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Review

Identification of Challenges for Second-Life Battery Systems—A Literature Review

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Abstract: Lithium-ion batteries (LIBs) have been proven to be increasingly popular and are the solution of choice for many companies and business models around the world. One major question for battery owners is how to deal with returning batteries if they still contain sufficient capacity for operation. In this case, those energy storages can still be used in different, less-required second-life applications, such as stationary battery storage systems, contributing to increased product sustainability and economic benefits at the same time. However, the second-life business model is still at an early stage of development due to the young EV market in combination with long vehicle lifetimes. As a consequence, there are several barriers in various thematic fields, complicating the rededication process for LIBs. This review paper focuses on a summary of barriers to second-life adoption published with scientific reference. Furthermore, barriers are clustered thematically to provide a transparent landscape picture and valuable insights into the rededication process of LIBs.

Keywords: battery second-life; reuse; challenges; battery life cycle; review

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1. Introduction

The electric vehicle market has experienced tremendous growth in recent years. In 2016, around 478 thousand battery electric vehicles (BEVs) were sold worldwide. Last year in 2022, there were already more than 5.2 million BEV sales, resulting in an average market growth rate of 49 percent per year (CAGR 2016–2022) [1]. In 2021, 86 percent more EVs were produced in Germany compared with the previous year [2].

Due to the steady increase in the number of electric vehicles, there will also be increasingly more battery packs in the future that have reached the end of their first life criterion. Currently, EV battery packs are expected to be applicable in the vehicle until they reach a state of health (SOH) of about 80%. The SOH of a vehicle battery can be determined in different ways. One approach is to calculate the ratio of the current capacity to the original capacity of the battery, whereby capacity describes the amount of electrical charge that the battery can store. [3] Since the high requirements of the vehicle application are no longer met but the condition of these end-of-life (EoL) batteries is still good at this point, recycling is often not the best option. Therefore, the business model of reusing the batteries in less-required applications arose where the capacity of the used batteries was still sufficient. This gives the used vehicle batteries a second life, which is why the term second-life battery (SLB) has become established.

During the repurposing procedure, the batteries go through several processing steps. First, the EoL batteries must be removed from the vehicles, collected, and transported to the repurposing facility. This is followed by an identification and condition assessment before the batteries are technically processed. Finally, the SLBs are ready to be integrated into a new, second-life application, such as stationary storage services. The process chain can therefore be divided into three main steps:

- End of first life, collection, and transport;

- Screening and condition diagnosis;
- Dismantling, processing, and integration.

In order to give structure to the research results, the three parts of the process chain serve as chapters and headings. In addition, the rentability and legal framework for SLBs have challenges that will be addressed in this paper. A thematic overview is provided in Figure 1.

Figure 1. Thematic overview of challenges for second life batteries.

In the best-case scenario, the process of reusing EV batteries for a second-life is economically viable, which could lead to cost reductions for EV buyers [4,5]. This economic benefit is particularly important since the high battery costs are limiting the market penetration of electric vehicles [6,7]. In addition, the extended lifetime in a second application reduces the environmental footprint of the battery, increasing the sustainability of EVs [8–10]. Even though existing pilot projects demonstrate the general feasibility of using SLBs [11–13], various barriers still need to be overcome.

This paper presents the obstacles associated with second-life batteries. First, the challenges along the process chain are discussed, followed by the economic and legal obstacles to the reallocation of EV batteries. The main challenges are summarized and numbered at the end of each chapter to provide an overview, whereby the selection process is mainly dependent on the number of citations for each challenge in the literature.

2. End of First Life, Collection, and Transport

According to projections by BloombergNEF, future EV sales will increase globally to 10 million in 2025 and 56 million in 2040 [14]. It is assumed that EV batteries can be used in the vehicle for 10–20 years [15,16]. As the market share of EVs has only begun to increase sharply in recent years, most EV batteries are still in their first life [17]. This means that although availability is assured for the long term, there will not be enough EoL batteries for a second use in the next few years. Especially for large second-life applications, there is currently a lack of product availability [18]. Furthermore, there is still uncertainty about how many of these batteries have a sufficiently good SOH to be used as SLBs [12]. At the same time, some modules might perform well enough to be used again in a vehicle (e.g., as part of a remanufacturing process), so they would not be available for a second-life application [19,20]. Hereby, it has to be considered that remanufacturing does not yet represent a valid business case either, as it suffers from some of the same hurdles as reuse.

According to the specifications of OEMs, EV batteries are no longer suitable for a vehicle application when they reach a residual capacity of about 80% [21–23]. In the literature, this value is considered to be the standard EoL criterion. However, some authors criticize this concrete definition. Saxena et al. [24] and Martinez-Laserna et al. [25]

emphasize the large dependence of the aging behavior in second-life on the former usage (stress) in first life. Thus, whether the SOH alone is sufficient as an EoL criterion is questionable. In order to ensure the reliability of the SOH value, many more batteries will have to reach the EoL in the future, and their aging behavior will have to be monitored in the second life in order to obtain statistical statements.

At a certain point, approximately at a SOH of 80%, it has been observed that accelerated, non-linear aging of the vehicle battery occurs, which also makes the prediction of further aging behavior more challenging [26]. Therefore, it is important that the rededication to the second-life application occur, before the accelerated aging of the battery. However, the exact prediction of this optimal moment is quite complex and not yet predictable [27,28]. This behavior is represented in Figure 2. The reason for this is that battery aging varies greatly, as influencing factors such as temperature and load profile are highly individual. Thus, there are also batteries that can operate even with a SOH below 80% without experiencing accelerated aging. This makes it difficult to predict the remaining life of the battery system, even if the SOH is known. Here again, statistical evaluations would help make decisions about the further use of aged batteries.

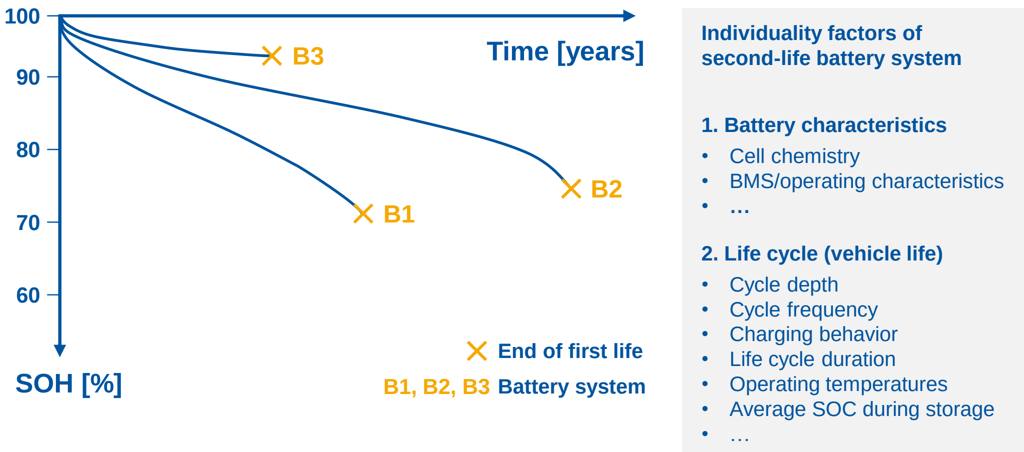

Figure 2. Individuality factors of second-life battery systems.

At the end of the first life, the batteries must be removed from the vehicle. This process should not be underestimated, as many batteries are designed specifically for their vehicle, permanently installed in it, and therefore difficult to extract [20]. After the removal, the LIBs must be sent to the rededication facility. Since used batteries are classified as hazardous waste, the transport is subject to many regulations; for example, trained personnel and approved vehicles are required. This makes transportation more expensive, but nonetheless, a constant risk remains because the batteries are still functioning [29–31].

Due to safety issues and the resulting non-trivial transportation and packaging management, some logistic companies do not offer this kind of transport (also, air freight is not permitted), which makes it difficult for the rededication companies to find suitable business partners [9]. Especially if the removal, collection, and transportation of the EoL batteries are not done by the OEM or a central processing facility, there may be a lack of expertise [9,20,32]. This can be covered by financial means since there are transport companies that specialize in this type of hazardous goods. Due to the necessary compliance with the ADR treaty [33], however, this increases the cost of transport in the member states of the treaty. Table 1 summarizes the main barriers to end-of-life determination, collection, and transport of SLBs.

Table 1. The main barriers regarding end of first life, collection, and transport.

Individual Barriers	Source
Challenge 1: Uncertainty about how many EoL batteries have a sufficiently good SOH to be used as SLBs	[12]
Challenge 2: Difficulty in predicting whether a battery system is still suitable for rededication	[27,28]
Challenge 3: Transport is expensive due to regulations, involves safety risks	[29–31]

3. Screening and Condition Diagnosis

After the EoL batteries are collected and taken to the repurposing facility, they must be identified. According to the current status, there are no standardized concepts for the identification process. Since clear battery identification is not always given, it might be necessary to contact the manufacturer [28]. Moreover, due to insufficient labeling, automatic identification is difficult, resulting in a time-consuming identification process [34]. At this point, the planned introduction of a battery passport in the EU should be mentioned [35], which could ease the identification and evaluation of EoL batteries in the future. The battery passport is a digital information repository for products that can be used as a product ID and to track important product lifecycle information, e.g., value chain and usage history data, recycling recommendations [36]. Manufacturers, users, and recyclers, as well as regulators, will benefit from the battery passport in the future since it provides transparency along the complete value chain.

In order to make a reasonable decision about the future second-life application of the battery, an evaluation of the battery's SOH must be performed. The SOH describes how the battery capacity differs compared to a new battery, but there are uncertainties about how to exactly define it and how it should be evaluated [37]. The SOH degradation of a battery cell is caused by the aging process, which can be evaluated using battery aging models. However, other factors affecting the SOH, such as battery damage caused by vehicle collisions or short circuits, are difficult to determine, so the actual condition of the battery often remains unknown. That's why storing and managing EoL batteries always involves constant uncertainty [38].

The SOH determination still faces several barriers that need to be overcome. One of the most mentioned challenges in the literature is the great diversity of EoL batteries, which leads to a wide range of possibilities concerning the different aspects of batteries. Depending on the cell manufacturer and EV model, the batteries differ in cell chemistry, cell type, module dimension, power, capacity, refrigeration system, BMS, and functional characteristics of the battery, among others [11,39]. Due to the wide variety of batteries, even the SOH determination tests will differ for the different types, making it impossible to develop a unified technical procedure. Consequently, the screening process gets more complicated and possibly more expensive [11]. This becomes particularly challenging when a third-party acts as the system integrator [40].

Many studies also emphasize the large amount of time required for SOH determination, which again leads to an increase in rededication costs, questioning the economic viability [39,41,42]. Although there are already standards for determining battery parameters, such as ISO 12405-1 or USABC electric vehicle battery test procedures, they are time-consuming (up to 75 h) and therefore not suitable for mass rededication. This is why the realization and standardization of rapid test procedures are of particular interest to the battery industry [41]. Aside from the testing duration, another barrier is the required high-end, specialized testing equipment. Currently, after their first life, the EoL-batteries are typically sent to the recycler. However, many automotive recyclers neither have the right testing equipment nor the expertise on how to properly test the batteries and may not be able to estimate the SOH value [32,43].

The availability of battery data from the first life would be an advantage for the evaluation process. This can be achieved by tracking the usage history of the EV battery, for example, by the battery management system (BMS) [44]. According to Hua et al. [45], big data analysis techniques could help a lot here to accelerate the evaluation process. However, given the long design cycle of new EVs and the possibility that the manufacturers might not be willing to share battery data, it must be assumed that many EoL batteries will not come with data from the first life [26]. Without these data, it is difficult to decide whether or not used EV batteries would be suitable for second-life applications [12]. Additionally, not only the data from the first life is crucial; the precise requirements for the second-life applications are also important for a proper rededication decision since those are often new and unknown markets for the reuse companies [46]. However, life cycle data from the vehicle would not be entirely sufficient for the evaluation process. This is stated by Becker et al. [28], who noted that even if all the data from the first life were known, no well-founded decision could be made regarding the second use scenario because the strains and the resulting aging of the SLBs in the second-life were not yet sufficiently researched. However, it should be possible to provide lifetime estimations in second-life based on load scenario predictions and conservative assumptions. This means, it is possible to evaluate the remaining lifetime, even if only approximated. Therefore, battery aging estimates must be combined with the load scenarios, which is time consuming, especially since there are numerous areas of application for second life batteries and the load behavior can also vary. The main barriers discussed in this chapter are summarized in Table 2.

Table 2. The main barriers regarding screening.

Individual Barriers	Source
Challenge 4: Identification process not standardized, difficult and time-consuming	[28,34]
Challenge 5: Great variety of batteries makes uniform SOH determination and rededication challenging	[11]
Challenge 6: SOH determination without access to BMS data is time consuming and requires special equipment	[32,39,41,42]
Challenge 7: Lack of battery data from the first life complicates the decision of reuse	[12,26,44]

4. Dismantling, Processing, and Integration

Montes et al. [47] identified three main configurations of how EV batteries can be adapted in second-life applications, depending on the pack and the second-life scenario. Multiple EV packs can be directly connected without disassembly, or the packs can be refurbished at the module or even cell level [47]. For the latter two options, it is necessary to disassemble and process the EoL battery packs before reusing them in a second-life application. In addition, for an accurate SOH determination without access to BMS data, a battery disassembly is usually required. When disassembly is considered, it is recommended to disassemble down to the module level and reuse the retired modules (or packs) directly because complete battery disassembly to cells is difficult and expensive today [48,49]. After disassembly, the batteries must be visually inspected before all modules and components are tested. Subsequently, degraded modules could be replaced, whereby those with significantly low SOH are substituted, so that in the end the conditions of all modules are similar. This process is called remanufacturing (or refurbishing) and is not necessarily a part of the second-life process chain. The goal of this process is to achieve high homogeneity among all modules in the battery pack. This is especially crucial since the worst module determines the maximum power of the battery pack [50]. In addition, since the new application of the battery pack may differ greatly from the application in the EV, the modules sometimes may need to be reconfigured. However, the approach of battery reconfiguration is still part of research and is rarely used in the industry [28].

The major challenge for disassembly is its extensive nature and the fact that it is currently performed manually, which significantly increases the cost of rededication. According to calculations by Rallo et al. [51], the dismantling costs account for more than half the price of a new battery pack [40,51]. However, this value serves only as an approximation, as the dismantling costs depend in particular on the labor costs of the individual site or country. Further, the effort of the battery disassembly process is mainly dependent on the battery structure as well as interconnections. Accordingly, factors such as the number of bolts and fasteners and accessibility determine the cost of disassembly and rededication.

One additional cost factor is the fact that battery systems are usually operated at about 400 V DC (a rising number of systems are even using a higher level of about 800 V DC), which means that high voltage trained staff is needed for disassembly. In addition, the amount of time required to open the battery pack and remove the individual modules from the system also has a major impact on the overall profitability. [34] One solution to this would be to avoid the disassembly by rededicating at pack level. Another option is to automate the technical processing. The automation, however, requires high investment costs, as the EoL batteries differ greatly in their designs (including battery parameters such as performance values). Batteries vary depending on vehicle type and OEM, and even within a pack there may be multiple module designs. Therefore, a unique disassembly procedure must be developed for each new battery. The literature sees this as the main problem of technical processing since, in the absence of a universal battery standard, the battery disassembly process becomes very inconsistent [9,34,38,52]. This could also explain the lack of technological standards in the repurposing process, which are emphasized, among others, by Wrålsen et al. [30] and Abdel-Monem et al. [53].

Not only does the inhomogeneity of battery designs (cells, modules, and packs) need to be considered, but also the different SOH of used batteries and the larger cell-to-cell variability of second-life batteries compared to their new counterparts complicate the reassembly of SLBs. This becomes a challenge when assembling new battery strings since, as described above, the similarity of cell capacities is significant for battery performance and future lifetime. Especially for large second-life applications with a wide range of capacities, it becomes difficult to assemble a matched string [12,19].

Another challenge of the repurposing process is the development of a new BMS, which might be necessary if access to the existing BMS is not possible. [19,20] Whether a new BMS is needed also depends on the OEM providing the appropriate communication interface (e.g., DBC files), which is often not the case due to the resulting disclosure of sensitive data. However, this problem will potentially be solved with the new EU battery regulation, which will be addressed again in Chapter 6. It should be considered that the development of a new BMS leads to significant additional effort and higher rededication costs [54], especially since the new BMS becomes more challenging. This is caused by the balancing necessity of larger performance differences in the case of SLBs compared to new batteries [55].

If the battery packs are reused directly, i.e., without replacing or reconfiguring individual modules, the original BMS of the OEM can be leveraged. The least costly situation is when the communication interface is provided. If this is not the case, the development and use of a gateway are necessary. The gateway translates information into different arrays. As a result, the final receiver cannot know the original CAN codification and protocol from the vehicle, which provides a higher security level [56]. In any case, also an energy management system (EMS) must be implemented, which communicates with the BMS of the battery packs and with the power converter [47]. However, the development of an EMS is always required, even when new battery systems are used. An overview of the discussed options is provided in Figure 3.

Finally, the large number of possible reuse scenarios and the resulting variety of requirements complicate the technical preparation and the system adjustment in general [28]. When it comes to integration into second-life applications, the literature again points to a lack of technological standards as well as a lack of long-term experience. The limited data, for example, on how SLBs will perform in different applications makes it difficult to evaluate other second-life application scenarios [6,9,57]. In the future, representative load profiles for various stationary applications would help to estimate the remaining life of battery systems.

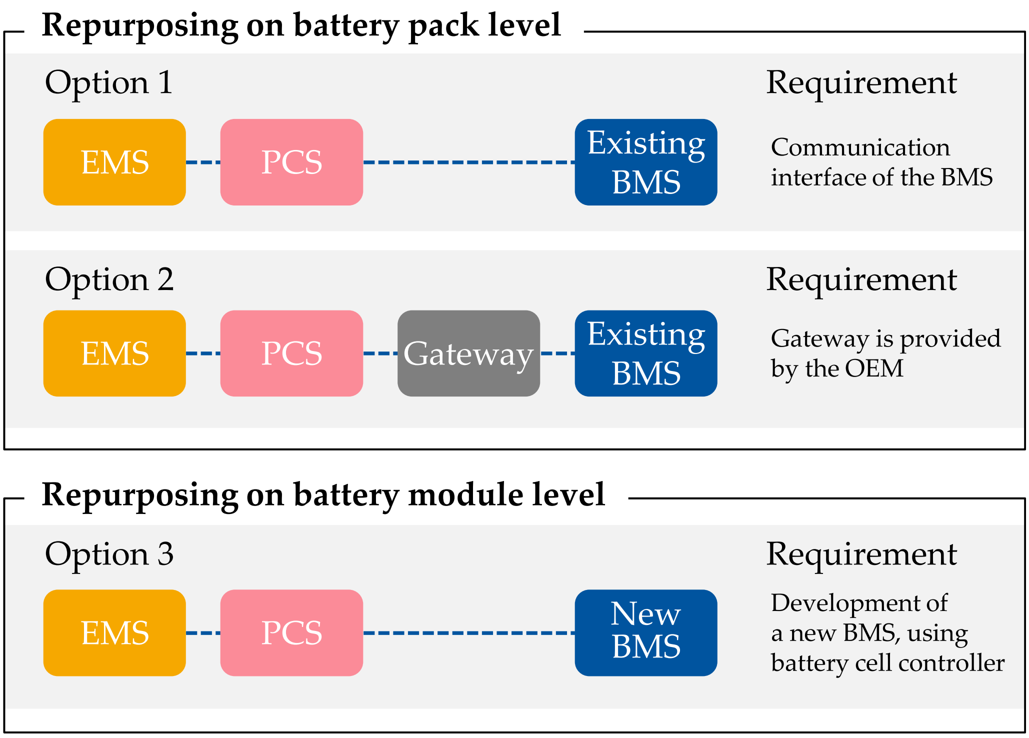

Figure 3. Repurposing options depending on the BMS communication.

In Table 3 the main barriers regarding the dismantling, processing and integration of SLBs are summarized.

Table 3. The main barriers regarding Dismantling and Processing.

Individual Barriers	Source
Challenge 8: Inconsistent disassembly and difficult automation because of the absence of a unified battery standard	[34,38,52]
Challenge 9: Difficulties in assembling a matched battery string	[12,19]
Challenge 10: Potential need to develop a new BMS and/or EMS to control retired batteries	[19,20,47]
Challenge 11: Missing long-term experience in processing and integrating SLBs	[6,9]

5. Rentability

An aspect that is mentioned in several studies regarding the rentability of SLBs is the price competitiveness between retired batteries and new battery systems [46,58,59]. Since batteries for second use are repurposed after their first use phase (approximately between 10 and 20 years [15,16]), they must prove themselves in terms of €/kWh against future battery systems, which already benefit from cost reductions through production and material innovations. On the other hand, even if research and industry continue to develop and improve battery systems, the cost savings could be offset by future innovations due to rising material prices, which would lead to a stable price level and could make second-life batteries competitive.

Another cluster of issues addresses the problem that repurposed battery systems are perceived by customers as second-hand goods, which reduces the perceived value of the storage systems due to potentially necessary breakdowns, maintenance, or repairs [12,28]. Wu et al. [60] also elaborate that market penetration may be hindered by customers' concerns about the quality of used battery systems due to inconsistent information. They therefore emphasize the need for a comprehensible traceability and evaluation mechanism for battery quality to counteract unnecessary consumer concerns. In addition to this psychological phenomenon, the uncertainty regarding the residual value and capacity of the battery adds to the difficulty, resulting in lower prices that customers are willing to pay. The same effect applies to leasing options, which represent a possible business case for second-life systems [29]. The mentioned factors increase the need for the provision of costly product warranties, decreasing the rentability of second-life even further [28].

Furthermore, the steps of condition assessment and reconditioning of battery packs receive much criticism regarding their economic viability. As already mentioned in Chapter 4, the cost of battery disassembly and technical processing alone can already account for more than half the price of a new battery system [40,51]. Haram et al. also note that the cost of reconditioning a SLB could make it unprofitable [11]. The potentially expensive rededication of the battery pack for second-life applications limits financing options due to economic uncertainty, reducing the attractiveness of a SLB case [46].

According to Wu et al. [60], considering the acquisition cost of second-life batteries, the evaluation of second-life rentability becomes even harder since there is a market price range for retired batteries. Starting at the lower range limit, which is the "willing to sell a retired battery," up to the realistic evaluated market price based on remaining SOH and the current market price. Finally, Wu et al. [60] state: "Consumers may have concerns about the economic feasibility of a second-life. To demonstrate the viability of the life cycle strategy, pilot projects in selected cities would provide valuable learning."

In summary, the challenges show that reliable SOH assessment and estimation of the remaining life are two highly relevant research areas that affect the profitability of SLBs. As a result, a method is needed to evaluate SLBs in terms of their remaining residual value at a low cost.

The economic barriers for second-life batteries outlined in this chapter and summarized in Table 4 increase the questionability of whether SLB systems can compete economically with new batteries.

Table 4. The main barriers regarding rentability.

Individual Barriers	Source
Challenge 12: Price competitiveness between second-life batteries and first-life battery systems	[46,58,59]
Challenge 13: Used goods are perceived with a lower value	[12,28]
Challenge 14: Uncertainty regarding residual value and capacity lower the "willing price to pay"	[29]
Challenge 15: Costs for condition assessment, rededication and subsequent warranties question the economic viability.	[9,28]

6. Legal Framework

Many of the mentioned barriers exist due to a lack of information as well as insufficient regulations regarding the further use of battery systems. A similar scenario can be seen with regard to the legal framework for second-life [4,45,61]. Thus, many authors consider the uncertain liability picture for SLBs to be a noteworthy challenge. Currently, there is no clear legal framework regarding the transfer of liability from the OEM to the SLB provider [34,46]. However, it should be noted that with the new EU battery regulation, which is expected to come into force in the first half of 2023 [62], clearer regulations regarding SLB liability will be introduced. For instance, producers of batteries will bear extended producer responsibility [63]. As this is only a proposal at this stage, it should be considered that the regulations can still change until the final publication.

Due to unknown duty cycles in the second-life, the safety of SLBs cannot be fully assured, so the risk of potential damage remains [29]. Therefore, clear liability and ownership regulations are crucial for this. According to Viswanathan, Kintner-Meyer [29], and Elkind [46], OEMs, in this case the automakers, might prevent a second use if they were still liable for their batteries. Should this be the case, a second-life for the EV batteries would only be possible if the OEMs themselves were involved in the repurposing process and not only third parties [38].

Problems in the insurance market present another barrier regarding SLBs liability. Since there are no previous statistics that would allow an accurate evaluation of the coverage, there are hardly any insurance providers that offer liability protection, making it difficult for SLB Companies to ensure product warranties. The effectiveness of any second use procedure, however, will depend utterly on warranties. Companies may therefore be hesitant to enter the SLB market [12,38].

In contrast to the insufficient regulations described above, repurposing of EoL batteries is made difficult by the existing regulations for electric utilities, which are said to be among the most complex in the industry [46]. Chapter 2 already mentioned the regulations for the transport of SLBs, which are classified as hazardous waste. Energy storage incentive programs sometimes unintentionally discourage the use of used batteries as they exclude used assets from eligibility. In addition, state and local authorities may oppose the use of spent batteries because of concerns about fire safety and other potential negative environmental impacts of these new applications [46,59].

It is also unclear who will be responsible for the disposal and recycling of the battery at the end of its second-life, although this is also to be remedied with the new EU battery regulation [63]. Currently, the manufacturer is obligated to take the batteries back from the owners and ensure a proper disposal. However, the secondary use of the batteries makes it difficult to decide whether this obligation should be transferred to the repurposing company, as the batteries have already been on the market and sometimes have been technically modified during the rededication process [39,64]. One option would be an individual agreement between the manufacturer and the SLB provider regarding the management of the EoL batteries [65].

First life usage data is critical for battery identification and condition determination. However, this raises privacy issues, so OEMs may be reluctant to share this data [34]. Therefore, this is also one of the multiple legal issues, summarized in Table 5, that still need to be clarified and that currently hinder the willingness of the private sector to invest in second-life.

Table 5. The main legal barriers.

Individual Barriers	Source
Challenge 16: Uncertain liability picture. E.g., regarding the transfer of liability from OEM to SLB provider	[34,46]
Challenge 17: Automakers might prevent a second use if they were still liable for their batteries	[29,46]
Challenge 18: Absence of previous statistics lead to problems in the insurance market	[12,38]
Challenge 19: Existing regulations for electric utilities complicate the repurposing process	[9]
Challenge 20: It is unclear who will be responsible for disposal and recycling at the end of the second life	[39,64]
Challenge 21: Privacy issues hamper the sharing of first life usage data by the OEM	[34]

7. Further Barriers

Since the EV battery is designed only for its vehicle application, several barriers arise in its second-life, starting with safety issues. To minimize safety risks, new LIBs are subjected to extensive safety testing before they are used in their applications [66]. In their second-lives, however, this raises safety issues because the batteries are no longer in the original application for which they were designed. In addition, due to possible minor abuses inside the batteries, used batteries tend to have greater safety problems than new batteries [67]. However, since the SLBs are mostly used in stationary storage systems, where the requirements are lower than in EVs, safety issues of this kind are expected to be exceptions. Nevertheless, safety tests of EoL batteries are urgently needed, such as those presented in the already existing standards UL 1974 and IEC 62933-5-3 [68]. Zhu et al. [40] suggest that safety tests should not be performed randomly but rather on the more unstable systems because of the variability of used batteries [40].

As already apparent in the previous chapters, more experimental data are needed to determine the industrial applicability of SLBs. The lack of this data hinders the precise battery lifetime prediction, which in turn makes it difficult to determine warranty periods and battery ownership models [57]. In addition, there is still a great deal of uncertainty regarding the performance of the battery in its second-life and its further aging behavior [28,59]. It is also unclear which LIB chemistry will be used in EVs in the future and how much new batteries will cost [9].

Another challenge is the necessary coordination of all the actors involved in the supply chain of the repurposing process, such as the car manufacturers, rededication companies, system integrators, purchasers of SLBs, and subsequently recovery companies. Particularly, the sharing of sensitive data, such as battery parameters and usage histories, could present a problem in this regard [28]. On the other hand, the collaboration of OEMs and ESS integrators would promote the development of SLBs by developing viable business models [69].

Another interesting point that should be considered is the delayed material recycling due to the reuse of batteries. If EoL batteries from the EVs are used for an additional lifetime (6–10 years), this may, on a large scale, lead to a shortage of materials that would otherwise have been obtained through recycling. Therefore, more battery materials, such as lithium and other metals, would have to be mined to meet the demand [10]. On the other hand, stationary storage will be a necessary product in the future to enable the energy transition. As a result, battery systems will have to be used anyway for the associated applications, which in turn tie up resources again.

There are also concerns that the batteries will not be recycled at all if there are too many players in the value chain. In addition, there is the argument that with further technology development, the raw materials of the batteries are of higher use in new batteries, which speaks for direct recycling instead of a second-life [9]. In Table 6, the most important barriers named in this chapter are summarized.

Table 6. Other important barriers.

Individual Barriers	Source
Challenge 22: Safety concerns for the second use of retired batteries	[40]
Challenge 23: Necessary coordination of all the actors involved in the supply chain of the repurposing process	[28]

8. Conclusions and Future Work

This article summarizes the main challenges for the life-cycle strategy of second-life batteries. Based on a literature review, this publication is intended to provide a holistic overview of the current pain points and facilitate the identification of future solutions. Therefore, main challenges from literature are collected and clustered thematically into categories. Every chapter represents an individual category that ends with a table containing the specific literature review.

In total, 23 main challenges can be identified, which were defined as "main challenges" in particular due to their citation frequency and impact. Most challenges are located in the field of "legal barriers", highlighting the urgent need for regulation in the second-life battery market. Furthermore, during the literature research, profitability in particular was mentioned as a decisive market barrier with a high impact. Overall, the main highlights of this literature review are summarized below:

- Current barriers for battery second-life can be divided into five major areas: end-of-first-life, collection and transport, screening, processing, rentability, and the legal framework in particular.
- There are further barriers in different fields such as stakeholder management and data security, which are summarized under "other." However, the importance of these challenges is not inferior to the other barriers.
- The challenges most often mentioned in the literature focus on the wide variety of EoL batteries. The high level of diversification is influenced by numerous factors, such as cell chemistry, system architecture, user behavior, operating conditions, operating strategy, and market exit timing, leading to an unpredictable second-life product.
- Many challenges relate to the economic viability of second-life batteries, considering their competitiveness against new battery systems and technologies that profit from cost reductions. Secondarily, it is necessary to evaluate second-life batteries individually based on their remaining service life and storable energy. As a result, investment costs for system integrators vary, and a generally valid business case is difficult to calculate.

In the next step, the collected barriers based on literature will be validated by expert interviews. As a result, the main barriers seen by the industry need to be worked out in order to make them accessible for future scientific solutions.

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