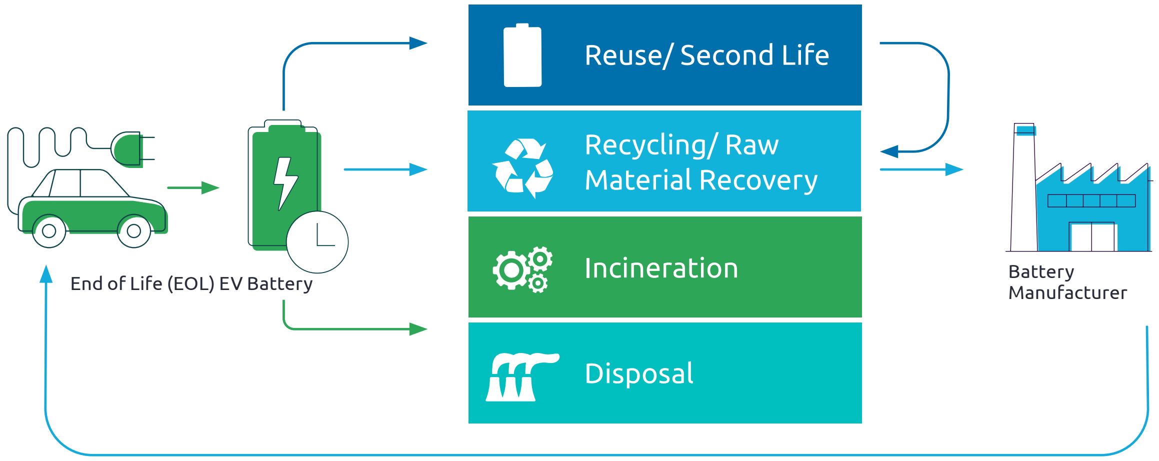
Recycling refers to the recovery of one or all raw materials from the battery after the end of its useful life.

3. Incineration

Battery materials can be used as fuel for other process. This fuel is achieved through incineration. However, the process carries the potential risk of toxic gases being released, which can contaminate the air.

4. Disposal

Disposal is considered the least energy efficient option for EOL batteries, as none of the batteries' components are reutilized. But it is often necessary, since other options can potentially expose workers to leaching chemicals and the release of electrolytes. Moreover, modern battery chemistries, such as lithium-ion, for most part, do not have truly efficient recycling facilities. As a result, discarded batteries can end up in landfills without having been through any recycling process. There is a risk that this number could increase.



What happens to a battery at EOL?

The four EOL solutions for batteries can be divided into two categories: sustainable and unsustainable. Naturally, we want to focus on the two solutions that maximize sustainability. That means ruling out both incineration and disposal. The former involves the release of harmful toxic gases for raw materials that have limited viability as fuel for other processes. The latter adheres to a set of dedicated processes. They are designed to limit the risk of human exposure to toxic chemicals and electrolytes. Though these processes are not considered sustainable, as none of the materials are reused, they are currently the predominant solution. This is because sustainable second-life and recycling alternatives are not currently economically viable or not yet suitable for mass adoption.

Second Life use cases need to be seamless, e.g. to utilize the usage in home energy storage and rely on standardization in battery design.

> *"Battery recycling and 2nd life use cases are exponentially rising in relevance."*
>
> *- Sebastian Tschödrich,*
> *Executive Vice President,*
> *Head of Automotive Global*

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[52] USABC: Electric Vehicle Battery Test Procedures Manual (2012)

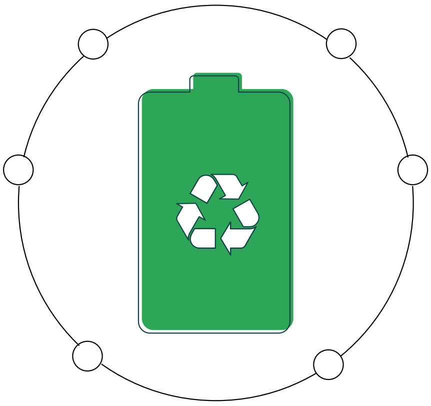
Key considerations

A general prerequisite for using batteries in second-life and recycling scenarios is the battery's state of health (SOH) check. This is an important step in determining remaining capacity and functional cells. The SOH check is used to evaluate the usefulness of a battery for second-life and recycling use cases. This is both cost and labor intensive at the moment.
The potential to deploy mass-market solutions here cannot be overstated. As such, technological development in SOH, now being more rapidly defined, is thriving. For example, one option is that wireless connections embedded in batteries could enable automatic and remote read-outs on a battery's vitals. The health check is a necessary step to provide a certification and battery status information for the secondary use of the batteries.

4.2 Reusing batteries

There are multiple emerging options for reusing batteries at EOL.
But overall, current solutions focus on the subsequent use of these batteries as energy stores (i.e., Energy Storage Systems (ESS) in different applications).

The primary reasons for the increasing relevance of energy storage are:



Energy consumption

A general increase in both the demand and usage of electricity

Increased interest in renewables

Focus on renewable energy generation and enablers (optimized production and storage of solar and wind over time)

Decentralized storage

Energy storage in remote locations, where generation it is more readily available

New technology

Smart grids, microgrids, V2X, V2G, and participation in energy markets via storage and usage

Peak-load shifting

Discharging and storing batteries during peak times and charging them when demand is low for electricity

Market activity

Leveraged price sensitivity (e.g., charging for EV storage when electricity is cheap and selling energy when electricity is expensive)

> *"The battery health check is crucial to enable second life use cases."*
>
> *- Simon Schäfer, Manager, CX E-Mobility*

Popular use cases

Of all the use cases currently being explored, most of the players in this industry opt for three that are dedicated to reusable batteries. The three use cases are:

1. Mobile applications

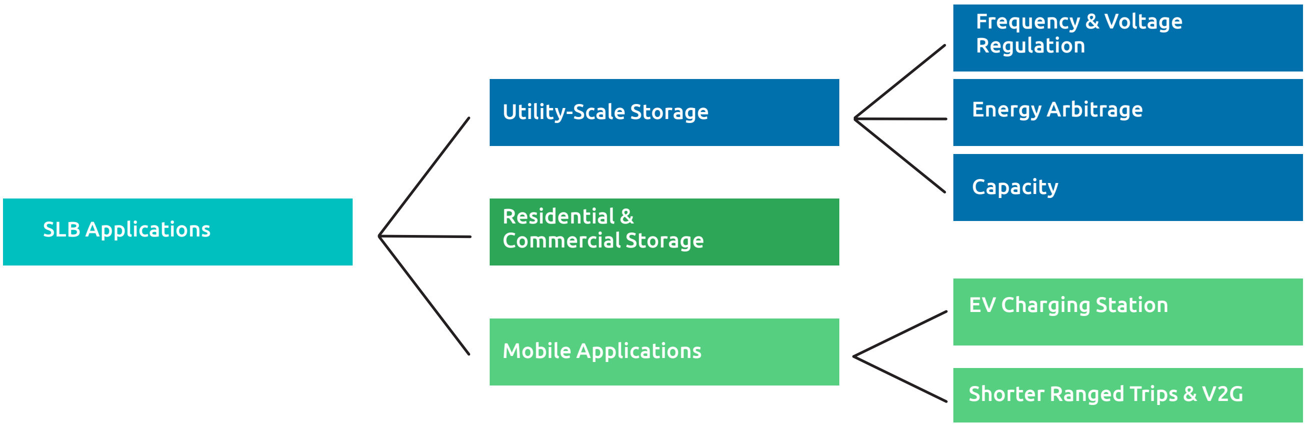
- Batteries or their parts can be reused in the mobility space, where less storage is required (e.g., small BEV, PHEVs, and micro mobility applications, such as scooters and bikes)
- EV Charging stations (buffer storage)

2. Utility-scale storage

- Frequency and voltage regulation (peak loads)
- Energy arbitrage (leveraging price differences in markets to reduce the cost of electricity)
- General capacity increase of storage systems (meeting the demand for additional storage systems, such as the relevance in storage of electricity generated through solar and wind)

3. Residential & commercial storage

- Both home and enterprise energy storage are increasingly popular



Applications of SLB

As reusable batteries support goals and respond to regulatory pressure, the market receives an influx of new players. Naturally, the number of active OEMs is set to increase.
For EOL solutions to be successful, manufacturers need to incorporate them during the conceptualization phase. This opens the door for competitors with a pioneering mindset. Consequently, these OEMs initiate an avalanche of innovation.
Mobility players benefit from the arrival of new OEMs, all of which are able to cut long-term overheads and deliver more sustainable transportation. But that's not all. The people either being transported or receiving deliveries can benefit from greener and more efficient utilities, such as energy grids and supply chains. Of course, battery production companies also stand to benefit tremendously from this new paradigm. Their batteries will have resale potential, meaning they can justify price shifts and consider buy-back options. Finally, many start-ups and SMEs with pioneering storage systems and the like will treat reusable batteries as new avenues for growth. Evidently, the market for second-life batteries is one of the most exciting sustainable solutions in recent years. Advances in technology and an influx of new players have stimulated a thriving industry. However, there are still no entirely mainstream solutions.
The majority of existing initiatives are still primarily focused on research projects or early-stage trials. Exploration of opportunities in this space are active in all major regions of EV development: North America, Europe, and Asia.

Notable second-life projects – Europe

Stakeholders Involved	Project/ Initiative Category	Project/Initiative Description	Year	Location
ECO STOR, NUVATION ENERGY	Large-Scale Energy Storage	Nuvation Energy and ECO STOR collaborated in the development of three energy storage systems to be deployed in Norway. Nissan Leaf battery packs will be utilized for large-scale energy storage. Two 50 kW / 150 kWh systems provide demand charge management to an office building and a school respectively. One 1 MW / 700 kWh containerized energy storage system provides transmission and distribution upgrade deferral services at a utility grid substation.	2021	Norway
EATON, NISSAN, BAM	Energy Storage (Microgrid)	The project is a collaboration between the Johan Cruiff Arena, Eaton, Nissan and BAM for one of Europe's largest microgrids using a hybrid first-life and second-life EV battery system in a commercial building.	2021	Netherlands
RENAULT, CONNECTED ENERGY LTD	Large-Scale Energy Storage	Renault and Connected Energy partnered for the development of sustainable and efficient ways of using electric vehicle batteries at the EOL of EVs to supply innovative and more affordable vehicle charging solutions. The batteries were supplied by Renault and were used in Connected Energy's E-STOR for stationary storage in electric vehicle charging.	2016	United Kingdom
MITSUBISHI. PSA EDF, FORSEE POWER, MMC	Energy Storage	A demonstration project by Mitsubishi and PSA for a high voltage, a low voltage and a bi-directional battery energy system to demonstrate efficient and economically feasible energy management practices based on the optimization of electricity storage, charging and generation technology with respect to existing demand.	2015	France
DAIMLER GETEC, REMONDIS, ENBW	Energy Storage	Battery storage unit with a total capacity of 13 MWh. Degraded EV batteries from Daimler EV models were used for second life application of grid energy storage. The batteries will be connected to the grid and the output will be sold on the German electricity balancing sector.	2015	Germany
BMW/ VATTENFALL, BOSCH	Energy Storage	A 2 MW, 2,800 kWh energy storage system comprised of 2,600 battery modules from more than 100 electric vehicles.	2016	Germany
AUDI, ENBW	Grid Stationary Storage	A storage facility, deployed by Audi and German Utility EnBW, useds second-life EV batteries from Audi to store power from EnBW's wind and photovoltaic parks. The facility is located at EnBW's CHP plant in Heilbronn and offers services to municipal utilities, industrial companies and operators of decentralized generation plants.	2020	Germany
STREET SCOOTER, DHL	Energy Storage	DHL uses Second Life batteries to create buffer storage, saving up to 20.000 tCO2 per year in one building.	2021	Germany
BETTERIES, MOBILIZE BY RENAULT GROUP	Modular Energy Storage	The german start-up betteries established a partnership with Mobilize to built a remanufacturing center at Renault Group. The battery upcycling process uses modules from Renault electric vehicles to assemble second life energy modules. Using vehicle data, monitoring, control and prediction the second life application uses technologies to enable a second usage and possibly a certification and warranty.	2021	France/ Germany

Notable second-life projects – Asia

Stakeholders Involved	Project/ Initiative Category	Project/Initiative Description	Year	Location
TOKYO ELECTRIC POWER HOLDINGS (TEPCO)	Grid Stationary Storage	The utility launched a storage battery business utilizing used EV batteries from China. The batteries will be purchased from trading companies in China, and around 20 to 30 EV batteries will be assembled into a containerized energy storage system for renewable-energy plants. Trials started in 2020 and full deployment is planned in 2021.	2020	Japan, China
HONDA, CATL	Second Life Research	Honda acquired 1% of CATL to attain a stable supply of EV batteries and to explore areas such as recycling and reuse.	2020	China
NISSAN SUMITOTO (4R ENERGY), GREEN CHARGE NETWORK	Solar-plus-storage	16 Nissan Leaf LIBs of 600 kWh/400 kWh were provided by Nissan, that will regulate energy from a solar plant.	2015	Japan

Notable second-life projects – United States

Stakeholders Involved	Project/ Initiative Category	Project/Initiative Description	Year	Location
HYUNDAI MOTORS, UNDERWRITER LABORATORIES (UL)	Energy Storage	Hyundai and UL signed a memorandum of understanding for enabling safe deployment and use of second-life battery storage systems. The collaboration initiative will include a safety testing and assessment, a North America product demonstration project, and evaluation process development.	2021	USA
GENERAL MOTORS, ABB	Solar-plus-storage	ABB and General Motors collaborated to demonstrate the use of second-life batteries for residential use. 5 Chevrolet Volt LIBs, 74 kW solar array & two 2 kW wind turbines were used to power a General Motors office building site.	2015	USA
BMW, PG&E	Pilot Storage Project	BMW collaborated with PG&E to provide nearly 100 BMW i3 batteries, equaling to around 100kW of grid resources.	2017	USA

Outstanding projects since 2015

Impact of second-life batteries

One of the key characteristics of a sustainable solution is its multifaceted results. One cause often leads to many effects. This is especially true of second-life batteries, which have the potential to transform our everyday lives.

Here are the primary points of impact:

1. Environmental impact:

- Battery material can be reused instead of producing new batteries dedicated to applications.
- Battery packs can be used as storage systems to enable the transition of renewable energy (increasing the storage of generated renewables, especially decentralized).

2. Reduced cost of EVs:

- One major expense for EVs is the battery. With reusable model, either the whole batter or some of its parts can be reused and commercially utilized. This reduces the TCO of the EV. Clear commercial models have not yet been established (e.g., customer cashback for the battery or OEM collection). To highlight potential solutions here, taking the battery back could mean "pocketing" the value of the second-life battery or calculating it into the selling price of the EV).

3. Decreased cost of ESS:

- Reuse batteries can be used as energy storage systems.
- Though already attractive, reduced costs can bolster the relevance of ESS.
  This leads to greater support for market demand.

4. Technology push and support of transitioning EVs

- There is increasing potential for remote, fast-charging solutions (e.g., adaptive solutions, such as those developed by EON).
- New charging technologies can emerge across the board, including vehicle-to-grid and bidirectional charging.
  Thus, participation in energy markets, such as microgrids, will be a common occurrence.

> *"Modern cell chemistry and advanced battery analytics provide the necessary technical prerequisites for successful 2nd life applications.Further enhancements are necessary in standardized interfaces of battery management systems on module and pack level. The planned new EU Battery regulation is potentially the expected framework under which new successful business models can evolve. "*
>
> *- Marcus Fiege, Senior Solution Architect E-Mobility, Capgemini Engineering*

Key considerations

When it comes to reusing batteries, there's no one-size-fits-all solution. For one thing, dedicated use cases depend on the remaining quality of the battery (i.e., the battery's SOH), its dimensions, chemical composition, and the underlying battery design and architecture. Moreover, second-life batteries now require special consideration. Advanced technology is beginning to increase the average lifetime of batteries. Much of this technology is still in its infancy. But it's electrifying industry experts around the world. One such example is the future of LFP batteries.

LFP batteries are at the forefront of extended longevity. The longer a battery's lifetime, the more likely it is to endure and perhaps even exceed a vehicle's lifetime. For EV battery manufacturers, such an achievement gives them unparalleled bragging rights. Consumers want to avoid hidden costs wherever possible. Moreover, a vehicle that require a midlife battery change defeats the purpose of electric vehicles. If a manufacturer can tick all of these boxes, they will command the kind of respect that justifies price shifts. As the life of the battery begins to exceed the life of the vehicle, alternative second-life applications become a secondary consideration. For example, if the LFP battery still operates at over 80% capacity, it could potentially be transplanted into another vehicle. Of course, all of these developments precede recycling options. With this in mind, second-life solution cannot be considered the be-all and end-all for batteries. Rather, it must be considered part of a comprehensive approach to EOL.

4.3 Recycling batteries

The recycling of EV batteries is especially relevant when second-life use cases are no longer an option due to reduced energy density or capacity. Disposing of batteries should be avoided at all costs due to its extremely hazardous effect on our surroundings. Heaps of electronic waste containing lead and other toxic chemicals can pose a danger to both people and the environment.

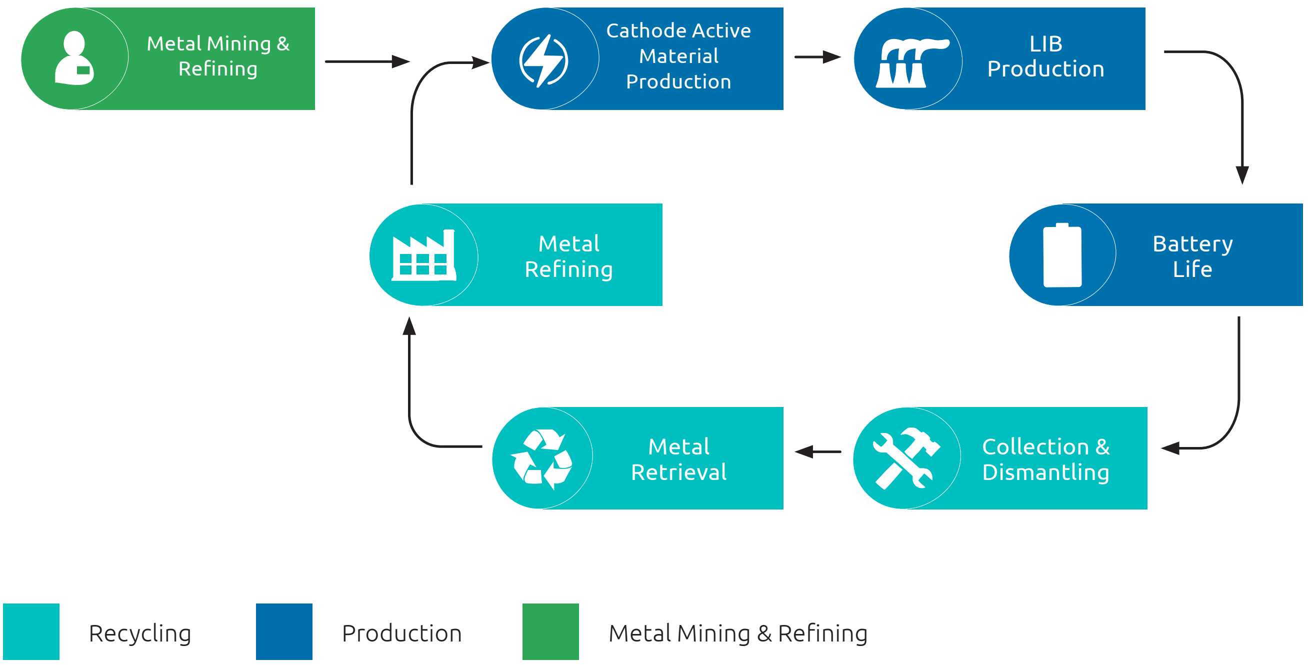
Disposing of batteries wastes many precious and often expensive materials used in their production. Same with metals that have highly fluctuating prices like cobalt or nickel. All of these should be recovered. This way we can avoid relying on unstable deliveries and companies with questionable backgrounds that often make use of ethically problematic practices that plague large parts of the mining industry. This also helps European OEMs become more independent regarding raw materials, given their common geographical disadvantages.

When it comes to sustainability, recent cases show improvements in the circular economy and supply chain where materials from EV batteries are more often reused, repaired, refurbished, and recycled to create a closed loop. The need for new materials decreases, while the 2nd life of batteries increases.

Putting a large focus on sustainability can work wonders when it comes to the living quality of local communities in areas where many of the materials mentioned above are mined. This includes avoiding involuntary resettlement, artisanal mining, harming indigenous people. If we keep successfully implementing all the good practices we have mentioned, we can minimalize the damage to these communities, while making everything more cost efficient in the long-term.

Right now, manufacturers are collaborating to explore the most promising recycling methods to identify a sustainable and economically feasible approach. The main challenge in the entire process is the fact that recycling batteries is simply not yet profitable due to inefficiencies, safety hazards, logistical challenges related to collection and transportation, and the evaluation of battery SOH which is the prerequisite for recycling cell materials.

According to the current estimation, EV battery recycling shows chances of profitability from 2025 onwards, in large part thanks to its widespread adoption and scaling effects. Countries like China are already showing great promise in that regard.



General process of recycling

Even though China remains one of the leading markets here, there's a huge future potential for Europe and North America, especially if they begin to act now. Establishing all necessary structures and systems will be vital to avoid falling behind in battery recycling and to have a chance at becoming future leaders.

Before looking at different recycling alternatives and initiatives let us highlight the geographical differences, with a focus on the US and EU, from a regulatory perspective.

TOPIC	US	EU
Directives	Directives in first, selected states regarding recycling	Overarching battery directive 2006/66/EC that covers collection rates, recycling efficiencies and mandatory usage of recycled material (directive to be approved by parliament in 2022)
Current recycling efforts	No/limited effort in the U.S. only specific states are putting policies in place and supporting the circular economy of batteries (e.g., California, Hawaii, North Carolina) important is that of the states, e.g., California (100% recycling and reuse) are showing effort, which is by far the most prevalent state in terms of EV adoption support and budget for research initiatives in recycling design for recycling and reuse is explored by leading manufacturers (e.g., Tesla, Ford, GM), but vast majority of battery manufacturers follow linear economic models (no circularity); but mostly driven by federal funded initiatives and pilot projects	Limited recycling due to cost and technological challenges (e.g., only 12% Aluminum, 22% cobalt, 8% manganese and 16% nickel are recycled) investment and regulations are in place or being developed for infrastructure building the base to enable growth and stability of the market extended producer responsibility (ERP): battery and component manufacturers are already responsible for waste management (particularly funding of collection and recycling programs)
Mandatory recycling efficiencies	—	2025 Recycling efficiency lithium-ion batteries: 65% by 2025 Material recovery rates for Co, Ni, Li, Cu: resp. 90%, 90%, 35% and 90% in 2025 ----- 2030 Recycling efficiency lithium-ion batteries: 70% by 2030 Material recovery rates for Co, Ni, Li, Cu: resp. 95%, 95%, 70% and 95% in
Mandatory recycling efficiencies	—	2030 and 2035, with 12% cobalt; 85% lead, 4% lithium and 4 % nickel from January 1st, 2030, incrementing up to 20% cobalt, 10 % lithium and 12% nickel from January 1st, 2035.2030

Comparative analysis of US and EU recycling

Having looked at the regulatory perspective, let's now turn to the technological side.

Three main processes, and a combination of the processes, are used for commercially recycling and extracting raw materials from end-of-life Li-Ion EVs, consumer electronics or 2nd life users.

The first such process is pyrometallurgy, used mainly for dismantled batteries, which are smelted so that their carbon-based compounds are burned. The alloy of valuable metals that we want to extract is treated with hydrometallurgical processes.

Next, we have hydrometallurgy, a three-step process consisting of leaching that dissolves metals, purification that separates them through chemical reactions, and metal recovery.

Finally, there is direct recycling with the goal of recovering functional cathode particle without degradation into elements. This one is showing quite promising results, but the restoration of initial capacity must still be proven.

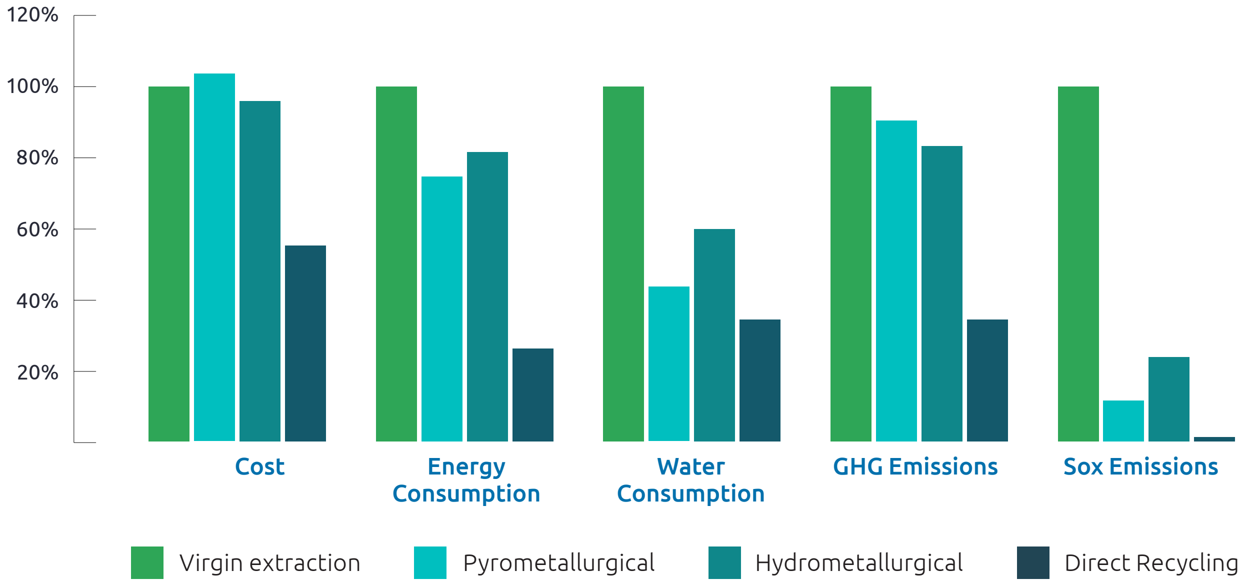
So far, there is no consensus as to which method is the most environmentally friendly and most effective. However, the two main dimensions of comparison are economic feasibility and sustainability. The following data presents a holistic view of the pros and cons of the three methods.

Processes	Pros	Cons	Recovered Materials	Recycling Companies
Hydrometallurgy	• Method is applicable to any battery chemistry and configuration. • Separation and the recovery processes are flexible to target specific metals. • Has high recovery rates for lithium. • Purity index is relatively high. • Energy efficient and no air emissions.	• The process has high operating cost, therefore not economical for lithium iron phosphate (LFP) batteries. Only feasible for Co and Ni batteries. • Cathode is broken down by acid. • The volume of process effluent to be treated, recycled or disposed is • high. • Anode materials such as graphite and some conductive additives are also irrecoverable.	• Copper • Aluminum • Cobalt • Li2CO3 Anode is destroyed	• Shenzhen Green Eco-manufacturer Hi-Tech Co. (China) • Retriev Technologies (Canada) • Recupyl S.A. (France)
Pyrometallurgy	• Expensive clean-up system is needed to avoid toxic air emissions.	• Expensive clean-up system is needed to avoid toxic air • emissions. • Economical for batteries with Ni and Co. • Is unable to recycle Li, Al or organics. • Is a capital and energy intensive process. • Requires further refinement for the extraction of elemental metals from the alloys.	• Copper • Nickel • Cobalt • Iron (partially) Anode is destroyed	• Umicore (Belgium) • JX Nippon Mining and Metals (Japan)
Direct Recycling	• Almost all battery materials can be recovered • Battery retains cathode structure • Feasible for LFP batteries • Enables the recycling of manufacturing scrap as well.	• Recovered material may not perform as well as virgin material. • Blending cathode materials could diminish value of recycled product. • Intricate and complex mechanical pre-treatments and separations are needed. • Process is not scaled up to industrial level yet	• Almost all components are recovered except separators	• OnTo Techb (USA)

Comparative analysis of recycling methods

The sustainability of recycling methods becomes apparent when compared to the detailed analysis of virgin extraction. Where cost is concerned, only pyrometallurgical recycling exceeds virgin extraction.

In every other category, the three methods of recycling show significantly lower values than virgin extraction. But the most noticeable difference by far is the value of direct recycling.



Benchmarks for Recycling methods

Key considerations

So, what has be done to increase the relevance of recycling EV batteries? The first set of actions is related to cost and profitability, since these show many areas in dire need of improvement. To achieve profitability, we need to take chemistry, location, and the entire process of recycling into account. This can be further accelerated by identifying standardized procedures and material extraction technologies – both of which will benefit a lot from a close collaboration between manufacturers and technological leaders. Standardization, in particular, is crucial for the current manual, labor- and cost-intensive process of disassembling the battery packs.

The second set of actions is related to purification processes and technologies. The best idea here would be to focus on identifying the technology set that enables the generation of pure materials that can be used in a closed loop to realize circular economy and supply chain potentials in the production of batteries. This technology should also be sustainability friendly, as the current state of battery manufacturing doesn't help a lot with their recycling and second-life goals.

4.4 Second-life and recycling potential

The OEMs of tomorrow must begin to consider the impact of EOL scenarios for batteries. Following such paradigm shifts as the 2016 Paris Agreement, businesses everywhere began thinking about how to meet and take advantage of new sustainability regulations. As a result, rechargeable batteries were put on pedestal and championed as one way to reduce emissions worldwide. And yet, there is still much work to do.

For a start, increased scrutiny of the lithium mining process is driving the demand for sustainable solutions. At present, innovations in end-of-life processes are among the most viable. But EOL must not be an afterthought. Rather, the maximum efficacy of such applications depends on considerations during the design stage. As such, the whole industry can benefit from second-life and recycling solutions.

The implementation of sustainable manufacturing will contribute to the longevity of the industry, making the transition from burgeoning to booming.

What second-life and recycling can do for OEMs:

Rapid growth in the EV market

In 2020, the compound annual growth rate for the global EV market was up 43% from 2015. It is expected to climb a further 47% by 2030. This in turn will lead to a 47% increase in battery demand worldwide.

Emerging application

Far from being the solutions of the future, EOL applications are already being implemented by forward-thinking OEMs. For example, battery parts are being harvested for use in devices with lower storage requirements, such as scooters and bicycles.

Demand driven by energy storage

At present, surplus energy and batteries need to be stored in special facilities. But this infrastructure is still being developed. As the number of batteries in circulation increases, so will the demand for second-life and recycling solutions.

Fluctuations in the materials market

Like all precious metals and minerals, the materials used in batteries are not easy to come by. As such, their market value varies depending on its scarcity. This stimulating innovation in battery chemistries. For example, LFP chemistries are being used as more affordable options for entry-level car segments.

Restrictive regulations strengthen growth

Regulations can be a hindrance. But with sustainability mandates set to touch all industries, there is great potential for growth. OEMs that adopt a new business model now can be better positioned to react to the increasingly restrictive regulations of tomorrow.

The ground up approach

The viability of EOL solutions depend on their level of integration – the earlier in the process the better. As such, OEMs are uniquely positioned to use these solutions as vectors for growth. For example, DfR requires players to completely rethink batteries from the ground up. This means efficiency can be built into every phase of production.

Underestimated growth

There is still a great deal of naivety in this space. Despite the inevitability of the shift in practices and operations, many players refuse to act on the opportunity. Despite delivery times of over two years, many well established players continue to focus on the production of batteries for new EVs. This leaves the market a lot of untapped potential.

As is often the case, there is no single solution for battery sustainability. It's not an either-or scenario. Rather, each specific case has its own requirements. It is essential that OEMs begin with a holistic strategy that includes both second-life and recycling solutions. A successful strategy must include an evaluation and analysis of the various dedicated use cases, industry players, and target markets. But this is only the bare minimum. An effective business model must also consider the development of economic validity and scalability, battery health, type, and specifications (mainly SOH); existing and emerging regulations, and company goals (e.g., instituting a circular economy and improving sustainability).

Valid use cases are currently being explored and leveraged. However, there are some sticking points. For example, second life and recycling are still rather expensive processes. This is especially true of the refurbishment and disassembly of current battery packs. Processes are not yet streamlined, and standardized solutions remain economically impractical. Though it is true no dominant solution exists, there are exciting developments in the works.

Challenges for a large-scale application of end-of-life use cases remain to be solved, increasing the relevance of a strong partner ecosystem and specific investments. Especially economic improvements to the comparably high costs of realizing end-of-life use cases, processes, and technical advantages are required to achieve the large-scale adaptation of use cases. Establishing dedicated partnerships (e.g., via investments, joint ventures, and strategic partnerships or collaboration) and sourcing strategies enable industry players to provide and scale second-life applications and recycling facilities in a joint effort. This is done by leveraging dedicated solutions for different players (e.g., via the standardized evaluation of battery state of health, which is one of the baseline requirements of end-of-life applications).

Business model outlook

Though it is still early days, exploration of new business models is beginning to show great promise for the industry's main players.
As businesses take bolder steps in the direction of sustainability, OEMs will be able to leverage new use cases. The uptake of technology and the development of smart grids will open up new revenue streams for businesses with revamped models. Decentralized storage space is just one example of future potential.
Of course, the viability of these models can only be determined after careful evaluation; however, initial analysis points to advantageous adoption.
In ECO STOR and Nuvation Energy's case, a model that included large-scale energy storage resulted in changes in demand and optimization at a utility grid substation.

> *"New revenue streams await OEMs with revamped business models."*
>
> *- Dr. Philipp Haaf, Director, Head of Electric Mobility*

All evidence suggests the adjustment of a business model is imperative for companies looking to achieve better alignment with sustainability goals.
The transformative potential of second-life and recycling solutions can only be maximized when built into a business model.
Back in 2015, Daimler GETEC, Remondis, and EnBW were early adopters. Today, the industry's biggest players have taken the same approach. Nissan, Honda, and Tokyo Electric Power Holdings (TEPCO) have all adjusted their operations and continue to invest in the new model. The future has a lot "in store" for EOL growth opportunities.

5

CONCLUSIONS

In the future, battery cells could be indistinguishable from the perpetual energy engines of science fiction. Such progress is a direct reaction to a unified cultural and regulatory paradigm shift.

The Paris Agreement and other low-carbon conventions have made the transition to electric vehicles a fixed horizon. Consequently, the world has embraced the need to phase out fossil fuels as quickly as possible. Ubiquitously accepted as a viable alternative, advanced batteries are leading the charge toward a more sustainable future. But the transition is not readymade. There is much room for improvement where the extraction of raw materials is concerned. In fact, this is one of the mandates handed out in Paris. But far from hindering development, the regulation has stirred an energetic response throughout the industry.

Investors rarely discover a sure thing. But with decarbonization already written into law, research and development in battery tech has moved into top gear. In an effort to mitigate the environmental impact of batteries, solutions are being developed at both ends of the process. Mining facilities are looking into more sustainable methods of extraction, such ethical cobalt and water management. Producers and manufacturers, too, are looking at ways to reduce the need for additional batteries, such as greater capacity and end-of-life solutions. The net result is a projected 700-fold increase in greener, recyclable batteries by 2040.

This mass adoption will lead to evolution right across the board. Urban infrastructure will undergo a profound transformation, overhauling energy grids and integrating charging stations. Noise and air pollution will reach levels of wellbeing not experienced since before the industrial revolution. Best of all, societal obligations placed upon businesses will power improvements in the public sector.

As noted, the rise of EV batteries is expected to reach every corner of industry. In this point of view, a great deal of potential for the future battery market has been explored. In conclusion, the following can be expected in the near future:

- The emergence of a battery value chain ecosystem
- Sustainable battery chemistries
- New modes of raw material sourcing
- Blockchain-facilitated transparency or a digital product passport with information about the battery history and tracing
- Fluctuations in the raw materials market
- New priorities for research and development
- Sustainable practices built into design
- Fully digitized and recycling-ready producers
- Second-life and recycling as vectors for overall business development
- New second-hand markets for batteries and vehicles

As batteries improve and even exceed our expectations, existing industries will begin to mature. For example, recycling processes will be refined and improved to accommodate the increased production of batteries. Moreover, new industries will reach maturity. Second-life options for batteries are already on the rise. But as our batteries begin outliving their hosts, they will need to be transplanted into other devices or used as grid storage.

The sooner OEMs can incorporate these strategies, the better positioned they will be to explore the highway of certainty for EV. With batteries being one of the most promising alternatives to fossil fuels in the passenger automotive sector, they are sure to maintain a thriving industry and accelerate the arrival of our greener future.

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