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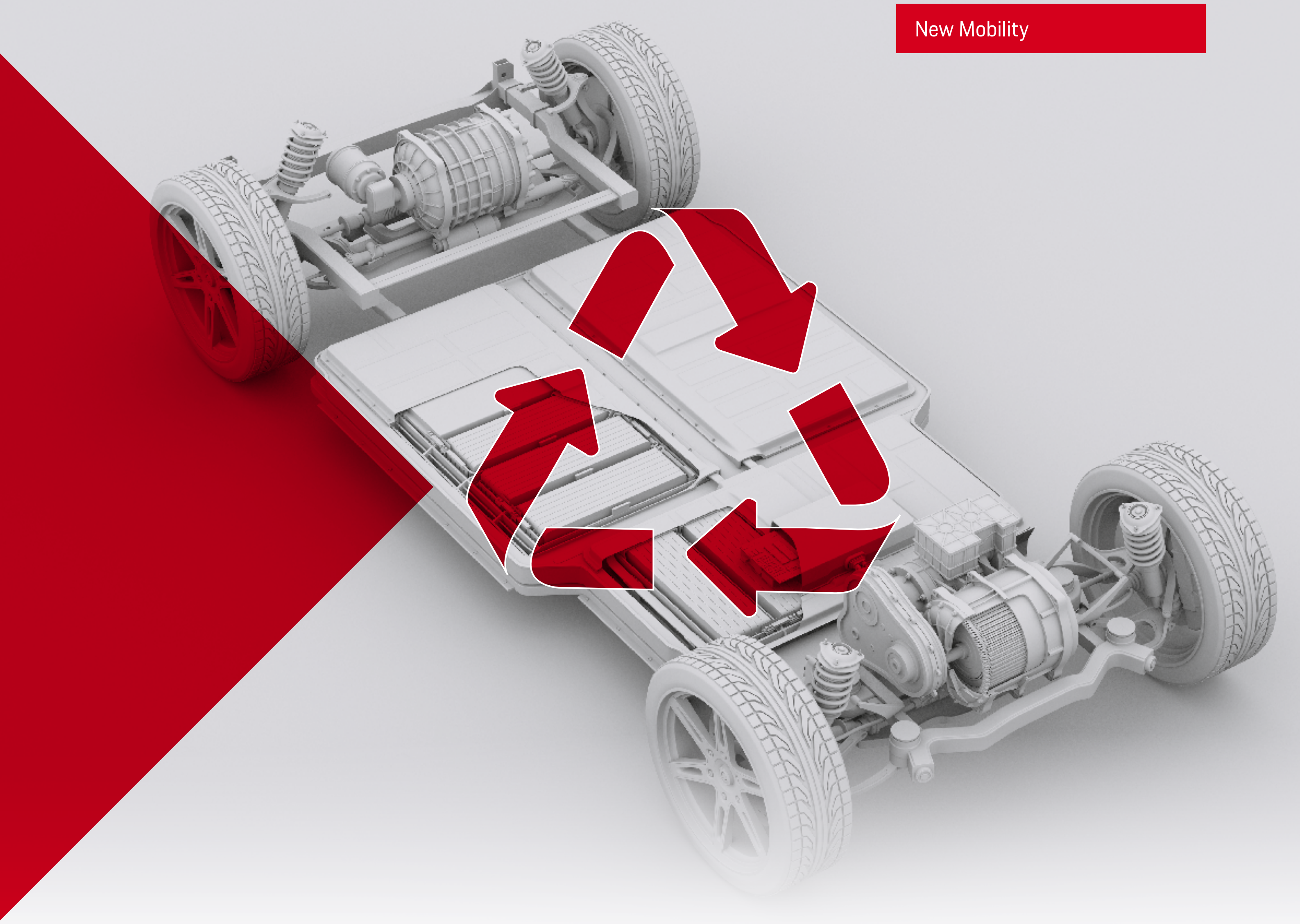

Understanding the Automotive Battery Life Cycle

A comprehensive analysis of current challenges in the circular economy of automotive batteries

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INSIGHTS

//01

Predictive battery analytics will become a standard procedure in battery life cycle management

//02

Only a certain proportion of used batteries will be feasible for second-life applications

//03

Battery recycling can support raw material supply and is likely to become economically attractive

Abstract

As societies see the global adoption of electrified passenger and commercial vehicles unfold, questions arise concerning the fate of automotive batteries after their use in electric vehicles (EVs)[1]. It has to be considered that the usable lifetime of a lithium-ion (Li-ion) battery is limited and regulations for battery take-back and disposal are in place (e.g., in Europe[2]). Additionally, awareness and the need for sustainable solutions are increasing in society and an improved traceability of materials[3], reduced carbon footprint, and increasing recycling quotas are being demanded. Yet, the key conflict between an extension of product lifetime in second-life applications and an earlier retrieval of critical materials via recycling is still to be resolved.

All together, these effects require solutions in the post-vehicular life of an automotive battery—the "secondary" life cycle. In this white paper, the secondary life cycle was analyzed using data from the early-stage market and three key takeaways were subsequently derived:

Predictive battery analytics will become a standard procedure in battery life cycle management

Only a certain proportion of used batteries will be feasible for second-life applications

Battery recycling can support raw material supply and is likely to become economically attractive

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[1] Includes plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs)

[2] See https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32006L0066

[3] "A Vision for a Sustainable Battery Value Chain in 2030–Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation" (World Economic Forum, 2019)

Introduction: The battery life cycle

With the widespread use of electric vehicles in volume segments, the use of lithium-based batteries is becoming a mass-market business for the automotive sector. The life cycle of an automotive traction battery is structured along two main paths: the primary life cycle, which lasts until the end of the battery's first life in the vehicle, and the secondary life cycle that follows. In this white paper, the focus lies on the latter. The term "end-of-life battery" (EoL) is used in this context to describe a battery at the end of its first life in an electric vehicle. EoL batteries are being analyzed in order to determine their state of health (SoH), which provides valuable information about their further deployment: a prospective use in their second life or a direct path towards recycling. In each case, batteries have to be collected and transported.

With respect to the second life, the primary use case for EoL automotive batteries is a utilization in stationary energy storage systems (ESS), e.g., for grid stabilization or as a buffer in high-power charging (HPC) stations. Any use in such systems usually requires a repurposing which includes repairs, preparatory work, and modifications to the battery. An alternative use case for a second life will be the re-utilization of modules in a vehicle as a remanufactured spare part[4]. The latter is still at an early stage but is well known from internal combustion engine (ICE) components and will be developed in coming years for battery components as well.

On the other hand, recycling can be carried out in a variety of mechanical and chemical processes, primarily serving the purpose of reattaining raw materials, which can then be used to manufacture new battery cells: in other words, the circular economy. A circular economy for batteries does not only lead to a reduction in the battery's carbon footprint, but can also reduce dependency on primary material suppliers[5].

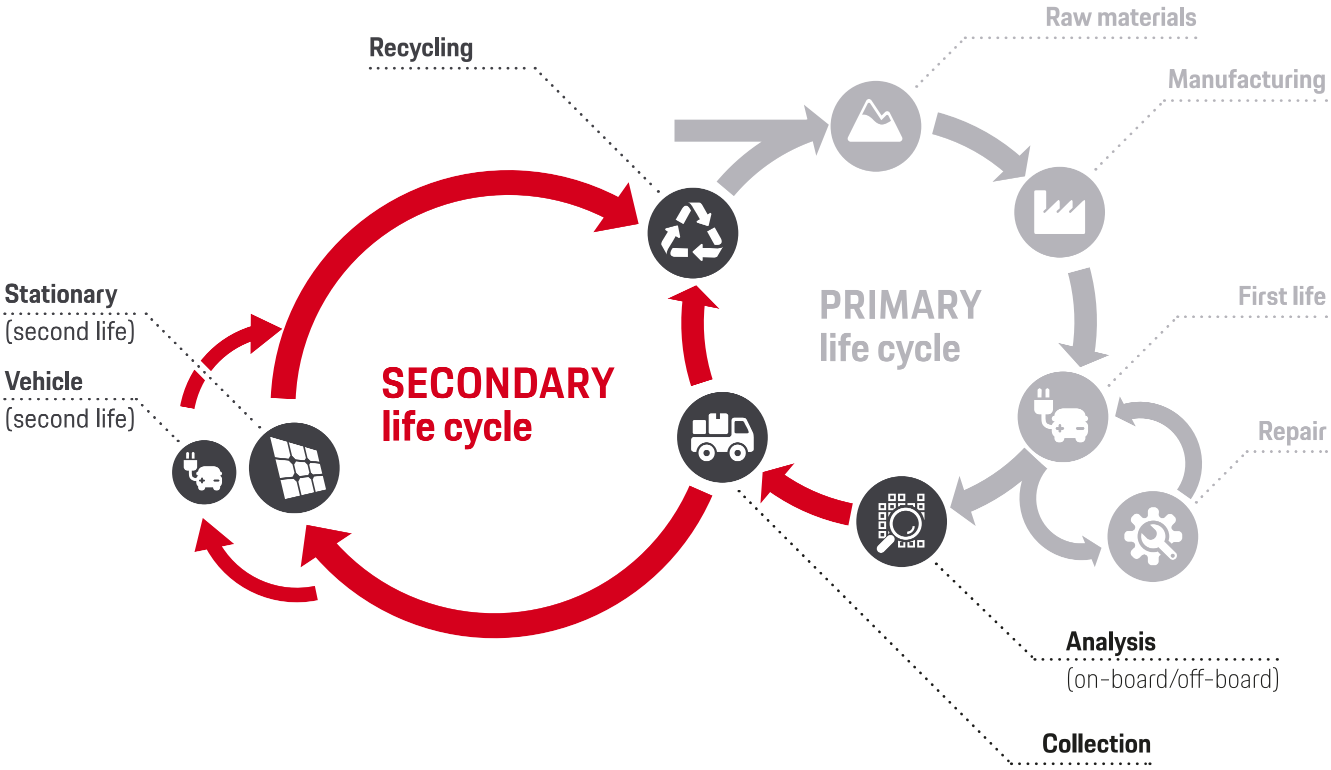

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Figure 1. The stages of the battery life cycle

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[4] See https://www.volkswagen.de/de/elektrofahrzeuge/elektromobilitaet-erleben/elektroauto-technologie/zweites-leben-fuer-gebrauchte-akkus.html
[5] See https://www.volkswagenag.com/en/news/stories/2021/01/from-old-to-new-battery-recycling-in-salzgitter.html

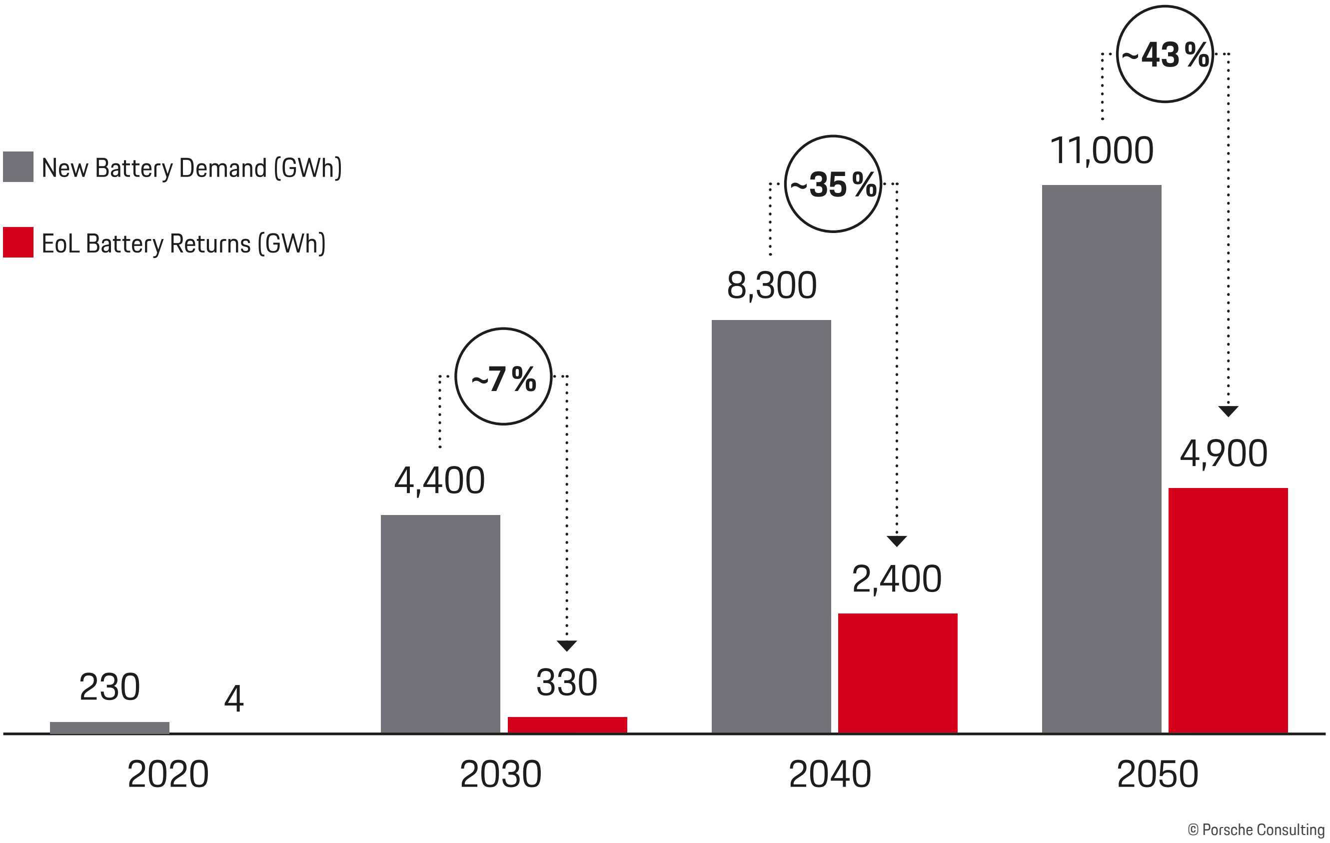

Figure 2. Global annual automotive battery sales and returns (in GWh) [progressive scenario]

For an assessment of the processes downstream of the life cycle, an evaluation of the installed base of automotive Li-ion batteries is necessary. Global annual demand of automotive battery capacity is forecasted to progressively increase, and will reach up to 4,400 GWh in 2030, 8,300 GWh in 2040, and more than 11,000 GWh by 2050[6], as illustrated in Figure 2. This ramp-up has been accelerated by recent political initiatives such as the EU Green Deal[7] in Europe and the EV strategy implemented by the Biden administration in the USA[8].

Based on empirical data and forecasts, the global volume of automotive batteries reaching the end of their first life can be projected by a mathematical model with 15 years' average vehicle lifetime. Technical failures and losses from accidents contribute to a small amount of the overall number of EoL batteries, but most importantly, the end of the working life of the vehicle determines the end of the first life of the battery. The same assumptions are applied for all cell chemistries.

While today's amount of EoL batteries is almost negligible, significant volumes of returned automotive batteries can be expected in the mid-term future. End-of-life batteries could sum up to 330 GWh in 2030, 2,400 GWh in 2040 and 4,900 GWh in 2050[9] (see Figure 2).

Taking these return volumes into consideration, it becomes clear that in the foreseeable future, recycled material can only supply a part of raw material demand and will not be sufficient to cover all material needs given the aggressive ramp-up of the EV market, so new raw materials will have to be added in the foreseeable future to cover the rising demand. The trend, however, is clear: while in 2030, EoL battery capacity would only be sufficient to supply 7 percent of new automotive battery demand, the amount of EoL battery capacity will equal 43 percent of new demand in 2050, which would be beneficial for sustainability reasons as well for supporting raw material supply.

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[6] Source: Porsche Consulting
[7] See https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en
[8] See https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-biden-administration-advances-electric-vehicle-charging-infrastructure/
[9] Source: Porsche Consulting

Current challenges in the later stages of the battery life cycle are primarily concerning the establishment of adequate infrastructure and processes to collect, reuse, and recycle EoL batteries. Especially the industrialized parts of the world, which are considered the early adopters of e-mobility, have partly put regulations in place to ensure a proper disposal of EoL batteries (e.g., Europe[10], China[11]). In these regions, batteries from used vehicles can—but do not have to—be given back to the original equipment manufacturers (OEMs) free of charge. The OEM in that case will be responsible for analysis, temporary storage, and preparation as well as packaging and logistics for final exploitation into either second life or recycling. In the presence of such legislation, OEMs will also have to cover the costs of these proceedings.

A crucial factor and at the same time a source of uncertainty is the remainder of vehicles that leave the circular economy. Despite legislation, outflow will inevitably occur due to hoarding, improper disposal, or export to developing countries where collection, repurposing, and recycling processes are expected to lag behind industrialized countries. Historical data from Germany shows that export rates of end-of-life vehicles (ELVs) to developing countries are approximately 10 percent[12]. Additionally, for up to 19 percent[12] of ELVs, the whereabouts are not statistically recorded. It has to be noted that historical data mainly refers to combustion engine ELVs and that export rates of fully electric ELVs can be expected to be lower due to insufficient charging infrastructure in developing countries, at least in the next years. Even for batteries that remain inside the circular economy, the pivotal questions will be whether an EoL battery should be used in a potential second life or recycled directly and how the best possible path can be chosen.

In the following chapters, current challenges and limitations as well as recommendations will be elaborated in the form of three key takeaways for the secondary life cycle of batteries, starting with the application of predictive battery analytics as standard procedure. Subsequently, the feasibility of second-life applications for used batteries as well as the economic attractiveness of battery recycling through the support of raw material supply will be discussed.

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[10] See https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32006L0066

[11] See https://www.reuters.com/article/us-china-batteries-recycling-idUKKCN1GA0MG

[12] "Jahresbericht über die Altfahrzeug-Verwertungsquoten in Deutschland im Jahr 2016" (Umweltbundesamt, 2016)

01

Predictive battery analytics will become a standard procedure in battery life cycle management

Predictive battery analytics will become a standard procedure in battery life cycle management

"In God we trust; all others must bring data"—this quote attributed to William Edwards Deming, the pioneer of statistical process control, summarizes concisely that data measurement and analysis add value in nearly all areas of application. Batteries are no exception to this principle—yet until now, the use of battery data has hardly exhausted its potential and few data-based methods are implemented to assess the true value of a battery and the time remaining until its final end of life.

Analytics of batteries and transparency regarding their true degradation will be the essential enabler to allocate them to either a second life or a direct path toward recycling.

Thereby, the relevant measure that describes the effect of the battery degradation is the state of health (SoH). Often the SoH is referred to as the ratio between current capacity vs. initially specified capacity. However, it is in fact a generic figure that can be based on the measurement of various technical battery parameters, such as impedance or internal resistance, which can all be held as liable for the SoH determination[13]. So far, these technical parameters are obtained with specific testing devices that usually require the battery to be present at a workshop—either still within the car or in demounted state, which is time-consuming and requires mostly manual labor. Current SoH determination procedures are complex and still have limitations regarding their confidence level. Additionally, the SoH does not allow for exact conclusions about the battery's true health and without further details, a profound analysis of the battery life expectancy is not possible.

More sophisticated concepts for the analysis of the battery rely on enhanced sensor technology and more extensive connectivity as well as machine learning. In such state-of-the art battery analytics concepts, reference batteries are cycled and tested in a laboratory to feed an AI-based simulation model that mirrors the real battery—a "digital twin." Operational (real-time) data from real batteries in the field can then be processed and analyzed using the digital twin.

While gathering operational data from vehicles is already being carried out by OEMs (especially in the commercial vehicle sector, extensive use of telematics is common), the collection of real-time battery data of vehicles is mostly unexploited. Amongst other analytical models, the data of each vehicle can be used to check relevant battery parameters against predefined warning levels, to detect abnormal behaviors within the vehicle fleet, or to compare the actual battery state with digital laboratory models. Besides the detection of abnormal behaviors and quality issues, the historical battery data also allows to determine a battery-specific SoH and to predict the feasibility for a second life after EoL. The entire process is depicted in Figure 3.

It can be expected that the use of battery data from the fleet will drastically increase. In fact, country legislations might even require OEMs to incorporate part of such capabilities in their vehicles. China, for example, already enforces real-time monitoring (RTM) of battery data by law, which can serve as a basis for further analytics. Country-specific legislation such as data privacy acts will lead to regionally different boundaries for the utilization of (real-time) data.

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[13] Noura et al.: "A Review of Battery State of Health Estimation Methods: Hybrid Electric Vehicle Challenges", (World Electric Vehicle Journal, 2020)

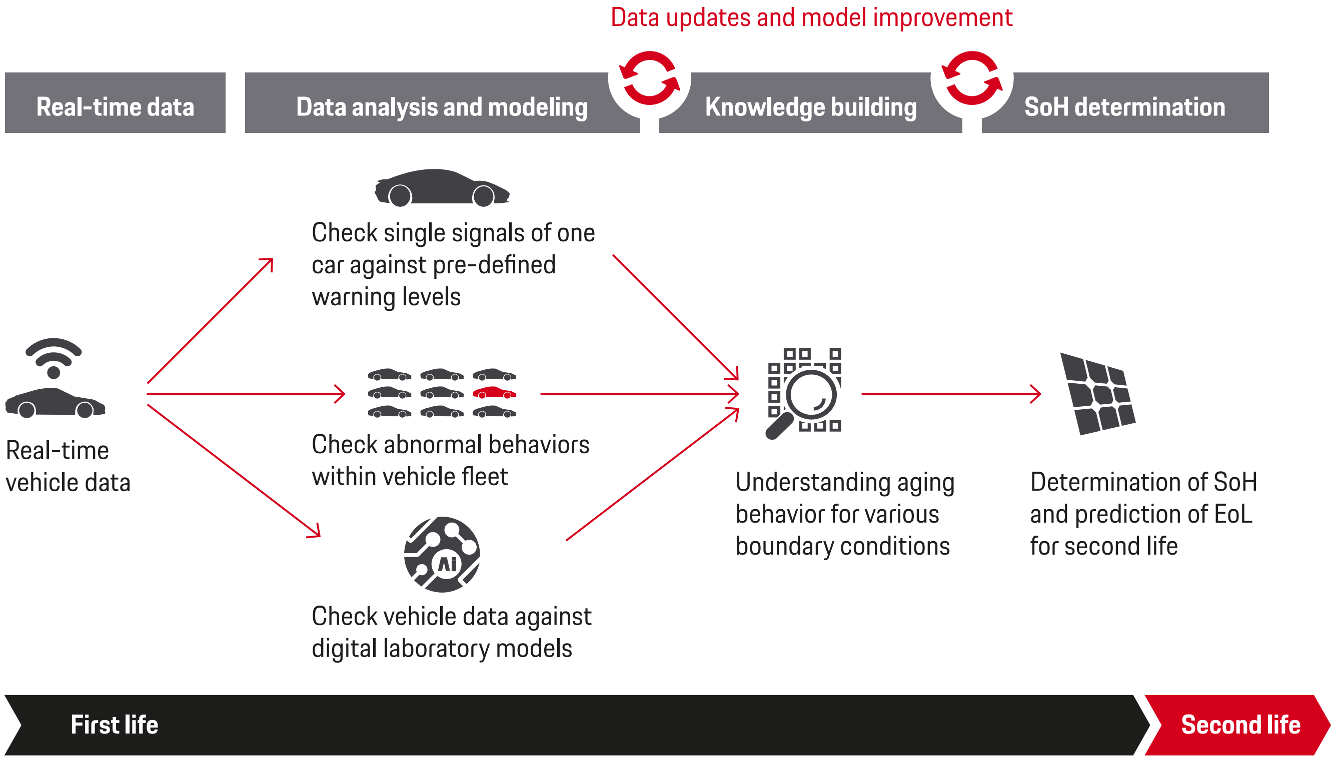

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Figure 3. Real-time vehicle data can be used to analyze battery SoH for second-life use

Specialized companies already created business models around the analytics of automotive batteries. One of them is the German start-up TWAICE[14].

// Dr. Stephan Rohr
Co-Founder and Managing Director
TWAICE

> »"A holistic management of batteries leveraging field data will be a crucial factor for OEMs to be successful in e-mobility."

All in all, predictive battery analytics is not only a cost efficiency tool to reduce manual labor for analysis at dealerships and workshops, but other monetization models from the use of real-time battery data will also arise, like extended warranties or certificates for used EVs based on actual treatment data. Especially in the later stage of the first-life usage, the determination of the SoH and the prediction of the EoL based on data is a key technology to determine the fate of the battery in its remaining life cycle, as only batteries with a relatively high SoH at the end of their first life can be expected to be applicable for a second-life utilization.

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[14] See www.twaice.com

02

Only a certain proportion of used batteries will be feasible for second-life applications

Only a certain proportion of used batteries will be feasible for second-life applications

After the first life of the battery in the vehicle, its overall life span might not be entirely over, but there is still potential for a re-utilization in second-life applications, depending on degradation. By general convention, the end of life of automotive batteries is considered to be reached if their SoH has passed below 70–80 percent of the initially rated value[15]. In addition, optical, functional, or thermal saliences might lead to a declaration as a critical battery. These are defective or damaged batteries (e.g., from crashed vehicles), which contain the risk of fire or thermal runaway. Critical batteries are subjected to higher requirements in terms of handling, packaging, and transport and cannot be devoted to second-life applications but must be recycled straightaway.

The main use case for a re-utilization of EoL automotive batteries can be found in stationary energy storage systems (ESS). With the rise of renewable energies, the demand for such systems for use cases like peak shaving, backup power, or cost-optimized energy supply will grow. This yields significant market potential for both new and used Li-ion batteries. Energy storage systems are available in different sizes and serve manifold use cases, for example as home storage systems with capacities below 50 kWh, buffer storages at high-power charging (HPC) stations with >100kWh capacity, and utility-sized systems in the MWh scale, which are used to regulate primary energy supply to and from the grid—especially for renewable energy sources.

Another use case that should be mentioned in this context is the remanufacturing of used batteries for a reutilization as a spare part, which is an approach that has traditionally been applied for certain components of combustion engines. OEMs are continuously investigating this to see if it can be a viable case for batteries. In such use cases, modules with relatively high SoH could be extracted from EoL battery packs and might serve as spare parts for vehicles in the field either individually or reassembled into whole battery packs. However, such undertakings are currently at an early stage.

From a sustainability point of view, reusing used battery cells is worthwhile, as it extends battery lifetimes while serving the growing ESS market, which otherwise would require new batteries. As new batteries currently still impose a significant environmental footprint during their production, a utilization of second-life batteries can, in combination with ongoing production optimization, certainly cushion these effects. However, when it comes to the feasibility of used batteries for a second life, economic as well as technical boundary conditions need to be considered. Depending on the market development for stationary storage, the ESS capacity demand for lithium-based batteries might be smaller than the volume of available EoL batteries. The ESS demand will be at least 107 GWh p.a. in 2030[16], which would not be sufficient to digest the expected 330 GWh of EoL batteries in 2030 (Figure 2). Should a more aggressive ESS adoption occur (which is not unlikely given the increasing efforts in the transition to renew-

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[15] Saxena at al.: "Quantifying EV battery end-of-life through analysis of travel needs with vehicle powertrain models", (Journal of Power Sources, 2015)
[16] "Country Forecasts for Utility-Scale Energy Storage" (Guidehouse Research, 2017)

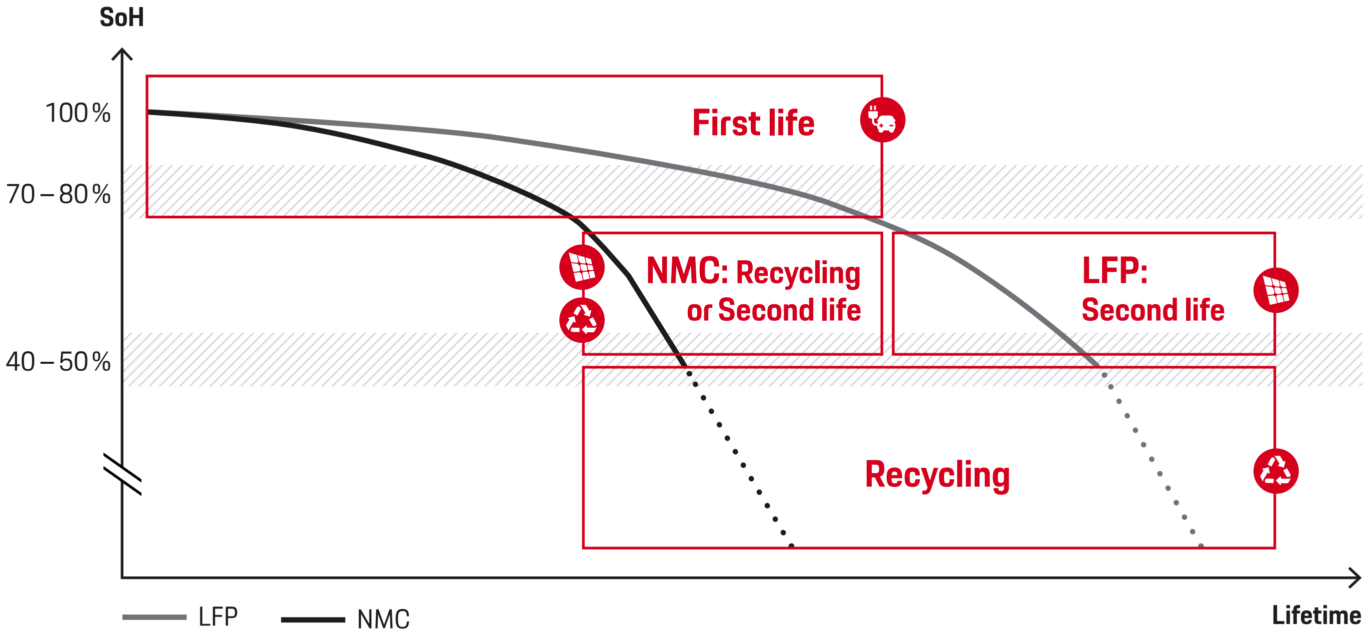

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Figure 4. Utilization phases of different automotive traction battery chemistries (schematic)

able energy), the potential capacity for a second-life battery installment might increase. Nonetheless, only relevant EoL batteries can be brought into the second-life process, i.e., the ones that proved to be technically most qualified. Here, "technically" refers to the SoH on the one hand, and to the cell chemistry on the other hand. For utilization in an ESS, a SoH in the range of 70-80 percent is still sufficient, and used automotive batteries might be deployed for as long as they reach a SoH of 40–50 percent (see Figure 4). Batteries that lack the necessary health and reliability need to be separated consequently and should be brought directly onto a recycling path.

However, it has to be considered that ESS have other requirements than automotive batteries in terms of cycling stability, power density, cooling, shock resistance, and safety and that different cell chemistries match these requirements in different ways. Nickel-manganese-cobalt (NMC) cell chemistries are currently the standard for automotive traction batteries. Apart from changes in the proportions of nickel, manganese, and cobalt (a reduction of cobalt is a current trend—see the next chapter), NMC chemistries will continue to be used in automotive traction batteries—at least for the next 10 years. On the other hand, lithium iron phosphate (LFP) as a cathode material has so far primarily been used for consumer batteries, but is becoming increasingly popular among automotive OEMs. While LFP batteries are currently only used in a minority of EVs, their relative share is expected to increase in coming years.

With regard to technical feasibility, LFP cells generally seem to be more suitable for a second life given their cycle stability and intrinsic safety. NMC cells show a weaker performance in these specifications which limits (but does not exclude) their usability for a second life in ESS (see Figure 4). It seems likely that low-cost cell chemistries (primarily LFP) will be used as much as possible in second-life applications, as they are technically more feasible and lack expensive cell

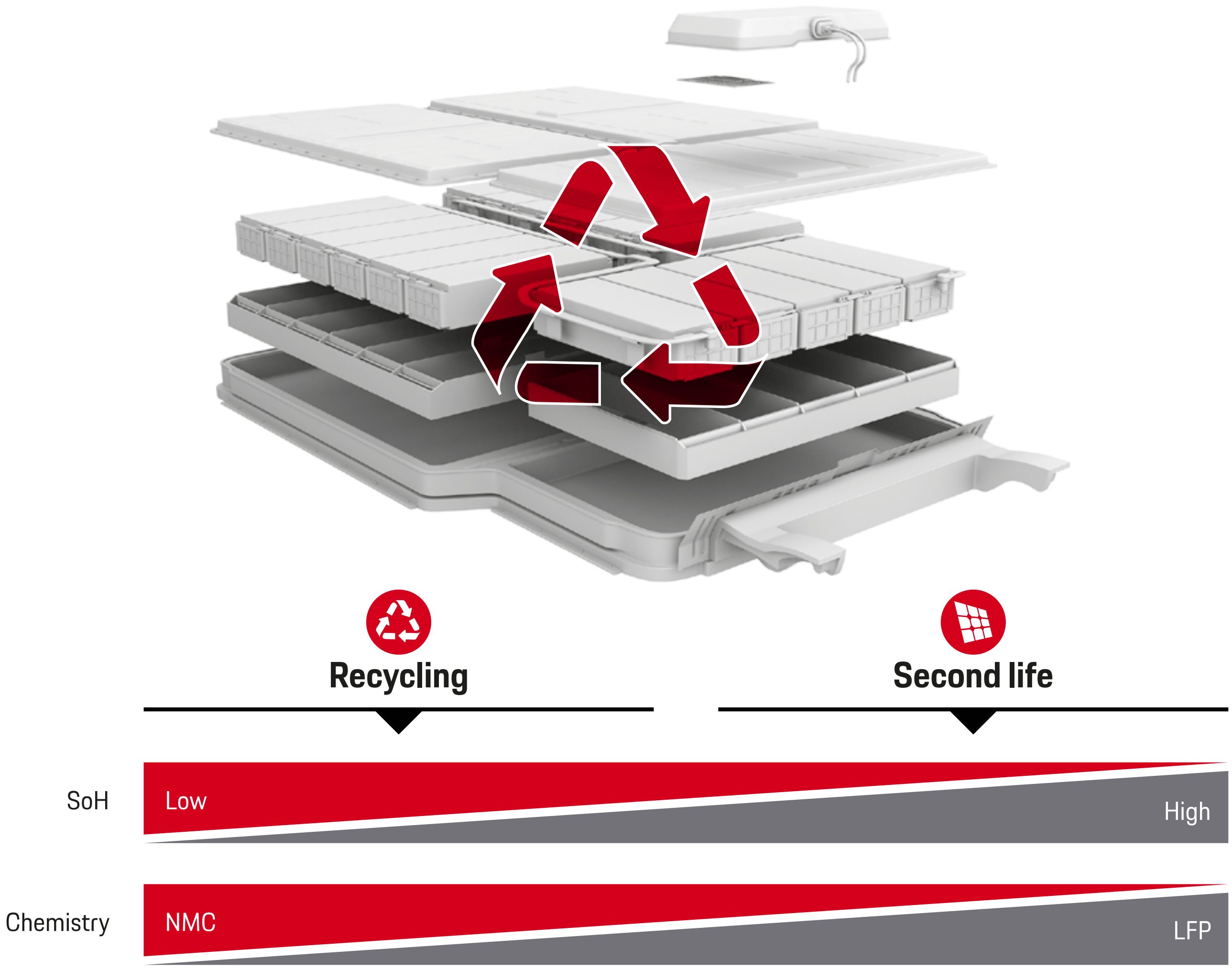

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Figure 5. Assessment of recycling vs. second life based on SoH and chemistry

materials that would make them attractive for recycling. Should the demand for second-life storage capacity exceed the volume of available LFP batteries, a replenishing with chemistries that include more valuable metals (e.g., NMC) can occur potentially.

Summarizing, it is likely that there will be an increased use of second-life batteries in the future, but as a general guideline, their feasibility will be highly dependent on SoH on the one hand and on cell chemistry on the other hand (see Figure 5). Batteries with suitable chemistry and sufficient SoH can be utilized in second-life applications, but in terms of their economic feasibility, additional costs have to be taken into account given the fact that virtually any second-life battery will have to go through repurposing processes (e.g., exchange of faulty modules, disassembly, and/or rearrangement of the packaging, cooling system, electrical, or electronic components). Considering these on-top processes and the rapid price decline of new batteries, it cannot be guaranteed that a repurposed used battery can compete economically with a new battery—this will greatly depend on the individual use case. The economics of a potential discount of used batteries are still mostly unresolved—yet another reason why advanced analytics are crucial.

03

Battery recycling can support raw material supply and is likely to become economically attractive

Battery recycling can support raw material supply and is likely to become economically attractive

Recycling is the decomposition of the battery's components in order to recover its raw materials. The configuration and efficiency of the recycling process are direct enablers for the circular economy of batteries. In this context it is essential to mention that recycling attractiveness is directly related to nickel and cobalt specifically, which each contain about >30 percent revenue potential per battery[17]. Regarding the increasingly popular LFP batteries, it should be noted that their recycling will be economically less attractive due to the absence of valuable metals. Hence, battery chemistries with a high content of nickel and cobalt are focused in the following cost and revenue breakdown of recycling processes—particularly NMC. Other battery types (e.g., solid-state) are currently still in an early stage of development and are not being considered.

NMC111[18] was the standard material mixture for automotive traction batteries until it was substituted in recent years with NMC622[19], which is the current standard that accounts for the vast majority of new automotive traction batteries. Hence, NMC111 is expected to be mainly found in batteries that will return in the next 10 years, while NMC622 will be the dominating cell chemistry of EoL batteries thereafter. Current material research shows increasing nickel content (80–90 percent) as well as decreasing manganese and cobalt content, e.g., NMC 811[20], which is expected to become the standard in the coming decade.

The recycling process itself generally considers dismantling and discharging of battery packs in a first step. Thereafter, the current industry standard is a combination of hydrometallurgy (chemical recovery, e.g. leaching) with pyrometallurgical (thermal recovery, i.e. smelting) or mechanical pre-processes (shredding). A contemporary process chain is depicted in Figure 6. The process itself or the combination of subprocesses varies for different applications and companies. Recycling plants with volumes of >1,000 t/year of recycling capacity have already been successfully proved[21].

At present, lithium from cathodes as well as electrolyte are not recovered in most industrial plants. Besides revenue potential, this could make an important contribution to sustainability and the economic viability of the recycling business. Therefore, an integration of lithium recovery processes is expected to be mandatory for battery recyclers in the future, which is also anticipated by research institutions like the German Institute for Applied Ecology (Öko-Institut e.V.)[22]. It has to be noted that Lithium can only be recovered in a hydrometallurgical process if black powder is used as input mass, i.e. if a mechanical treatment (shredding) is used as pre-process instead of pyrometallurgy (compare Figure 6).

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[17] Brückner et al.: "Industrial Recycling of Lithium-Ion Batteries—A Critical Review of Metallurgical Process Routes," (Metals, 2020)

[18] Nickel, manganese, cobalt in 33%/33%/33% mixture

[19] Nickel, manganese, cobalt in 60%/20%/20% mixture

[20] Nickel, manganese, cobalt in 80%/10%/10% mixture

[21] "Neues Verfahren verwertet Akkus von Elektrofahrzeugen" (VDI—Technik und Wirtschaft, September 18, 2020)

[22] See https://www.oeko.de/en/

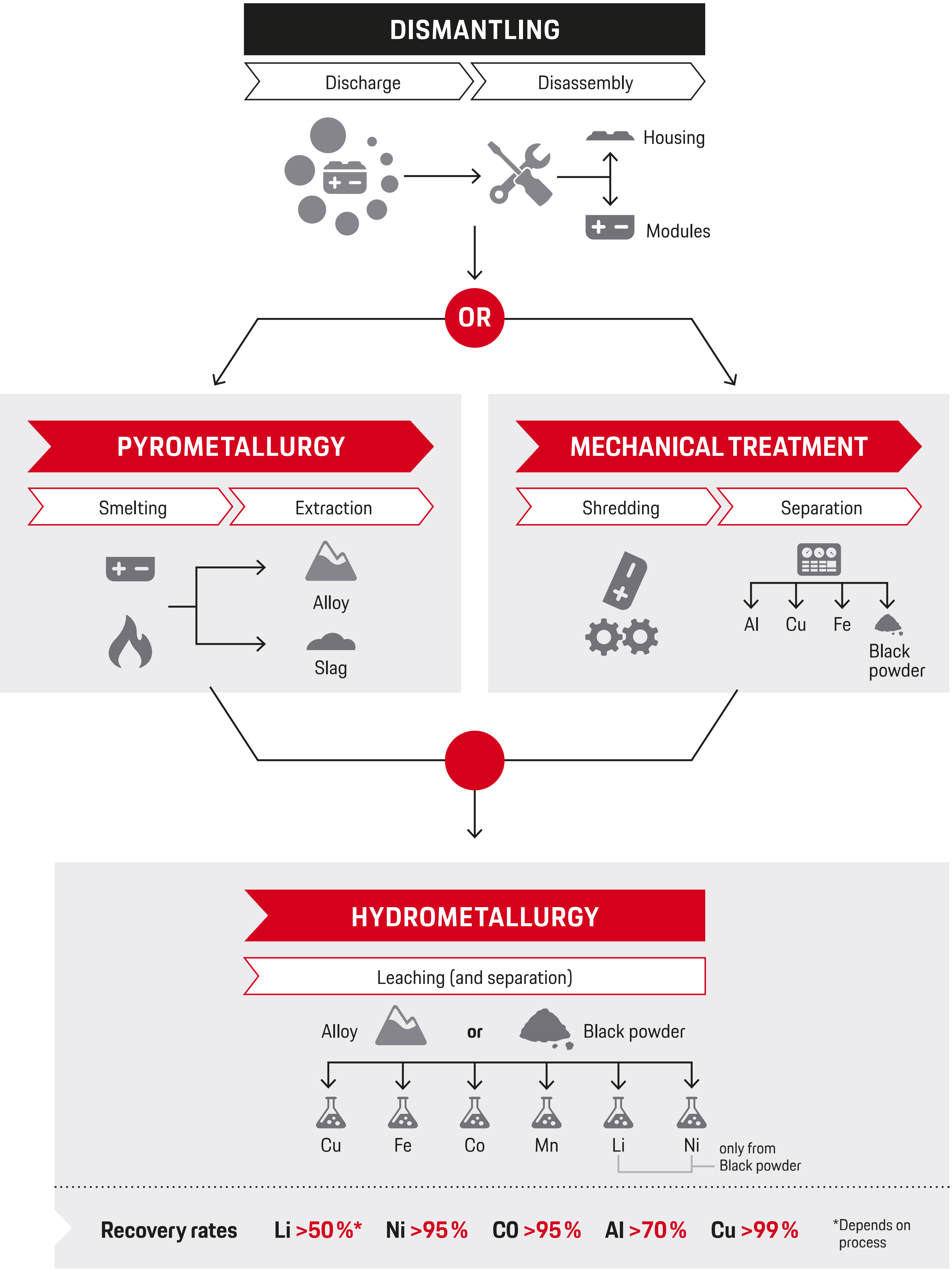

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Figure 6. Overview of contemporary recycling processes

// Dr. Matthias Buchert
Head of Division Resources
and Transport
(Öko-Institut e.V.)

> “Lithium is currently not in the focus of many recycling processes. However, the recovery of lithium will become increasingly important to ensure end-to-end responsibility and gain business success.”

Öko-Institut e.V.
Institut für angewandte Ökologie
Institute for Applied Ecology

Contemporary recycling processes can recover battery materials with high recovery rates (see Figure 6; electrolyte is not considered). However, even with highly efficient recycling processes, a circular economy also depends on the collection rate of used products. Looking at the entire global Li-ion battery market (i.e., also from non-automotive use cases such as power tools or electronics), only about 50 percent of end-of-life batteries currently find their way to recyclers[23]. Significant attention also needs to be addressed to sustainable life cycles. Recent EU legislative proposals[24] reveal collection targets of 65–75 percent and impose targets for the minimum proportion of recycled material in new battery cells[25]. In terms of recycling efficiency (as a ratio between the obtained output mass of material and the initial waste mass), the EU estimates that 65–70 percent of a lithium-based battery can be recycled (with material-dependent efficiencies up to >90 percent)[24]. Such a regulatory framework would expedite recycling activities and could potentially increase volumes and economies of scale. While today's recycling plants are predominantly underutilized, an increase in load factors will occur in the upcoming years. This will also have a crucial impact on these plants' operational costs, which are expected to decline drastically.

At the same time, battery recycling is strongly related to external factors in the industry. The economic feasibility of recycling is highly dependent on battery raw materials. Availability and market price development of raw materials will be crucial input parameters in the business case of battery recycling. For an assessment of the economic feasibility, revenue from recycled materials has to be compared to the operational costs of the recycling plant as well as costs for handling, packaging, and transport. Handling costs have a low contribution to the overall case but are expected to remain steady due to the involved manual labor. Packaging and logistics costs are expected to steadily decline and will have a significant cost impact to the overall business profitability. Hence, cost reduction potential is available through economies of scale.

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[23] “The lithium-ion battery end-of-life market – A baseline study” (Circular Energy Storage, 2018)

[24] See https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0798

[25] See https://ec.europa.eu/commission/presscorner/detail/en/qanda_20_2311

Apart from economies of scale on the cost side, raw material revenues are the main contributor to leverage economic viability. Raw material prices for batteries have historically been subjected to a large volatility and a raw material scarcity could occur depending on the electrification strategies of OEMs and the subsequent demand. Such material scarcity will inevitably derive an increase of raw material prices.

Furthermore, it has to be considered that the economics of carbon pricing can contribute positively to the overall economic feasibility of recycling. Battery production is currently CO_2-intensive and battery recycling is one, besides other levers (e.g., process innovations along the whole value chain) to save CO_2 emissions. CO_2 savings due to recycling are highly dependent on the recycling processes used. While pyrometallurgical processes cause higher CO_2 emissions due to larger energy demand, purely hydrometallurgical processes have higher CO_2 savings potential. On average, CO_2 savings of 20 kg CO_2 eq per kWh of recycled battery can be assumed, taking both, pyro- & hydrometallurgy into account[26]. As governments around the world impose prices for the emission of CO_2 and other greenhouse gases (GHG), a reduction in the mining and refining process of battery materials will ultimately result in a financial benefit. At one of the major CO_2 pricing spot markets, the European Emission Trading System (EU ETS)[27], which is based on a cap-and-trade structure, the CO_2 price has gradually increased and was between 30 and 55 €/t CO_2eq in 2021[28]. Research institutions and NGOs demand higher CO_2 prices with a wide range from €50/t CO_2eq (in 2020)[29] up to €180/t CO_2eq (in 2030)[30].

Due to the uncertain development of both raw materials and CO_2 pricing, two scenarios have been calculated for the economic attractiveness of battery recycling, as illustrated in Figure 7. Both scenarios consider the transition from NMC111 to NMC622 to NMC811.

[26] Aichberger et al.: "Environmental Life Cycle Impacts of Automotive Batteries Based on a Literature Review", (Energies, 2020)

[27] See https://ec.europa.eu/clima/policies/ets_en

[28] See https://icapcarbonaction.com/en/ets-prices

[29] "Klimaschutz auf Kurs bringen—Wie eine CO_2-Bepreisung sozial ausgewogen wirkt," (Agora Verkehrswende & Agora Energiewende, 2019)

[30] "Politikberatung kompakt: Für eine sozialverträgliche CO_2-Bepreisung," (Deutsches Institut für Wirtschaftsforschung, 2019)

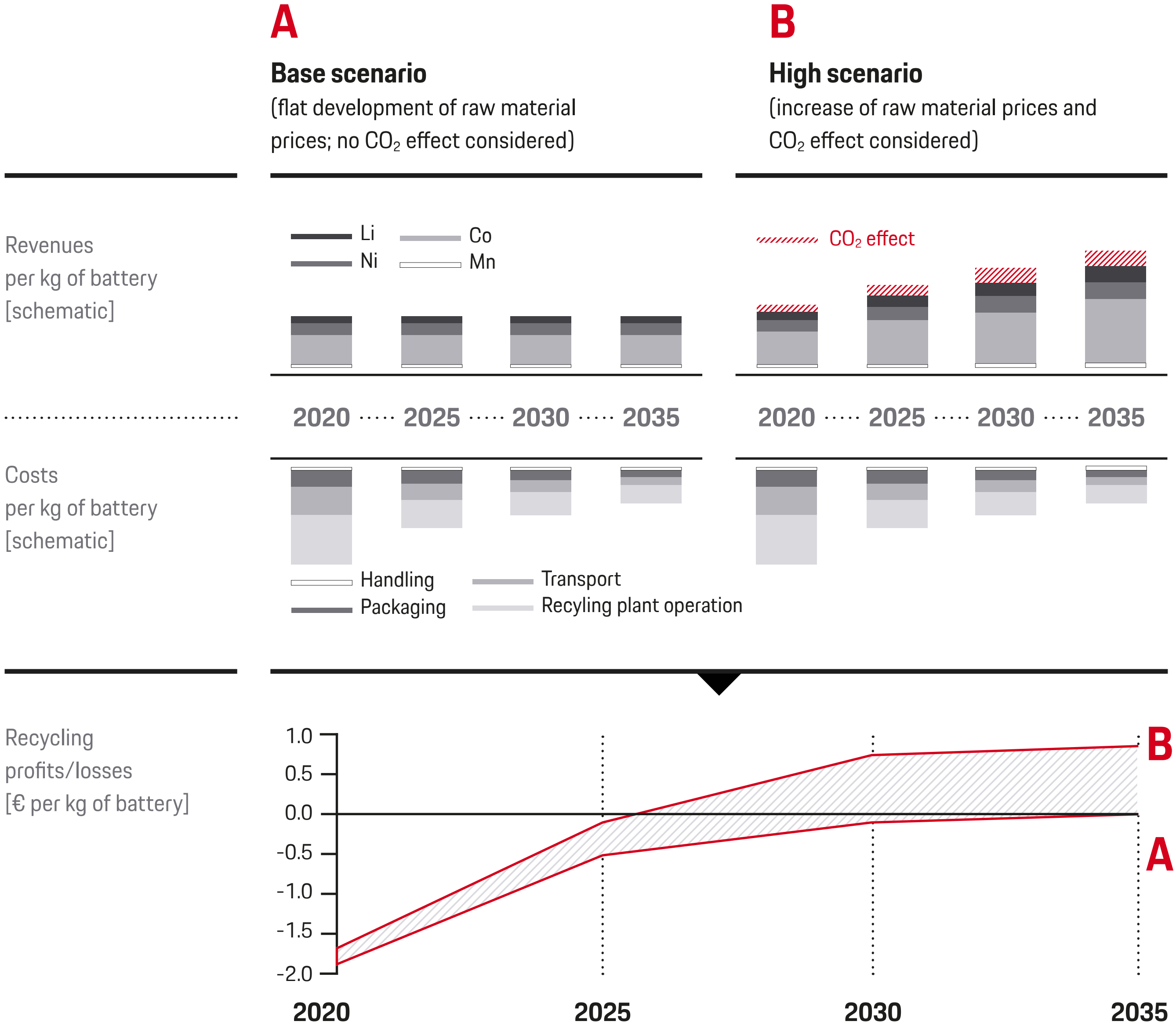

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Figure 7. Cost and revenue structure of the entire recycling value chain

In the moderate scenario (scenario A), raw material prices are assumed to develop steadily and no CO_2 effect has been considered. In this case, the profitability of battery recycling will only be boosted by scale effects on the cost side—in terms of transport, packaging, and plant operations—given the increasing volume of EoL batteries.

In the high scenario (scenario B), a commonly discussed increase of raw material prices is assumed due to a possible resource scarcity, which could be the consequence of accelerated electrification strategies of OEMs. In this scenario, the market prices for recycled materials will rise as well.

Additionally, savings of 20 kg CO_2 eq per kWh or 3 kg CO_2 eq per kg of battery[31] (industry average, including pyro- and hydrometallurgical processes) as well as CO_2 prices of €50 (2020), €100 (2025), and €150 (2030+) per ton of CO_2eq have been applied. Both effects will impose further economic benefit together with the cost savings from scenario A.

As of now, recycling (considered over the entire value chain including handling, packaging, and transport) is not profitable, given current cost levels as well as raw material and CO_2 prices. Cost savings alone might hardly be able to turn it into a positive business case, as shown by scenario A. An increase in raw material prices combined with economic effects from avoided CO_2 emissions are required for profitability, as demonstrated in scenario B, which will see a break-even between 2025 and 2030. Still, profitability in both scenarios suffers from the transition in cell chemistry, as valuable materials—particularly cobalt—are currently being reduced in the cells.

Economic viability of could further be boosted by the aforementioned legislations which require to incorporate a minimum proportion of recycled material in new battery cells. In such a case, a strong demand for recycled material could lead to an even sharper increase of recycling revenue and prices of recycled material could potentially even surpass new material prices. Although this is not predictable at the moment, such extraordinary effects have to be kept in mind.

For OEMs, stepping into the recycling market might be a worthwhile approach to participate in a potentially profitable business as well as to support raw material supply. Still, the main obstacle for OEMs is the lack of ownership of the batteries. Except for manufacturer-operated fleets (e.g., prototypes, car sharing vehicles, etc.), OEMs do not own the batteries. Other than through battery rentals (practiced by only a few OEMs), buybacks are the only real concept of regaining ownership of batteries. While there might be feasible solutions for used vehicles and batteries occurring at OEM dealerships, buyback and collection from non-OEM locations such as dismantlers or independent used-vehicle dealers will be a major hurdle.

In the past, third-party controlled collection systems emerged for valuable or consumable vehicle components (e.g., lead acid batteries and catalytic converters) as the scrap supply grew. Dedicated companies have specialized in these high-value components and have been able to form profitable business models around their collection. Also for batteries, the establishment of a third-party aftermarket is not an unlikely scenario. It can be expected that players in the existing value creation chain (e.g., raw material producers, cell manufacturers, recyclers, and waste management companies) will expand their fields of activity to get hold of the batteries at the neuralgic point at the end of the first life. Should OEMs be willing to step into the recycling market, they will need to develop new concepts to regain ownership of EoL batteries.

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[31] Assuming an energy density of 150 Wh per kg

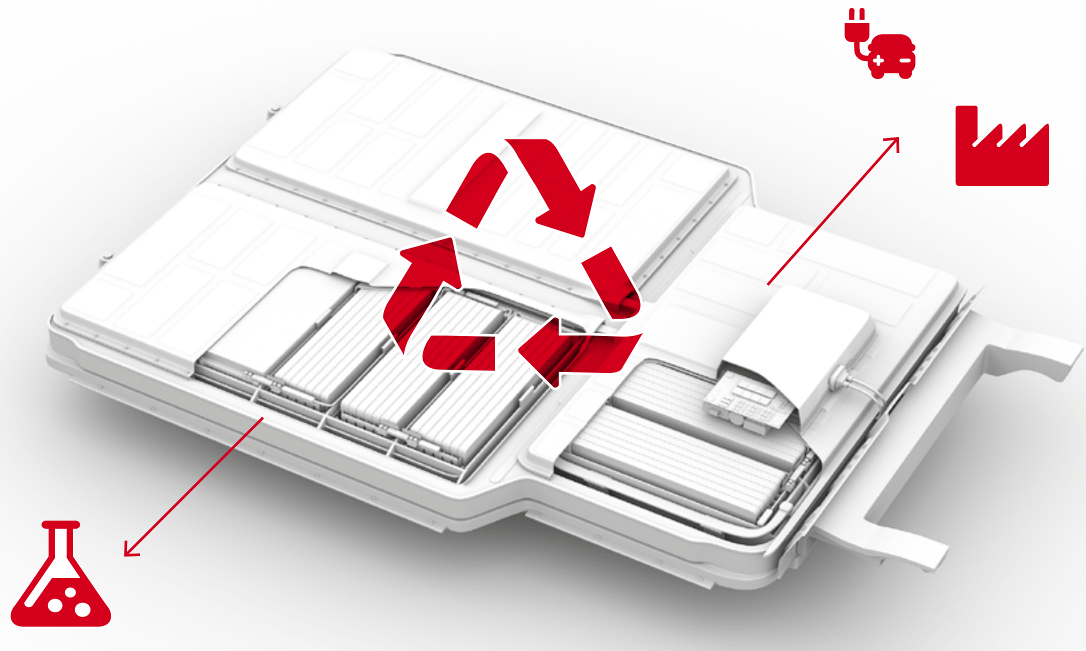
Conclusions

EoL batteries can either be recycled directly or reused in second-life applications—such as stationary storage systems or potentially as remanufactured spare parts.

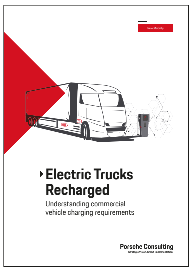
Regarding a second life, technical and economic hurdles will have to be considered. Not only is the energy storage market—the main use case for second-life batteries—potentially too small to digest all EoL automotive batteries, but moreover, compromises regarding technical feasibility need to be taken into account. This is especially true of NMC cells—which leads to the conclusion that primarily LFP cells will be used in second-life systems. All in all, a second life can be encouraged by sustainability targets and will be a worthwhile approach under certain conditions. Thereby, predictive battery analytics are a crucial enabler for secondary battery life cycles, and new business models will evolve based on the analysis of real-time data during first-life battery usage. Yet, for the individual use case, cell chemistry, SoH, and economic boundary conditions will have to be considered.

Independently of whether batteries serve in a second life or not, at the very end of the life cycle, a majority of them will be recycled. Thereby, regulatory frameworks can support with measures such as collection targets, obligatory proportions for recycled materials in new cells as well as target recycling efficiencies. Recycling processes can recover raw materials with high recovery rates, yet it is currently challenging to cover the preceding costs (handling, packaging, transport, and the operation of the recycling plant) with the revenues from raw material sales. An increase in Eol battery volumes will lead to scale effects on the cost side. On the revenue side, CO_2 savings can play a substantial role for future profitability. The other lever is the raw material pricing. If raw material scarcity and a subsequent increase in prices are to be expected, the profitability of the recycling business will be boosted.

The key success factors for OEMs are to anticipate raw material demand, develop concepts to regain ownership, and to strategically position themselves in the market. Vertical integration (either by partnering or by integrating their own recycling business) will be a worthwhile approach for OEMs, not just in order to take a share of the market but also to hedge against raw material scarcities.



Further reading



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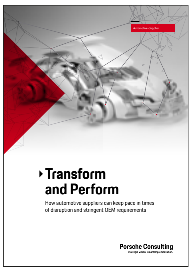

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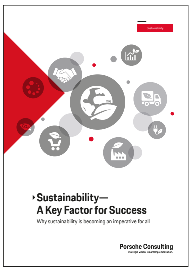

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Authors

Eike
Gernant
Partner

Frank
Seuster
Partner

Dr. Fabian
Duffner
Senior Manager

Martin
Jambor
Manager

Co-Authors

Dr. Michael König
Lukas Mauler

Contact
☎ + 49 170 911 4356
✉ eike.gernant@porsche-consulting.com

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List of abbreviations

BEV	battery electric vehicle
CO_2eq	CO_2 equivalent
ELV	end-of-life vehicle
EoL battery	end-of-life battery
ESS	energy storage system
EU ETS	European Emission Trading System
EV	electric vehicle (umbrella term for BEVs and PHEVs)
GHG	greenhouse gases
HPC	high-power charging
ICE	internal combustion engine
LFP	lithium iron phosphate
Li-ion	lithium-ion
NMC	nickel manganese cobalt
OEM	original equipment manufacturer (term for carmaker in this context)
(P)HEV	(plug-in) hybrid electric vehicle
RTM	real-time monitoring
SoC	state of charge
SoH	state of health

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