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Perspective

Challenges of second-life concepts for retired electric vehicle batteries

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SUMMARY

Identifying the optimal way to process retired batteries has gained attention from academics and industry. High energy and power density requirements of electric vehicles (EVs) might cause batteries to be retired together with the vehicle that could still be used in other applications. Therefore, transferring batteries into "second-life" applications has the potential to optimize costs and resource utilization. The scope of this work is to give a perspective on challenges that hinder second-life business models. First, the battery life cycle is considered, showing potential costly phases that are necessary for second life applications. After this, requirements of typically discussed second-life applications and battery availability challenges are analyzed. Advanced battery diagnostics are necessary, and missing open standards for the exchange of design and status information are described. Exploiting the potential of a second life requires addressing challenges during the development process. Therefore, the last section describes challenges of developing multi-life battery systems.

INTRODUCTION

In the last years, electric vehicles (EVs) have gained significant market shares in many countries.[1] With rising production volumes of EVs, questions on how to handle large amounts of retired vehicle batteries have gained a lot of attention in research publications.[2–5] With the fast rise of battery utilization in the energy and mobility sector, material shortages and rising material prices are likely to be seen within the next decade, before mining and raw material processing can sufficiently be ramped up.[6,7] Recycling concepts for lithium-ion batteries have been developed and are now ready for large-scale industrial implementation, but they cannot recover all critical materials.[8–11] To further decrease the costs of EV ownership and improve the ecological advantage of EVs, making sure that the batteries can be utilized to their full lifetime capabilities becomes increasingly important. To address this, much research is performed in the field of battery aging mitigation and lifetime expansion on the system and material level.[12–14] Furthermore, second-life applications for retired vehicle batteries are being discussed and tested in pilot projects and are the focus of this work. Zhu et al. provide a comprehensive overview of industrial projects for second-life battery applications.[15] Stationary storage systems are the dominant application described as use cases for retired vehicle batteries.[16–19]

Looking at outlooks regarding the growth of the stationary battery and EV markets and installed capacities, battery capacities in mobile applications will be an order of magnitude higher compared with the stationary storage sector. The International

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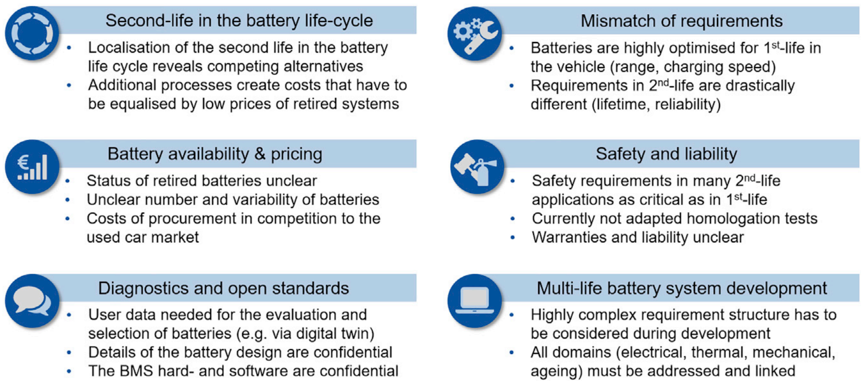

Figure 1. Categories of challenges
An overview of the six categories of challenges of second-life concepts for retired electric vehicle batteries that are described in this work.

Energy Agency (IEA) estimates that battery EV sales will be approximately 47 million per year in 2030 if the climate goals of the Paris Agreement are reached.[20,21] Bloomberg estimates global sales of EVs to be 26 million in 2030.[22] Using the current average battery capacity of approximately 50 kWh per vehicle as a conservative estimate, this would mean that for the battery EV sector alone, 1,300 to 2,340 GWh battery capacity will go into operation each year.[23–25] In contrast, the IEA expects a stationary battery storage demand in 2030 of approximately 180 GWh per year.[26] The International Renewable Energy Agency estimates that the total installed capacity of stationary batteries in 2030 will be 421 GWh.[27]

On the one hand, these numbers show the immense role retired vehicle batteries could play in the stationary storage system market when retired batteries can be successfully introduced into the market, while on the other hand, it shows that second life in a stationary system will not be the standard pathway for a majority of retired batteries. For manufacturers of second-life battery systems to be competitive in the stationary storage market, challenges that go along with using retired vehicle batteries must be understood, and selecting the most promising batteries out of the large pool of retired vehicle batteries in a fast and reliable way will be a deciding factor.

This perspective discusses challenges that have to be addressed before the second use of retired vehicle batteries can become an economically viable option for stationary storage manufacturers. The first part of the paper defines the battery life cycle and describes processes that need to be added to the life cycle to enable the use of the batteries in second-life applications. The main part of this work focuses on challenges deriving from the requirements of potential second-life applications and retired battery availability and health, as well as battery diagnostics and lifetime prediction uncertainties. Here, the emphasis lies in helping future manufacturers of second-life storage systems choose the right approach regarding use case identification, battery sourcing, and diagnostics. Figure 1 shows the general outline of the challenges discussed in this perspective.

During the description of the challenges, it will become evident at certain points that an integrated development and coordination between vehicle and second-life system manufacturers is beneficial. Addressing a possible second life already in the development process of the vehicle battery can greatly improve the practicability of the transfer process between first and second life.

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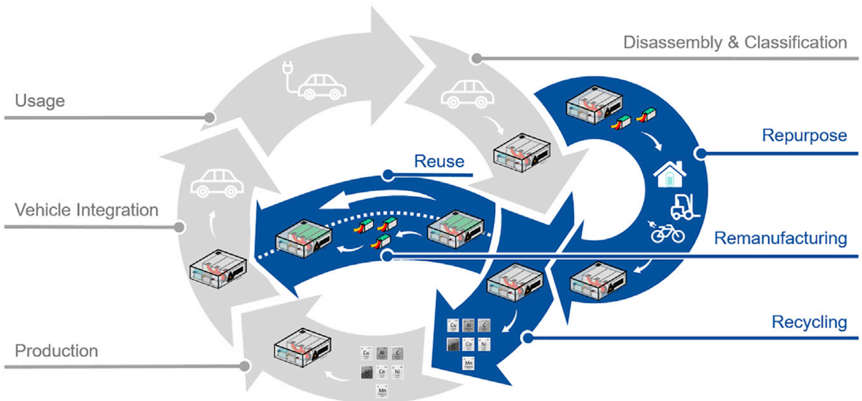

Figure 2. The battery life cycle

The life cycle of battery systems with the four additional pathways that are necessary for an efficient circular economy approach based on Hu et al.[5]

BATTERY LIFE CYCLE

In general, the product life cycle describes the phases of a product from defining product requirements and development to recycling after the end of life.[28] In the engineering of a product, the consideration of the whole life cycle is key to achieving sustainable and cost-effective products.[29] For many usages, adapted descriptions of the product life cycle exist. Figure 2 illustrates the product life cycle for lithium-ion batteries in EVs based on Kampker et al.[30] The goal of the circular economy is the effective and efficient usage of secondary resources.[31] This circular approach is especially relevant for sustainable production and utilization.

The battery life cycle consists of the main stages of production, development, and vehicle integration as well as usage and down-streamed processes at the end of life. After the defined end of life, disassembly of the vehicle can start the second life. During the classification of the battery systems, the condition of the components, like battery cells, electronics, and housing, is assessed. Influencing factors are all parameters over the product life so far. This starts with potential quality issues in production and covers everything up until the end of the usage time. For usage, especially the actual power profiles with peak power, the temperature conditions, which are mainly influenced by thermal management, and charging habits are of major relevance.[12,32–34] Based on the assessment during classification, four alternate pathways are distinguished.

A battery system that shows a high state of health and good further prospects for degradation might be used in the same application without any modifications. This process can be defined as "reuse."[35] An example of the reuse of a battery system is that the battery of one EV is used as a replacement part for a vehicle of the same model range. "Repurpose" describes the usage of the battery in another application. Vital for a successful repurposing is the suitability of the used battery for the second-life scenario. Thus, the second-life scenario and its requirements have to be well understood and the condition of the battery has to be evaluated before the implementation in the scenario. During the process of repurposing, a limited disassembly and reassembly of the battery are initiated. For example, connectors can be changed to integrate the vehicle battery into a stationary storage system. The aim is to reuse all major assemblies to limit the depth of disassembly and, in consequence, the correlating process costs. Figure 3 shows the labor-intensive process of manual battery disassembly.

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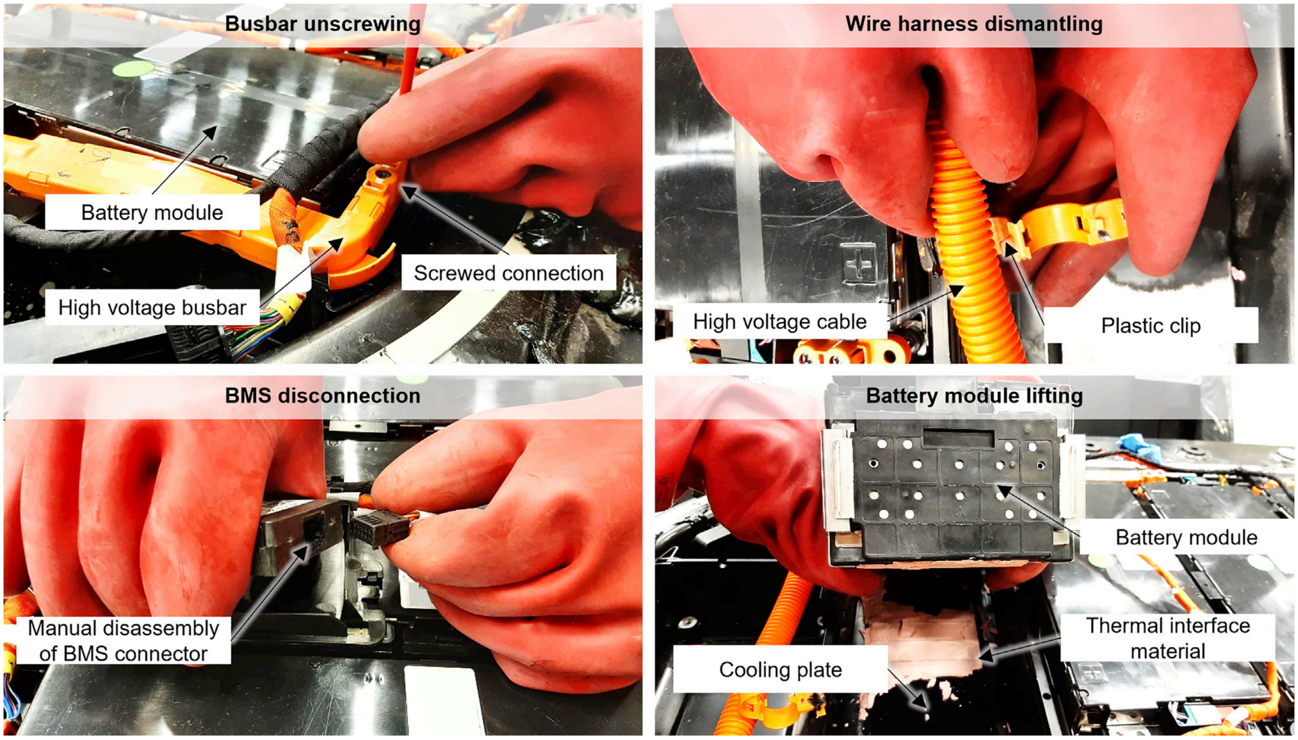

Figure 3. Manual battery pack disassembly
Parts of a battery pack disassembly performed at PEM of RWTH Aachen University are shown, focusing on steps that typically cannot be automated. Almost all steps need to be carried out under high voltage conditions and require a multitude of manual steps like unscrewing connections, disconnecting clips, and unplugging connectors. Thermal interface materials are mostly glued and require high forces for separation.

During the disassembly process, components can be omitted or added to integrate new or changed functions. Repurposing can include activities such as the replacement or repair of core components.[36] In contrast, "remanufacturing" is defined as the combination of reusing and repairing a product while replacing some components with new ones to rebuild a product with original specifications.[37] This leads to resource-saving handling of batteries due to the usage of already produced components and reduced energy consumption during the process.[38] On the other side, there are challenges in the increasing effort to ensure the traceability of the new components installed.[39] "Recycling" of a battery is the process in which the raw materials are reclaimed and used as the starting point for the production of new batteries. There are various methods, such as thermal conditioning, mechanical processing, pyrometallurgical processing, hydrometallurgical processing, and direct recycling.[31] Most recycling processes use a combination of different methods.

A generic description of the currently used process of determining the further pathway for batteries that have reached their end of life in a vehicle is shown in Figure 4. After delivery to the place of further processing, the process of reassignment can start. In the beginning, examination and testing of the battery are necessary. The tests are a key point in the system classification and the later process determination. Challenges during this process step are described in more detail later. Depending on the classification results, the scenario is chosen, following one of the four pathways described earlier. For the highest potential batteries, the remanufacturing scenario can be used. For suitable batteries with lower health indications, the repurpose scenario is typically the way to go. In the case of a less promising lifetime prognosis,

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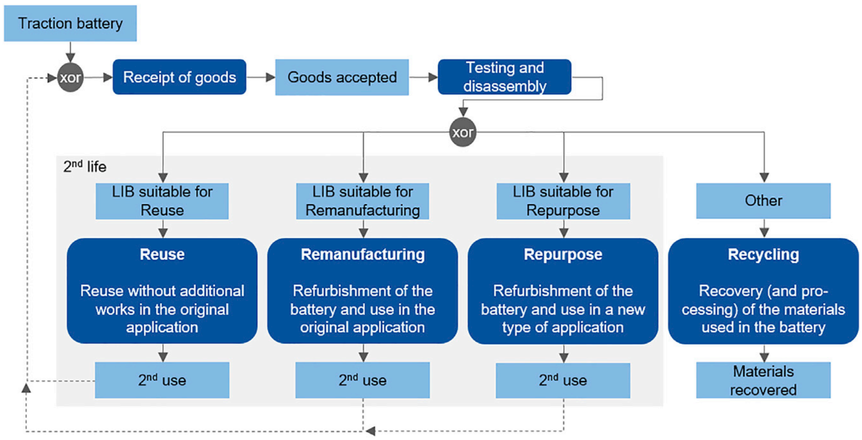

Figure 4. The process of second-life determination

Retired batteries traditionally need to be tested and disassembled to determine whether they are suitable for one of the second-life categories (reuse, remanufacture, repurpose) or must be handed over into a recycling process.

the actual end of life is reached, and no further active use of the battery is possible. Here, the batteries are directly transferred into a recycling process to support circular economy principles and allow a less wasteful production of new batteries.

CHALLENGES FOR SECOND-LIFE BATTERY DEVELOPERS

Critical operating requirements of second-life applications

Stationary applications are the number one use case for retired EV batteries.[15,40–43] The reasoning behind this premise is that requirements for range and, therefore, energy density, as well as power capability during fast charging, are very high in mobile applications. When capacity decreases and internal resistance rises during the service life of the vehicle, the battery will reach a point when it can no longer fulfill its role in a mobile application. Focusing on these aspects alone results in stationary applications being identified as ideal fields for the further use of retired vehicle batteries. The next section describes two typical stationary applications, often discussed as such second-life use cases. Analyzing these applications allows us to identify critical requirements.

Requirements for home storage systems

One of such second-life applications is home storage systems, typically combined with a roof-mounted photovoltaic (PV) system. The purpose of the energy storage in this application is to store the solar energy generated during the day, peaking at mid-day, so it can be consumed in the evening when residents return from work and solar power is no longer available.[44] The purpose of the system is that one cycle is performed per day with high depths of discharge (DODs) on sunny days. The "Scientific Measurement and Evaluation Program, Solar Power Storage 2.0" describes typical systems and their operation in Germany, showing the average number of equivalent full cycles per year is about 250.[45] Research in the field of PV home storage systems tries to increase the lifetime of the systems to gain a competitive cost advantage.[46] Especially in the market of private home storage systems, potential savings must be high enough for the end user to tolerate more regular construction works during system replacement. The reduced energy density of the system results in larger space requirements in the private home compared with new battery systems. Additionally, limited warranties, as further discussed later in this perspective, have a high impact on this market.

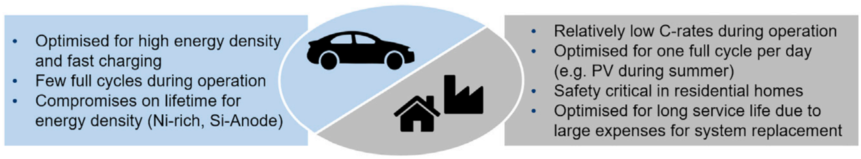

Figure 5. Requirements for EVs and stationary storage systems
Vehicle and stationary applications show drastically different requirements for the energy storage system.

Requirements for industrial load leveling storage systems

A second application, discussed in the context of second-life options, is commercial storage systems to reduce the peak load and demand rate to reduce electricity costs.[47] Depending on the underlying power profile of the company and the amount of flexibility the company needs, systems are usually only oversized to compensate for the aging-related capacity loss to reduce initial investments. Peak load reduction aims at leveling the grid load to reduce the maximum power demand from the grid or to shift heavy loads to times with low electricity prices. Storage times are therefore short with cycles not longer than one workday.[47] Therefore, cycle lifetime is again an essential requirement that developers of storage systems for peak power reduction need to account for in order to reduce the initial oversizing and allow for sufficient service life.

For retired passenger vehicle batteries to be viable in such applications, costs must be drastically lower than those of systems designed with fresh cells. Only then is dramatic oversizing of the system possible, aiming at decreasing the DOD to achieve a competitive service life. Otherwise, costs must be low enough to enable more frequent battery replacement, taking into account costs for the system itself as well as overheads for transportation, construction, and off times.

Mismatch of passenger vehicle requirements

Passenger EV battery sizes are continuously growing, resulting in very low average DODs for daily trips. Batteries in modern EVs are optimized for high range and high power during charging rather than cyclic lifetime. New vehicle battery technologies, such as nickel-rich cathodes or silicon-blend anodes, are therefore focusing on energy density over a cyclic lifetime.[8–10] Bringing retired vehicle batteries into applications with high cyclic lifetime requirements, such as load leveling systems or home storage systems, is problematic given the mismatch in battery optimization targets of the private vehicle and stationary storage system sectors.

The shorter lifetime of retired batteries causes expenses not only based on the direct costs of replacing the system but also caused by installation, transportation, and downtime of the system. Since these costs cannot be reduced using retired batteries, it remains questionable whether a reduction of total costs is achievable. Figure 5 summarizes the conflicting requirements of EVs and stationary systems.

Electric long- and medium-range trucks operate under conditions closer to those of stationary storage systems, namely smaller oversizing compared with the operational requirements and higher utilization. As will be discussed later, retired truck batteries might be more suitable for stationary second-life applications, further reducing the prospects of private EV second-life concepts. Stationary applications with typically low cycle count, such as grid-level operating reserves or emergency power supplies for critical infrastructure, seem more suitable for using retired vehicle batteries than the two cases discussed here, but other factors described in the following sections are equally challenging to overcome.

Safety and reliability requirements, warranties, and product liability

Designing safe and reliable battery systems, even utilizing new cells, is a challenging engineering task. Failures in batteries with large energy contents, present in EVs and most stationary storage systems, can have catastrophic impacts, inflicting large economic damages and, in the worst case, even endangering human life.[48–52]

Looking at the three potential second-life applications presented earlier, it becomes clear that even with lower requirements in terms of energy and power density, safety and reliability requirements are generally not changing. Especially for energy storage systems installed in residential buildings, often in the basement of family homes, battery fires can be life threatening. For stationary applications offering peak load reduction or grid-level operating reserves, typically in the megawatt-hour scale, any critical failure of a cell that cannot be isolated can inflict large economic damages on the system operator.[49] With these risks in mind, manufacturers take great care to design safe and reliable battery systems, and safety tests are a standard process during any development process.[53] Even single catastrophic events can undermine customer trust in a product or product range. A prominent example of this is the Samsung Galaxy Note 7 battery's design error that caused some of their mobile devices to catch fire during charging. The error led to Samsung canceling the sale of the product, and the damage to customer trust led to a reduction in sales of the whole mobile phone branch of 15% in 2016.[54] The recall and lower sales figures meant that operating profits in the mobile division of Samsung went down by 96%.[54] While Samsung's mobile business was able to recover, many young and medium-sized manufacturers of stationary storage systems might not have the resilience to rebuild customer trust.

Manufacturers take great care to design safe and reliable battery systems, and safety tests are a standard process during any development process, following testing regimes specifically tailored to a given application.[53] Testing is performed on representative production samples during homologation.

Managing the potential risks stemming from an unregulated second-life battery market is key to its success. Regulations and testing standards need to be developed and updated.[55] UL 1974 is such a new standard, covering the process of used battery safety and performance evaluation.[56] For the certification of the second-life battery system itself, UL 1974 refers to the same standards that are used for systems built with fresh battery cells and components. Another standard regarding the safety of second-life battery systems is IEC 62933-5-3, but at this time, it is unclear how testing standards could be adapted to cover battery systems built from used battery components and especially how the varying quality of used batteries would affect testing representability.[57]

Additionally, producers offering second-life battery solutions must compete in an open market against competitors using new battery cells and modules. Warranties and service life promises must therefore be comparable or proportional to a reduction in price. Since the original cell manufacturers of the storage system will no longer cover the retired system with warranties and will probably refuse product liability, when the application and/or construction of the battery system is changed, the exposure to safety and reliability problems lies solely on the second-life system

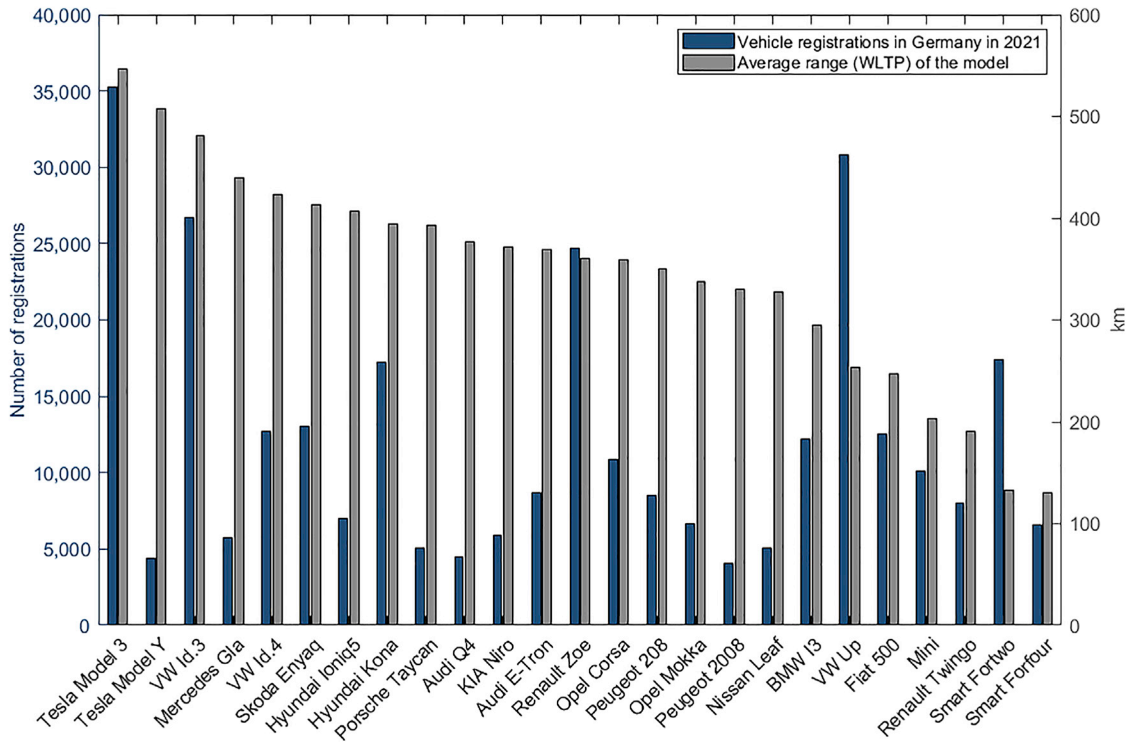

Figure 6. New vehicle registrations

Vehicle registration numbers of the 25 models most sold in Germany in 2021 are shown in descending order of WLTP ranges based on data from EV Database[23] and Kraftfahrt-Bundesamt.[24]

manufacturer. Without clear guidelines from regulatory bodies, it remains questionable whether these legal issues can be resolved.

Battery availability

EV sales are continuously growing. In theory, this will mean that once the vehicles reach their end of life, many batteries will be available for secondary applications. To be able to estimate used battery availability, it is necessary to look deeper into the scenarios in which EVs are retired. Many studies regarding the use of retired vehicle batteries in second-life applications are based on the estimation that the first use ends once the battery's remaining capacity has reached 70%–80% of its initial value or once the internal resistance of the pack has doubled, significantly reducing the power performance during charging.[35,58,59] When EVs first went into series production in the early 2010s, ranges were low, between 100 and 200 km.[60,61] Based on this low initial value, it was fair to assume that once the range lowered to 80%, finding new users for a used vehicle would be a challenging task, and many of those batteries would leave the mobile application. Saxena et al. have suggested alternative end-of-life criteria that are determined by user needs rather than fixed theoretical values.[62] Additionally, the used car market has to be considered.

In the past years, battery sizes have grown significantly. Figure 6 shows the number of new vehicle registrations in Germany in the year 2021 for the 25 best-selling models in descending order of their range. The market seems to favor vehicles with ranges around the median of 360 km, but vehicles with less than 200 km of initial range still have a market share of approximately 9%. The Volkswagen Up was the model with the second most registrations this year, having a range well below

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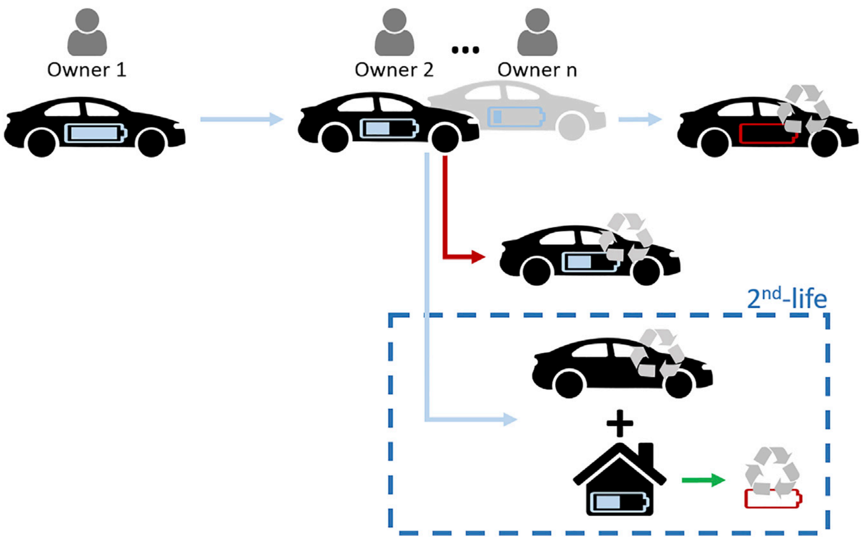

Figure 7. Second-life manufacturers in competition with the used car market

The used car market has a similar capability to increase battery utilization as second-life applications. Second-life system manufacturers have the additional burden to sell or recycle the vehicle without the battery system

80% of the median of vehicles sold. It is therefore evident that users with very different requirements regarding range participate in the car market today.

There is no technical reason why a functioning used car market should not continue to be able to match used cars with lower technical capabilities to users with corresponding needs. Analyzing the drivetrain of the Volkswagen ID.3, Wassiliadis et al. have recently shown how, under realistic usage patterns, the lifetime of modern EV batteries far exceeds the 8-year warranty, guaranteeing 70% remaining capacity.[19] To estimate whether the rest of the vehicle reaches its end of life at a sufficiently earlier time often enough for second-life storage manufacturers to focus on this sector, the lifetimes of the non-drivetrain components have to be considered. The average age of private cars in Germany is around 9–10 years, meaning other vehicle components, such as body, brakes, and interior, are already designed in a way that they do not limit the lifetime of the vehicle prematurely.[63] Since vehicle components other than the battery undergo similarly, or in the case of the braking system even less, wear in an EV, there is no reason for the lifetime of the non-drivetrain to be a limiting factor for the full vehicle lifetime under normal use. This would mean that in many cases, the battery would be able to reach its end of life inside the vehicle it was originally delivered in, traveling through the hand of users with decreasing range requirements and budgets. In many cases, a secondary use in a stationary application is therefore obsolete while at the same time offering a superior option both from an economical and an ecological perspective by enabling the battery to reach its end of life during operation and preventing obsolete vehicles without batteries that need to be scrapped. Figure 7 shows how vehicles will change hands from owner to owner. In the best case, owner n will use the vehicle until the battery has reached its end of life, resulting in the vehicle and battery being recycled simultaneously. The red arrow marks the undesirable case where no new owner for the vehicle can be found, and the vehicle is transferred into recycling with a battery that has not reached its end of life. Here, second-life applications, marked by the yellow box, come into play. As described earlier, the battery is removed from the vehicle and transferred into an application with new requirements, allowing the battery to reach its end of life before recycling. It becomes evident that the second-life system manufacturer operates in competition with the used car market.

Potentials for secondary usage scenarios emerge when the lifetime of the battery and the rest of the vehicle do not sufficiently align. The following section will present a closer look at such scenarios.

Batteries from crashed vehicles

One such situation where the vehicle reaches its end of life before the battery is vehicle crashes that render the vehicle unusable but the battery intact. Especially at young vehicle ages, this scenario offers the chance to obtain a largely unaged battery. The vehicle owner will probably be willing to sell the battery at a low price since, without the vehicle, the battery has no use to the operator, and replacement vehicles will be delivered with a new battery anyway. The significant challenge that a manufacturer of stationary systems faces when trying to use batteries from crashed vehicles is reliably selecting batteries that are safe to use in a secondary application. The diagnosis of such systems needs to be performed individually for each battery and cannot solely rely on sensor data, since the measurement systems went through the crash as well and might be damaged. Consequently, this means that potentially damaged batteries would have to be transported to the manufacturer of the stationary storage system and manually diagnosed. This causes high costs, even for the batteries that are then diagnosed as unusable. Uncertainties in the status diagnosis of the battery will remain, even after extensive checks on the crashed battery, and are further aggravating the issues described in the previous section. Because of this, our expectations that batteries reclaimed from crashed vehicles will play a large role in a competitive second-life storage market are low.

Batteries in very short-range small cars

As we discussed earlier, for a battery to reach the point of a useful value of zero in the mobile application, it does not necessarily have to reach its knee point, or the point where it is unable to continue safe operation at less challenging load profiles. This scenario is the one most often discussed in second-life studies, but as described before, leaving behind the fixed 80% state of health (SOH) end-of-life criterion makes a more in-depth analysis necessary. The beginning of this section described that small EVs with low ranges between 100 and 200 km still play a relevant role in the car market. Since these vehicles already attract a limited customer base, only using the vehicle on short trips, any further aging-related reduction of range makes it quickly unattractive for most users on the secondary market. Therefore, when the SOH reaches the often-quoted 70%–80% range, continued use in a vehicle is unlikely. Since even short trips require high DODs, for those kinds of vehicles, it can be expected that this point is reached earlier in the vehicle lifetime than, for example, in the ID.3 analyzed by Wassiliadis et al. in 2022.[64] Because users might be inclined to search for a replacement battery because the rest of the vehicle is still perfectly usable, some manufacturers of these short-range EVs offer battery replacements.[65] This makes it possible for stationary system manufacturers to work directly with the car manufacturers to source these batteries. With battery capacities increasing, even in low-cost vehicles like the Dacia Spring or Volkswagen Up, it has to be monitored whether the segment of very short-range small cars will still be relevant in the future car market.[66,67] When used EVs are becoming available at competitive costs, this segment might be under threat as a whole.

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Batteries from commercial applications

In contrast to private users, commercial buyers of EVs are much more inclined to optimize their investment into the technical capability of their battery systems with respect to their operational requirements. The way of allowing a sufficient operational lifetime in these commercial systems is to oversize the battery so that aging-related capacity reduction can be compensated over the planned lifetime. In many cases, commercial operators of EVs have very strict requirements regarding range and charging speeds, directly resulting from their commercial activities. Busses might be required to be able to serve defined routes, and long-range trucks need a certain range for charging to synchronize with driver resting times over the full usage time of the vehicle.[68,69] With these requirements, a planned retirement of the battery system at an SOH of 70% results in the need to oversize the battery system by 43%, significantly increasing initial investments. Therefore, the 70%–80% SOH end-of-life criterion is usually a realistic estimation for commercial users that have to manage the trade-off between initial investment costs and saving in total costs over the lifetime of the system. A long cyclic lifetime can have a high impact on profitability for long-range electric trucks, so rather than solely maximizing energy density, cycle life is one of the key development goals in truck battery design.[70] These batteries optimized for long cycle life, leaving service with good SOHs of around 70%–80%, are particularly interesting for second-life storage manufacturers.

Long-range electric trucks are only beginning to enter the market, so it remains unclear when retired batteries are becoming widely available. Professional users oftentimes have the option to allocate older vehicles to less demanding usage profiles, for example by changing the bus's route or using the truck for shorter routes. Therefore, even though operators might select the vehicles based on an end of life at 80% SOH, the ability to move older buses to shorter, less demanding routes or sell used trucks to companies with lower range requirements might result in batteries leaving the fleet with lower SOHs. Nevertheless, the commercial vehicle sector seems to be more attractive for second-life storage manufacturers because batteries are more often optimized for longer lifetimes, and the end-of-life criterion of 80% SOH is more realistic here.

Diagnostic methods and open standards for battery management system integration

Knowing the status of a used battery and being able to estimate the future life is a key factor in deciding an optimal pathway for its future use. In the following section, the current situation regarding battery diagnostics and the proposal regarding batteries and waste batteries made by the European Commission on December 10, 2020, will be discussed. In the second part of this section, the current options for reusing the battery management system of used batteries are described, and challenges regarding open standards are evaluated.

Options for battery health estimation

Currently, status diagnostics inside vehicles focus on giving the user correct information about the remaining driving range over the lifetime of the battery.[71–73] This SOH value is generally part of the data that can be easily obtained from the battery management system, even for third parties using controller area network (CAN) communication readers. This status value, however, is not sufficient to evaluate the future trajectory of the capacity, so second-life system integrators with better insights into the remaining lifetime of the battery will have a competitive advantage. Different lifetime prognosis algorithms are described in the literature.[74–77] As discussed in the context of crashed batteries, performing elaborate measurements on an individual battery to determine its value in a second-life application is not economical. Therefore, the most economical way of selecting the batteries most suitable for second-life applications is by utilizing methods that can work with the data already available from battery management systems, meaning no extra measurements need to be performed and the data are solely obtained by sensors already installed in the battery system.

Data-based machine-learning methods are the most promising methods working in this efficient way. Li et al. proposed an efficient cloud-based method for lifetime prognosis.[78] Of course, data-based methods require sufficient training data, and the historical data of the individual battery under evaluation must be disclosed to apply the trained algorithms. Digital twins of battery systems, as described in Li et al.,[79] are very well suited to perform these tasks of operational data collection and processing. However, who has access to the information stored in the digital twin framework poses new challenges. While the disclosure of individual battery status data might increase the quality of diagnostics and increase the possible resale value of an EV or battery, privacy issues emerge. Knowing the vehicle specifications, motion profiles, and user patterns can be obtained from SOC data, meaning many users might not be willing to give up this sensitive information without compensation or on open, public platforms. It is, therefore, probable that vehicle manufacturers will be directly involved in providing access to the battery's digital twin and lifetime prognosis information, given that they have access to all the relevant data. It can be expected that corporate partnerships between vehicle and second-life storage manufacturers will be most capable of selecting batteries for second-life systems in a competitive stationary storage market with a surplus of retired vehicle batteries with drastically varying remaining service life. It was mentioned before that the used car market would be the biggest competitor for second-life storage manufacturers in procuring batteries for their products. All improvements in lifetime prognosis methods, reducing uncertainties regarding the remaining service life of a vehicle battery, are not only benefiting the second-life manufacturer but also help strengthen the used market for vehicles. More confidence in the remaining lifetime of an EV will result in more users being willing to buy used, resulting in fewer vehicles being retired prematurely, with high enough SOHs to be further processed in the second-life market.

The EU battery passport proposal

Details about a battery's design and composition are also usually undisclosed to the public to protect trade secrets and intellectual property, making it hard for companies to explore options for the manufacturing of second-life storage systems outside of strict confidentiality agreements. To address this and other problems, the European Commission is planning to change its battery directive, making it mandatory for manufacturers of battery systems larger than 2 kWh to give information about their systems.[80] The proposal describes an electronic exchange system, making a battery's composition, manufacturing, technical performance, and sustainability parameters available, either publicly or to accredited companies. Additionally, the European Commission proposes that operators manage a database for each individual battery, a so-called "battery passport." This database is supposed to store sufficient information to determine the SOH and expected lifetime of the batteries. Capacity, power capability, and internal resistance are supposed to be accessible by scanning a QR code on the battery. In contrast to the database for information about the system's initial composition, it is not disclosed by the commission whether they are willing to create a platform for the exchange of dynamic individual battery data, so the real-life implementation of the proposal remains unclear.

It is also unclear whether the data planned to be part of the battery passport can be directly used for data-driven lifetime prognosis methods.

The second use of battery electronics

In contrast to being transparent about a battery's design and performance, transparency regarding BMS software and algorithms is currently not being discussed. The intelligent design of a BMS can offer significant competitive advantages to vehicle manufacturers, for example regarding range estimation accuracy or fast charging performance. A manufacturer of a second-life stationary system, therefore, faces the challenge of gaining access to this sensitive information to be able to reuse complete modules or battery packs. Having to develop and connect new BMS hardware and software that can work with a large variety of retired batteries causes high costs, effectively limiting the value of the retired battery further.

As described earlier, repurposing vehicle batteries in second-life systems normally means that the composition of the batteries is changed. The battery packs get disassembled, in most cases at least to the module level, diagnosed, sorted, and reconfigured to form the second-life system. The new pack architecture, with a new arrangement of serial and parallel modules or cells originating in different retired vehicle batteries, requires a new BMS structure as well as new BMS control and diagnostic functions. Even after combining modules or cells with similar aging statuses to form the second-life system, it is unavoidable that parameters such as capacity and internal resistance will further diverge during the second-life operation.[81] Therefore, balancing strategies become increasingly important in the second life and might require new balancing systems not needed in the mobile application. To be able to repurpose the BMS in this case, for example by keeping the BMS slaves connected to the modules, the configuration of the BMS software will have to be changed to allow it to communicate with the new BMS master of the second-life system or with the reconfigured repurposed BMS master of the vehicle battery. Additionally, the new application requires a reconfiguration of key control parameters. Adapting voltage limits, current derating, and a reevaluation of the usable energy and SOC window are important to optimize the operation and lifetime given the new operational environment of the system.

Stationary system manufacturers working together with vehicle manufacturers in corporate partnerships might be a solution, offering a significant strategic advantage, compared with independent second-life storage manufacturers, by giving the second-life system integrators access to the BMS programming. Current pilot projects, most of the time involving the vehicle manufacturer, support this thesis.[15]

INTEGRATED DEVELOPMENT OF MULTI-LIFE BATTERY SYSTEMS

Challenges of development processes for multi-life battery systems

Today, the market requirements for the second life of a vehicle battery are still largely unclear or unconsidered during vehicle battery development. As described earlier, the time in the battery life cycle at which the first life ends and an evaluation regarding a second-life usage can be performed is not predetermined. Currently, an SOH of 80% is often determined as the time at which the first life ends but is dependent on a broad spectrum of influence factors. Another challenge arises from limited knowledge about the second-life use cases during the initial development of the battery system. Therefore, considering a possible second life with its requirements and optimizing a battery system for its complete life cycle during the initial development of the vehicle battery is not practiced today. Nevertheless, strategic partnerships between EV manufacturers and stationary storage manufacturers can address part of the challenges, like the challenge of the lack of knowledge about requirements, and enable such an integrated approach to product development since second-life applications can be preselected. By simultaneously optimizing the battery system for both life cycles, the potential of the battery system for second-life applications can be exploited already in first-life development by identifying design elements and construction methods that benefit the second-life usability without affecting the first-life system in a negative way. This results in a significant improvement in the suitability of the used battery system for second-life applications. An integrated approach to the development of the battery systems comes with its own challenges, though. Requirements of the planned first- and second-life applications must be considered and are leading to very complex requirement structures. Since no vehicle manufacturer will be able to compromise the fulfillment of first-life requirements, it is especially important that solutions are identified that improve the second-life suitability without leading to disadvantages (e.g., additional costs) in the vehicle application. Identifying and designing those solutions during the integrated development process is a complex task and requires a methodical approach.

Using model-based systems engineering methods to optimize the first-life battery system regarding the second life

To consider first- and second-life requirements and their relationships in the integrated development and optimization of battery systems, different physical behavior models are necessary.

The specificity of the battery system behavior models that accurately model the performance of the system is that the models are designed by experts of thermal, mechanical, and electrical domains. These individual models from different domains are highly interdependent. Additionally, battery systems age with aging rates that are dependent on parameters that need to be obtained from other modeling domains, e.g., the thermal performance. Therefore, the behavioral models must describe the design of the first-life battery system, the life cycle of the battery system, and the design for a second life, as well as manufacturing and economic aspects. Between these behavioral models, various dependencies must be handled for successful integrated development and optimization. For example, battery temperatures during use affect the electrical performance, and electrical load profiles and temperatures influence the aging of the system. Furthermore, the dependency of the model inputs and outputs on the different requirements resulting from the first- and second-life applications must be managed. These dependencies between models, as well as between models and requirements, are currently inadequately mapped for multi-life battery systems.

An approach to mastering these dependencies is to build a central development model using model-based systems engineering (MBSE) methods.[82–84] Several MBSE methods are existing,[85] such as SYSMOD,[86] FAS4M,[87,88] and the Motego method.[89,90] Differences between the MBSE approaches lie especially in the way of how they link development results and model the logical product description. The Motego method is particularly suitable for the integrated development and optimization of battery systems, since this method facilitates the integration and interconnection of executable models in the solution description.

This way, existing models within different specialized modeling environments can be linked. For example, thermal models created in dedicated thermal modeling software and aging models created in Python or MATLAB can be connected by using the Motego method and modeling framework.

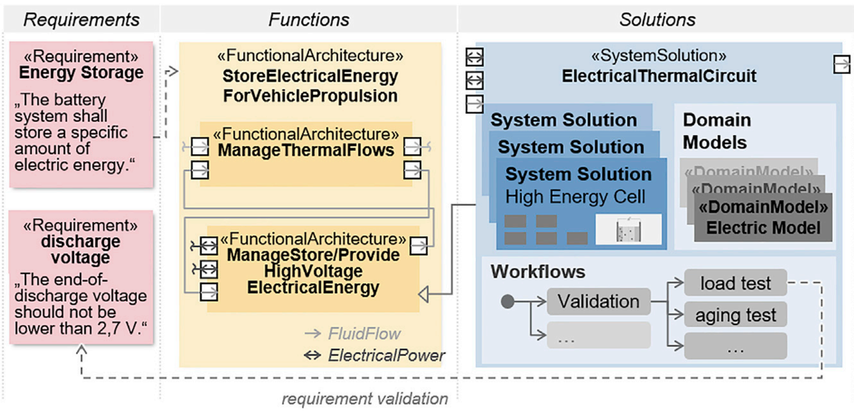

Figure 8. Extract from the Motego method applied to a battery system

Basis for model-based systems engineering methods is the system model with the layers requirements, functions, solutions, and product realization. To identify solutions that meet certain requirements, the solutions of the Motego method include domain models, like electrical, thermal, and aging models of batteries.

In the Motego method, all development artifacts, from requirements to functions and solutions, are seamlessly linked. Figure 8 shows this seamless connection for a segment of the battery system. The central elements of the Motego are the solution-neutral description of the product's architecture in the functions area and the associated solutions area. Within the solutions area, the realization of the functions is described through the principle solution, consisting of parameters and simple physical models.[90,91] Additionally, this simple product description is linked to all domain models and workflows that are necessary for design, validation, optimization, production planning, and cost calculation.[89,92,93] These models are essential for development decisions and for testing the solution concerning the fulfilment of the requirements for both the first life and the planned second life of the battery.[93]

In conclusion, the Motego method is well suited to link development artifacts comprehensively that are necessary for integrated product development and optimization. A prerequisite for creating a system model with the Motego method to support the integrated development and optimization of the battery system is the availability of models that describe the usage of the battery system in the first life. In particular, this includes models that predict precisely and reliably the remaining lifetime and condition of the battery after a defined usage period. Only through prediction of the remaining life and battery condition at the transition point between first and second life is it possible to already develop a second-life battery system during the development process for the first-life application. While such lifetime prediction models are available and achieve ever-increasing accuracy, their output depends on realistic estimations of the first-life usage patterns and circumstances.

To find the most suitable design of the battery system for both life cycles, the digital twin of the battery systems in the system model must meet the requirements of both life cycles as well as possible. To find this optimum efficiently, sensitivity analyses and optimization algorithms are suitable and help to manage uncertainties about first-life usage patterns and environments. Due to the modeling of the battery system parameters and the integration and interconnection of domain models, the system model, once carefully created and validated, offers the best prerequisites to manage the complexity of developing multi-life battery systems.

CONCLUSIONS AND OUTLOOK

Second life is a promising path to increase the usage time of battery systems, thereby decreasing the total lifetime costs and increasing resource utilization. In theory, the predicted yearly production volume of batteries in mobile applications easily generates enough retired batteries to supply the stationary sector, even considering the reduced starting SOH. For second-life batteries to become widely adopted in the stationary sector, several challenges need to be addressed by regulators and industry actors.

Even with lower requirements in terms of energy and power density, other requirements, especially in the field of safety and reliability, are as critical in stationary applications as in the mobility sector. Standards for the evaluation and homologation of battery systems based on retired vehicle batteries must be developed and rolled out to ensure that aging-related reliability and safety concerns are controlled.

A second area with great challenges for manufacturers of second-life battery systems lies in the sourcing of old yet still usable vehicle batteries. Many vehicle batteries will be able to reach their safe end of life in the mobile application by changing hands to users with lower range and charging-speed requirements, making the transfer into a stationary application unnecessary.

In all described scenarios, second-life stationary storage manufacturers will compete with others on the used vehicle market, most of the time facing the extra burden of having to buy complete vehicles to obtain only the battery for further use. Removing batteries for second-life applications and scrapping the rest of the vehicle at the early stages of its life cycle will not be the most economical and ecological pathway in most cases. Commercial vehicles with strict requirements for their operation mode, like long-haul trucks, might be a more likely source. Partnering with a manufacturer of commercial EVs, like trucks and buses, seems to be the best option for second-life storage manufacturers to reliably source batteries with a sufficient remaining lifetime. In a future study, we will publish findings regarding used battery pricing to evaluate business models for second-life storage manufacturers further.

In terms of battery diagnostics and the exchange of battery status data, controlled platforms need to be developed, going further than the current battery directive issued by the European Commission, to create an open and transparent market for used vehicle batteries. Currently, only a partnership between a stationary storage system manufacturer and a vehicle manufacturer allows the exchange of relevant status data and information about pack design, material composition, and BMS software functionality.

The integrated development of multi-life battery systems is the logical next step to optimize battery utilization across multiple usage scenarios. Model-based system engineering provides the necessary methods and tools to support this complex development approach.

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AUTHOR CONTRIBUTIONS

Conceptualization, M.F.B. and W.L.; investigation, M.F.B., M.H.F., B.S., and K.S.; writing – original draft, M.F.B., M.H.F., B.S., and K.S.; writing – review & editing, M.F.B., M.H.F., B.S., K.S., H.H.H., and W.L.; funding acquisition, H.H.H. and D.U.S.; supervision, H.H.H., D.U.S., and W.L.

DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

We support inclusive, diverse, and equitable conduct of research.

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