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Research Article

Enabling Circular Business Models: Preconditions and Key Performance Indicators for the Market Launch of Repurposed Second-Life Lithium-Ion Batteries From Electric Vehicles

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With the rise of electric vehicles (EVs) and thus lithium-ion batteries (LIBs), the number of end-of-life (EoL) LIBs after their first life in EVs is about to increase significantly. These end-of-first-life (EoFL) EV LIBs still have sufficient energy density for less-demanding second-life applications like stationary battery energy storage systems (BESSs) or mobile applications (e.g., forklifts, tools). Repurposing EoFL EV LIBs extends their lifespan, offering sustainability benefits and supporting several United Nations (UN) Sustainable Development Goals (SDGs). However, prevailing market entry barriers, such as high repurposing costs, little information on battery history and aging, or lacking performance indicators, hinder the widespread implementation of second-life applications. Thus, this study aims to identify preconditions for considering and selecting useful EoFL LIBs and to determine key performance indicators (KPIs) to minimize economic risks for a successful second-life market launch. KPIs were rated according to importance using a Likert scale, and reference values were introduced. A mixed-methods approach, using expert interviews, an exploratory workshop, and an online survey, was applied. Twelve important preconditions were identified, with the "availability of information on battery specification" and "compliance with standards and regulations" considered very important. In addition, 12 KPIs were derived, covering six economic, three environmental, and three technical and safety-related indicators. The KPIs "state of safety (SoS)" and "resource savings (R_{sav})" were rated as highly important. Overall, the findings provide performance measurement guidance for repurposing companies, facilitating the market launch and adoption of second-life applications. Future research can build on these results and investigate variations among different battery types, ultimately promoting a circular economy.

Keywords: circular business models; circular economy; end-of-life lithium-ion battery; key performance indicator; repurposing; second-life battery storage system

1. Introduction

Electromobility is a major influencing factor for the global increase in production and sales of lithium-ion batteries (LIBs) [1]. In the automotive sector alone, LIB demand has risen by 65%, from around 330 GWh in 2021 to 550 GWh in 2022, with forecasts pointing to an even greater increase over the next 10 years [2]. All over the world, different policies increasingly aim to boost electric vehicles (EVs): the Green Deal in the European Union [3] with its corresponding RePowerEU Plan [4], the Inflation Reduction Act (IRA) in the United States [5], direct incentives along the EV supply chain by

Chinese governments, or the promotion of domestic EV manufacturing in India by the production-linked incentive (PLI) scheme for the National Programme on Advanced Chemistry Cell (ACC) Battery Storage [6]. In 2022, around 30 million EVs were in use worldwide. This number is expected to rise to around 240 million in 2030, according to the Stated Policies Scenario of the International Energy Agency (IEA) [2]. As a result, there will be more and more LIBs on the long run that no longer meet EV specifications and thus reach their end-of-first-life (EoFL) [2], which usually is expected after eight to 10 years of operation in an EV [7, 8]. At present, a mileage of 160,000 km or a remaining capacity of at least 70% is guaranteed by the majority of European car manufacturers [9]. By 2025, according to the IEA [10], the capacity of EoFL EV LIBs worldwide is estimated at 100−120 GWh. In line with the waste hierarchy [11] and the third principle of the Circular Cars Initiative [12], these EoFL LIBs should follow the R-principles to extend their overall service life in a so-called second life. These R-principles encompass reuse, repair, refurbish, remanufacture, and repurpose [13]. Given that EV LIBs at their EoFL have a diminished remaining capacity and certain aging history, second-life LIB (SLB) applications with lower energy density requirements and less stressful operating conditions than EVs are considered more suitable [7, 14, 15]. Hence, an SLB in this study is a battery that has been retired from its original use in EVs and is repurposed for less demanding applications. Promising applications are, for example, stationary battery energy storage systems (BESSs) for peak shaving purposes or mobile applications such as forklifts or golf carts [16]. Therefore, repurposing of EoFL EV LIBs is currently a preferred option for service life extension. This R-principle involves sorting of different LIB technologies, analyzing the battery management system (BMS), and reconfiguring the EoFL cells, modules, or battery packs, provided their quality meets the necessary standards [17]. At a legal level, repurposing of EV LIBs is addressed in different documents, like, for example, the amended European Battery Regulation [18] or the US blueprint for LIBs [19]. In addition, specific documents on the circular economy can support organizations in transforming their linear business models into circular business models. Circular business models focus on extending product life cycles, minimizing waste, and maximizing resource efficiency by promoting the different R-principles throughout the entire value cycles [20]. For example, the international standard ISO 59020 provides guidance on how to measure and assess circularity performance within economic systems [21].

Using SLBs has the potential to generate diverse sustainability benefits [22]. Several recent studies show advantages such as the reduction of environmental impacts [23–26], the potential decrease of total EV ownership costs [8, 27, 28], a reduction in dependence on countries providing new LIBs [29], the promotion of sustainable and circular business models [30], and the creation of new green jobs [31]. Regarding the envisioned energy system transformation, efficient energy storage systems play a crucial role in mitigating the effects of renewable energy intermittency. Leveraging SLBs in BESS production could effectively address energy fluctuations and underscore the increasing need for energy storage [8, 15]. These sustainability improvements align with the United Nations (UN) Development Programme's Sustainable Development Goals (SDGs), particularly "Goal 7 Affordable and Clean Energy," "Goal 12 Responsible Consumption and Production," and "Goal 13 Climate Action." However, SLB applications have not yet achieved a major breakthrough on the market. Existing market entry barriers still prevent SLB applications from becoming widely available. These barriers are diverse, ranging from economic, political and regulatory to technical, safety-related, and social ones. At the economic level, a major gap exists in the lack of performance indicators [31]. As a first step, it is crucial for companies to have indicators to determine whether the necessary requirements for the market launch of SLB applications are met. This important decision can be guided by "preconditions" that help mitigate risks and identify available resources. When opting to repurpose LIBs, in the next step the integration of "key performance indicators" (KPIs) becomes integral for an effective performance measurement and management (PMM) system [32, 33]. So far, however, scientific literature does not address preconditions and KPIs for the market launch of SLB applications. It only includes KPIs for first-life LIBs (FLBs), such as in Armand et al. [34], Fink et al. [35], Dühnen et al. [14], or two reports from Batteries Europe [36, 37], with one specifically addressing safety KPIs [37].

Therefore, to further support the market launch and supply of EV SLB applications in line with the SDGs, the objectives of this study are to: (i) identify necessary preconditions; (ii) identify relevant KPIs; (iii) analyze the identified preconditions and KPIs according to their importance; and (iv) collect reference values for the KPIs. A mixed-methods approach was applied to achieve these objectives, including expert and problem-centered interviews, an online survey, and an explorative workshop.

2. Materials and Methods

The study design, shown in Figure 1 and described in more detail in the following, is based on a multi-scale and mixed-methods research process, integrating feedback loops at different stages to enhance engagement with stakeholders and uncover results iteratively.

2.1. Literature Analysis. In the first step, a thorough and systematic literature search was carried out in a wide range of media and online sources. After this initial research, a snowball search using previously discovered documents to identify further sources of relevant information was conducted. The resulting findings formed the basis for the empirical work of this study. Details on the keywords, search strings, topics, and sources of information used can be found in the Chapter 1.1 of the Supporting Information.

2.2. Data Collection and Validation. In this study, qualitative and quantitative research methods were applied. For the rationale behind the choice of both methods, see Sandelowski [38], who states that mixed methods help to broaden the scope of a study and improve its analytical power. Therefore, a

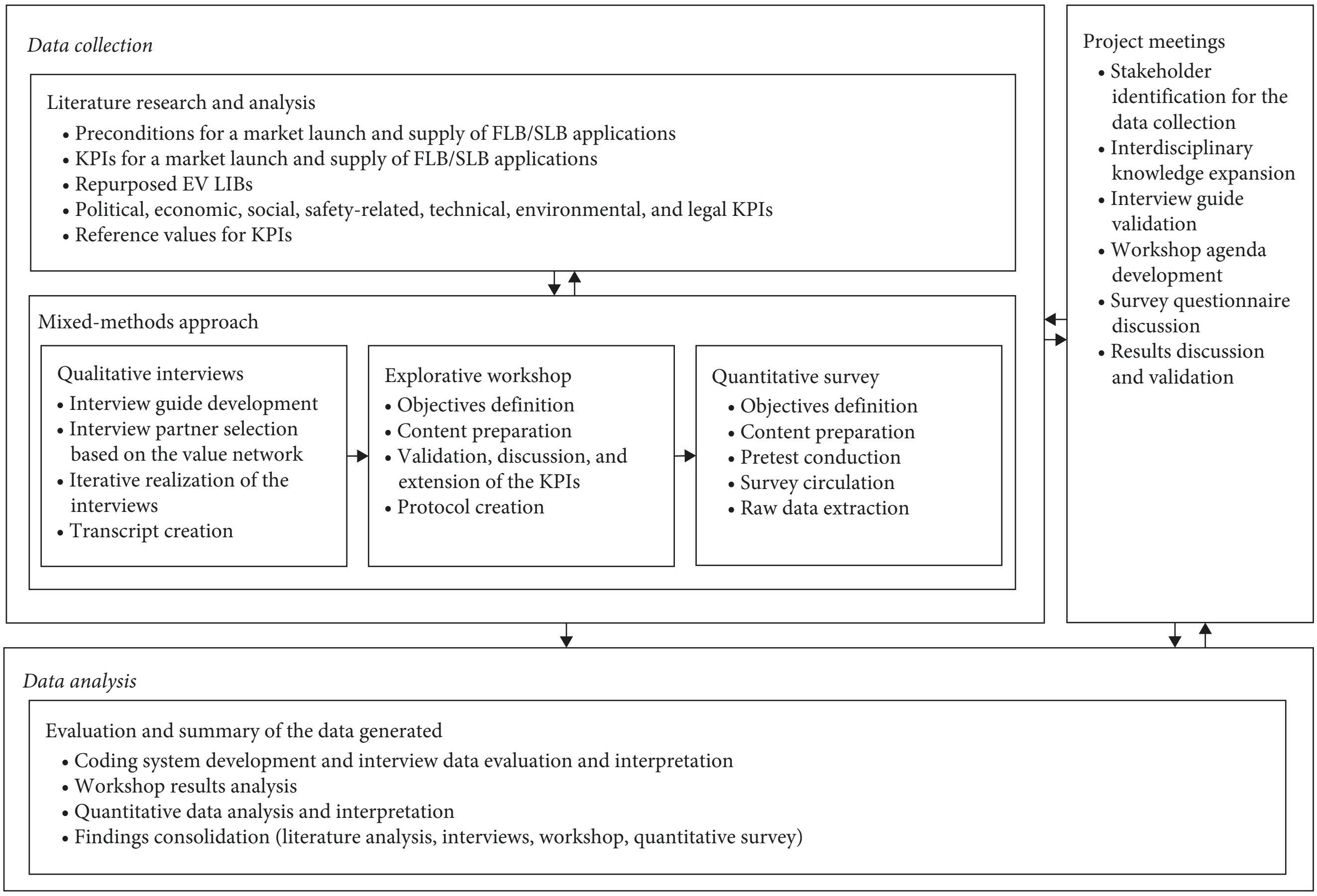

FIGURE 1: Applied iterative multilevel research design for data collection and analysis. EV, electric vehicle; FLB, first-life LIB; KPIs, key performance indicators; LIB, lithium-ion battery; SLB, second-life LIB.

quantitative testing study is often preceded by a qualitative, exploratory (hypothesis-generating) investigation [39]. The participants for both data collection methods were selected from a previously compiled contact list ($n = 290$) according to the research interest ("theoretical sampling"). The criteria for inclusion in the list required respondents to have prior knowledge of SLBs and to be actively involved in the LIB value network. In this context, a "value network" is the interconnected system of stakeholders collaborating to create, produce, and deliver goods or services, highlighting their interdependence within the LIB industry or ecosystem [40]. A particular emphasis was placed on experts based in Europe, as the regional focus of the study was on the European market and regulatory context. This approach aimed to ensure the heterogeneity of the interviewees and to identify representatives who are typical of their specific interest group, thereby improving the quality of the data and providing a wide range of insights. In addition, the participants of the quantitative survey had to give their consent to data processing in accordance with data protection regulations.

2.2.1. Qualitative Interviews. A series of expert and problem-centered interviews were conducted to gain first-hand insights into the research area. Expert interviews are effective for the collection of qualitative data in empirical social research, especially when it comes to deepening the knowledge of experts and addressing specific questions [41, 42]. The problem-centered interview introduced by Witzel [43], on the other hand, concentrates on gathering in-depth information on problems in poorly defined areas [44].

Qualitative interviews benefit from structuring techniques, with an interview guide playing a crucial role in maintaining coherence and situational relevance [43, 45]. For this study, an interview guide (cf., Table S1) was developed based on the situation-problem-implication-need (SPIN) approach [46]. If interviews encounter obstacles, the critical incident technique was to be applied [47]. The main objective of the interviews was to identify relevant preconditions and KPIs for a successful market launch of SLB applications.

Interview requests were sent to experts from the curated contact list via email and telephone at regular intervals. Initially, the focus was on engaging experts who are active in the field of SLBs across various stages of the LIB value network—those offering SLB solutions, conducting relevant research, or actively lecturing on the topic. The target group was subsequently broadened to include experts from the FLB sector who possess knowledge of SLBs, as well as experts from regulatory bodies, standardization organizations, and energy suppliers. In addition, recommendations from the interviews were leveraged to further expand the number of interviewees

Table 1: The interviewees' profile ($n=13$).

Expert ID	Expertise in the LIB value network	Organization type	Organization size	Duration (min)
E01	Supply first-life applications	Company	Medium	60
E02, E03*	Production of FLBs	Company	Medium	60
E04	Production of FLBs; repurposing of EoFL LIBs	Company	Medium	80
E05	Energy supply	Company	Very large	70
E06	R&D	Research institute	Very large	60
E07	R&D; standardization and regulation	Research institute	Very large	90
E08	Consultancy in the field of batteries	Company	Very large	80
E09	Modular power electronics	Company	Small	60
E10	R&D; LIB testing and analyzing	Company	Very large	70
E11	Repurposing of EoFL LIBs	Company	Medium	60
E12	Repurposing of EoFL LIBs	Company	Small	60
E13	Recycling and pretreatment of EoL LIBs	Company	Very large	60

Note: Organization size: micro (up to 9 employees), small (10–49 employees), medium (50–249 employees), large (250–499 employees), and very large (500 employees and more).

Abbreviations: EoFL, end-of-first-life; EoL, end-of-life; FLB, first-life LIB; LIBs, lithium-ion batteries; R&D, research and development.

*Simultaneous interview with two experts.

(following the "snowball principle"). This study adhered to the principle of theoretical saturation, determining that no new relevant insights were gained beyond 13 interviews, which were conducted anonymously between January and December 2022. Table 1 outlines the interviewees' profiles, including their expertise in the LIB value network, their organization type, and size.

2.2.2. Explorative Online Workshop. Utilizing workshops as a research methodology involves exploring specific scenarios to meet participants' expectations and generate reliable data [48]. In the context of the SafeLiBatt project (details on the project are provided in the Supporting Information), an exploratory online workshop was conducted on October 4, 2022. Invitations were sent to the experts from the contact list ($n=290$), 16 of whom responded positively to the invitation and took part in the workshop. These experts covered various sectors, including clusters and associations, consultancy, energy supply, LIB manufacturing, regulation, repurposing, research and development (R&D), as well as standardization. For the design and facilitation of the event, the project team played a central role. One part of the workshop was dedicated to KPIs. In this section, preliminary results of the interviews and literature analysis were presented, validated, discussed, and expanded. A recording of the workshop and protocols were created to capture and document all discussions. The workshop report is available in the technical report of Prenner et al. [49], and the presentation material used for the workshop is included in the Chapter 1.2.3 of the Supporting Information.

2.2.3. Quantitative Survey. Drawing from the literature analysis, findings from 13 qualitative interviews, and insights gained from a workshop, the online survey was developed using the tool SurveyMonkey. The language level was chosen to be suitable for the target group. Participants were required to agree to the data protection conditions in order to take part in the survey. The survey aimed to validate, rate, and potentially expand a compiled list of preconditions and KPIs that are essential for the market launch of SLB applications. For the importance rating, a 1–5 Likert scale was used, with 1 meaning "very important," 2 "important," 3 "moderately important," 4 "slightly important," and 5 "not important." In addition, the survey participants were able to provide relevant reference values for some KPIs. The complete version of the online survey can be found in Appendix A in the Supporting Information.

A pretest following Atteslander and Cromm [50] was conducted with five experts from the SafeLiBatt project to refine the survey and its content. This ensured the clarity of the questions to obtain reliable and valid information. Pretest results were not included in the final evaluation. For the main survey, it was not possible to conduct a full survey for economic reasons. Thus, probability sampling was used to reduce the number of samples [51]. Cluster sampling was deemed the most appropriate technique because the entire target population is not fully known, allowing for the formation of clusters within a smaller representation [51]. Overall, the survey was distributed between January and March 2023 via email to all contacts from the own contact list ($n=290$), promoted through email and LinkedIn within the SafeLiBatt project partner network, shared through the Batteries European Partnership Association (BEPA) newsletter ($n=641$) and the GSV Forum network ($n=1{,}000$). A total of 64 experts participated in the online survey, indicating a low response rate relative to the number of recipients. Reasons for nonresponse include ineligibility, inability to respond, or difficulties in establishing contact [51]. The authors of this study consider the high workload of experts in the field of LIBs to be the main reason for nonparticipation. In addition, indirect invitations via newsletters are often overlooked. More information on the distribution channels is available in the Chapter 1.2.2 of the Supporting Information.

Regarding the demographic and organization-related characteristics, the data shows that the majority of participants, almost 60%, belong to a company. The remaining percentages

Table 2: Descriptive statistics for the importance rating of the preconditions.

Preconditions	***N***	**Frequencies**					**Median**	**Std. deviation**
Importance rating (1–5)[a]	—	1	2	3	4	5	—	—
Information on battery specification and cell chemistry available	64	44	15	4	1	0	1.0	0.68
Compliance with relevant standards and regulations	64	38	18	4	3	1	1.0	0.92
Initial system values and battery history (incl. failures) of first-life available	63	31	24	6	1	1	2.0	0.84
Expertise in repurposing available	64	30	25	6	2	1	2.0	0.88
Easy to disassemble on pack level	61	28	18	7	6	2	2.0	1.13
No safety-related incidents and failures during first-life	63	26	21	13	3	0	2.0	0.90
Existing supplier stability	62	19	23	15	3	2	2.0	1.02
New BMS for repurposed application available	62	18	19	20	2	3	2.0	1.07
Easy to disassemble on module level	62	17	27	9	5	4	2.0	1.14
Min. 70%–80% remaining capacity	62	14	23	19	5	1	2.0	0.96
EoFL LIBs with similar performance available	62	13	20	19	8	2	2.0	1.07
Easy to disassemble on cell level[b]	62	8	11	14	11	18	3.0	1.40
Compatibility of the EoFL LIB properties with SLB application requirements[c]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Abbreviations: BMS, battery management system; EoFL, end-of-first-life; LIBs, lithium-ion batteries; SLB, second-life LIB.

[a] For the importance rating a 1–5 Likert scale was used, with 1 meaning "very important," 2 "important," 3 "moderately important," 4 "slightly important," and 5 "not important."

[b] Not included in the final precondition catalog due to low importance rating.

[c] This precondition was suggested by a respondent to the online survey and has not yet been ranked in terms of importance.

are distributed among 20.3% research institutions, 14.1% regulatory institutions, 4.7% clusters, networks, platforms, and associations, and 1.6% emergency service organizations (cf., Table S4). In terms of organization sizes, half of the study participants belong to a very large organization, 20.3% to small organizations, 14.1% each to micro and medium-sized organizations, and 1.6% to large organizations (cf., S6). Concerning the areas of activity within the LIB value network, the participants covered the entire value network, with the majority working in the R&D phase (cf., Table S5).

2.3. Data Analysis. The data obtained as part of the mixed-methods approach was analyzed using selected methodologies of qualitative and quantitative data analysis.

2.3.1. Qualitative Data Evaluation and Content Analysis. Qualitative content analysis is used to evaluate transcripts from qualitative data collection, involving exploration, interpretation, categorization, classification (including type formation), and theory construction [52]. Following Mayring's framework, both inductive and deductive category development approaches were applied [52]. Transcripts were coded using ATLAS.ti version 8.0.27.0, resulting in 22 categories that were eventually grouped into 4 category groups. Additional details are available in the Chapter 1.3 of the Supporting Information.

2.3.2. Quantitative Data Analysis. Statistical analyses of the quantitative data from the online survey were carried out using the IBM SPSS Statistics 26 tool. First, descriptive statistics were used to summarize the data and provide insights into the sample [53]. This involved analyzing the frequency distribution, the standard deviation, and the median. The median was chosen for this study because there is a highly skewed distribution. In this case, the median is often considered a more suitable measure of location than the mean [54]. In a next step, a nonparametric Kruskal–Wallis test was applied to determine whether there are statistically significant differences in the central tendency of the independent "organisation types" in relation to the "preconditions" and "KPIs." Due to the rather small sample size and the different group sizes within the organization types, the Kruskal–Wallis test was selected over more stringent tests [55]. For rejected Kruskal–Wallis tests, a Dunn–Bonferroni test was carried out for pairwise multiple-comparison to show which of the groups significantly differ from each other [56]. The results of the open-ended questions of the online survey were either included in the discussion if it was a general comment or feedback or added as a new KPI or precondition if applicable. Additional details on statements by the authors on open questions, data corrections, changes of terminology between the indicators in the online survey and the final version, as well as additional results of the statistical analyses that are not included in the main part of the paper, are presented in the Supporting Information.

3. Results and Discussion

3.1. Preconditions. In this study, "preconditions" are minimum requirements that must be met for an EoFL LIB to be considered for repurposing. Twelve preconditions were identified during the qualitative interviews. During the validation, evaluation, and expansion process of the preconditions from the interviews, which was facilitated by the online survey, one additional precondition was identified. Table 2 lists all these preconditions.

3.1.1. Statistical Analysis of the Precondition Importance Rating. Not all of the 64 survey participants completed the importance rating of the preconditions, as can be seen in Table 2. However, a total of at least 61 took part in all questions. It is assumed that the participants only answered the questions to which they were able to give a qualified answer. In terms of perceived importance, it could be noted that the preconditions are consistently considered very important or important. With "easy to disassemble on cell level" being one exception. This was also evident from the interviews, in which the interviewees stated that dismantling in repurposing facilities is currently largely carried out down to pack or module level, primarily for economic reasons. The preconditions most clearly regarded as very important are "information on battery specification and cell chemistry available" and "compliance with relevant standards and regulations," which both have a median of 1.0. As a result of the online survey, the precondition "compatibility of the EoFL LIB properties with SLB application requirements" was added retrospectively. Therefore, its importance has not yet been assessed. Based on the importance rating and the additional precondition identified during the online survey, the final catalog consists of 12 preconditions, which can serve as a checklist before starting repurposing of EoFL LIBs.

A Kruskal–Wallis test shows that the variable "organisation type" has no statistically significant influence on the individual preconditions, as the null hypothesis can be retained for each precondition ($\alpha \geq 0.05$). These results indicate that stakeholders from different types of organizations currently have the same opinion on the topic of preconditions. All numerical results of the Kruskal–Wallis *H*-test are available in the Tables S8, S12, S16, S21.

3.1.2. Structure and Underlying Information of the Preconditions. The preconditions identified can be organized into four categories: technical and safety-related, legal, environmental, and economic preconditions. Fulfillment of these preconditions using the list (cf., Table 2) can be checked if sufficient EoFL EV LIBs are available. The quantity of available EoFL EV LIBs refers to the total SLB quantity minus exports, damaged LIBs, and those stored in households. A high availability of EoFL LIBs is necessary, with the best case scenario being that no EoFL LIBs are exported to countries outside the EU in the future.

Technical and safety-related preconditions for repurposing LIBs include detailed "information on battery specification and cell chemistry available" such as information on the type of the cells or the cell integration (i.e., cell2module, cell2pack, cell2chassis). Another precondition is "initial system values and battery history of first-life available." Regarding initial system values, parameters like the date of manufacturing, ratings for nominal voltage, state of health (SoH), or capacity at begin-of-life (BoL) are considered relevant. With regard to data on the battery history, values on the LIB condition and safety over its entire life cycle (e.g., extreme values, damage mechanisms) are required according to the interviewees. These specifications should be provided by the manufacturer. According to Martinez-Laserna et al. [57], the technical viability of SLBs depends largely on the aging battery history of first-life. Interviewees emphasized in this context the importance of the operational range specified by the LIB manufacturer and its proximity to critical values. These values can be obtained by accessing BMS data or testing infrastructure. Testing infrastructure and measuring devices coupled with artificial intelligence (AI) or digital twin technology are being used increasingly, according to experts. As defined by the UL/ANSI/CAN Standard for Safety [17], this testing shall be conducted on the smallest intended disassembled unit for repurposing. In addition, experts highlighted that critical "safety-related incidents and failures during the first-life" must be absent for repurposing consideration. Based on an analysis of safety-related incidents, repairs, or information on the use of the battery, potential exposure circumstances (e.g., vehicle crash) must be identified, and if found, the LIB shall not be considered for repurposing [17]. However, if there is no evidence of an external or internal failure, the battery may be repurposed in the case of an accident [58]. Moreover, if possible, only the faulty module (or cell, depending on the battery design) can be replaced, according to an expert. Original equipment manufacturers (OEMs) typically hold information on initial system values, end-of-life (EoL) reasons, and accident events. Starting second-life operations without this knowledge carries a high product liability risk in the view of the interviewees. In the future, the battery passport will oblige OEMs to release (a certain part of) the history data, which could make application-related default values for LIB history available. The precondition "remaining capacity" must be seen in relation to the initial capacity and can be taken from the BMS. According to experts, 70% is a generally accepted value from the automotive industry. Furthermore, experts highlighted the importance of the availability of a "new BMS for the repurposed application" which enables safe control (e.g., charging rate, voltage limits, cell balancing). In addition, "EoFL LIBs with similar performance available" is necessary according to the interviewees, especially regarding the voltage level, charging curves, SoH, and capacity. Using EoFL LIBs of different performance levels would be feasible but raises control technology costs. These costs can be reduced through strategies of standardization and modularization that simplify system designs, implementing advanced BMS that optimize performance, employing machine learning (ML) algorithms for real-time performance predictions, achieving economies of scale, or working with manufacturers/OEMs. In the current ideal case, however, the SLB application uses LIBs from one specific EV model [14]. In any case, cells used for repurposing shall be of the same model and manufacturer [17]. One new technical and safety-related precondition emerged from the online survey, the precondition "compatibility of the EoFL LIB properties with SLB application requirements." This precondition was highlighted to ensure a safe use of the SLB application. Moreover, it needs to be ensured that modules/cells remain interchangeable as formats evolve.

At a legal level, the precondition "compliance with relevant standards and regulations" could be identified during the expert interviews. This includes SLB standards like the UL 1974 and IEC 63330, as well as standards and regulations

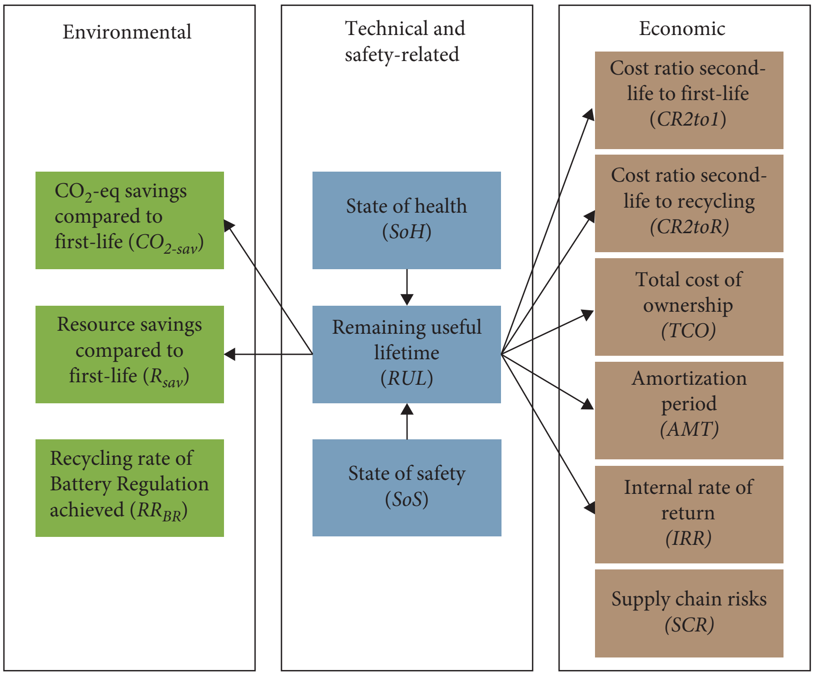

Figure 2: Twelve KPIs for the market launch of repurposed EV LIBs, which can be categorized into environmental, technical and safety-related, and economic KPIs. The arrows show the dependencies and interlinkages between the KPIs. EV, electric vehicle; KPIs, key performance indicators; LIBs, lithium-ion batteries.

concerning LIBs (e.g., UL 1642), transportation (e.g., SAE J2950, UN 38.3), and application-specific standards (e.g., UL 9540, IEC 62933-5-1, IEC 62933-5-2). To put SLB applications on the market, the repurposing company needs to be, of course, in line with any relevant market-related legal requirements.

With regard to the environmental dimension, repurposability was defined as a precondition, whereby it is a question of "easy dismantling" battery packs down to the module or the cell level, facilitated, for example, by screw or plug-in connections instead of using adhesives. Here, the extended producer responsibility (EPR), which is addressed in the Battery Regulation [18], is seen as an influencing factor by the interviewees. According to one survey participant, depending on the LIB design, dismantling down to cell level could become more attractive in the future. In this context, however, the trends toward cell2pack or cell2chassiss are more of a barrier [31].

At an economic level, "expertise in repurposing available" was identified as one precondition during the interviews. This includes expertise on the design for safety and safe dismantling of EoFL LIBs, particularly for modules with voltages exceeding 60 V, requiring specialized training for electrical safety, as well as for BMS installation and robustness assessment. Moreover, an "existing supplier stability" offering a continuous supply of EoFL LIBs was regarded as an essential precondition by the interviewees.

3.2. KPIs.

3.2. KPIs. In this study, "KPIs" are quantitatively or qualitatively measurable values that must be achieved for a successful market launch of SLB applications. This involves setting targets (the desired level of performance), keeping track of progress against that target, and fostering continuous improvement. In this way, the success of a business model can be objectively monitored, evaluated, and controlled with company internal PMM systems [59, 60]. In most cases, the KPIs are determined by various sub-indicators (="soft KPIs"). These sub-indicators can be interlinked and have an influence on each other. However, not all sub-indicators are applicable to every company but must be selected on a situation-specific basis. In the following sub-chapters, the identified KPIs are described and illustrated regarding their perceived importance, interlinkages, sub-indicators, and reference values.

Figure 2 shows an overview of all KPIs, which are categorized into three different groups: technical and safety-related KPIs, economic KPIs, and environmental KPIs. The "SoH," the "state of safety" (SoS), and the "remaining useful life" (RUL) belong to the technical and safety-related KPIs. These KPIs are particularly important, as aging processes change the LIB parameters, which, in turn, have an influence on critical safety aspects such as thermal runaway or onset temperature. The "cost ratio second-life to first-life" (CR2to1), the "cost ratio second-life to recycling" (CR2toR), the "total cost of ownership" (TCO), the "internal rate of return" (IRR), the "amortisation period" (AMT), and "supply chain risks" (SCR) form the economic KPIs. The TCO and IRR were retrospectively added resulting from the online survey. "CO_2-equivalent (CO_2-eq) savings compared to first-life" ($CO_{2\text{-sav}}$), "resource savings compared to first-life" (R_{sav}), and the "recycling rate of Battery Regulation achieved" (RR_{BR}) are considered environmental KPIs. The technical and safety-related KPIs and ultimately the summarized KPI RUL have an influence on most of the KPIs of the other two groups. As far as the economic KPIs are concerned, the RUL determines the price

Table 3: Descriptive statistics for the importance rating of the KPIs.

KPIs	N	Frequencies					Median	Std. Deviation
Importance rating (1–5)[a]	—	1	2	3	4	5	—	—
SoS[b]	56	41	13	1	1	0	1.0	0.61
R_{sav}	56	28	21	3	2	2	1.5	0.98
CR2to1	56	24	27	3	2	0	2.0	0.74
SoH	56	23	31	0	1	1	2.0	0.74
RR_{BR}	56	23	18	11	2	2	2.0	1.04
$\text{CO}_{2\text{-sav}}$	56	21	25	8	0	2	2.0	0.92
CR2toR	55	17	19	18	1	0	2.0	0.85
SCR	55	15	18	12	9	1	2.0	1.11
RUL	56	14	29	13	0	0	2.0	0.70
AMT	56	14	24	11	5	2	2.0	1.04
TCO[c]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
IRR[c]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Abbreviations: AMT, amortization period; $\text{CO}_{2\text{-sav}}$, CO_2-eq savings compared to first-life; CR2to1, cost ratio second-life to first-life; CR2toR, cost ratio second-life to recycling; IRR, internal rate of return; KPIs, key performance indicators; RR_{BR}, recycling rate of battery regulation achieved; R_{sav}, resource savings compared to first-life; RUL, remaining useful life; SCR, Supply chain risk; SoH, state of health; SoS, state of safety; TCO, total cost of ownership.

[a] For the importance rating a 1–5 Likert scale was used, with 1 meaning “very important,” 2 “important,” 3 “moderately important,” 4 “slightly important,” and 5 “not important.”

[b] Currently under definition; it will most likely be a %-value (0 = sure thermal runaway; 100 = completely inert).

[c] This KPI was suggested by a respondent to the online survey and has not yet been ranked in terms of importance.

and cost ratios, as well as the TCO, the IRR and the AMT. For the environmental KPIs, the RUL influences the $\text{CO}_{2\text{-sav}}$ and the RR_{BR}. The longer the RUL, the higher the savings and reductions.

3.2.1. Statistical Analysis of the KPI Importance Rating. Table 3 indicates that not all of the 64 survey participants completed the KPI importance rating. However, a total of at least 56 took part in all questions. It is assumed that participants responded only to the questions for which they could provide a qualified answer. Regarding the perceived importance of the KPIs, the descriptive statistics show that the KPIs were consistently rated as important and very important during the survey. The SoS stands out in particular as a very important KPI with a median of 1.0. Moreover, the environmental KPI R_{sav} was also considered to be of high importance with a median of 1.5. As a result of the online survey, the KPIs TCO and IRR were added retrospectively and thus have not yet been assessed in terms of their importance. Based on the importance rating and the additional KPIs identified during the online survey, the final catalog consists of 12 KPIs, which must be assessed for a successful market launch of SLB applications. The final selection of KPIs is shown in Figure 2.

A Kruskal–Wallis test shows that the variable “organisation type” has a statistically significant influence on two of the KPIs, the CR2toR and the R_{sav} ($\alpha \leq 0.05$) (cf., Tables S16 and S21). A subsequent pairwise comparison test according to Dunn–Bonferroni shows that the organization types “regulatory institutions” and “research institutions” differ significantly from “companies” in terms of the importance rating of the KPI CR2toR. The numerical values indicate that stakeholders from companies tend to consider this KPI to be less important than stakeholders from the other organization types (cf., Table S17 and Figure S6). With regard to the KPI R_{sav}, the organization types “clusters, networks, platforms, and associations” differ significantly from “emergency service organizations,” “companies,” and “research institutions” as well as “companies” from “regulatory institutions.” Based on the numerical values of the test, stakeholders from “clusters, networks, platforms, and associations” consider this KPI to be the least important compared to all other stakeholder groups. However, “regulatory institutions” and “research institutions” also appear to consider it less important (cf., Table S22 and Figure S7). All other results of the Kruskal–Wallis H-test (cf., Tables S12, S16, and S21) indicate that stakeholders from different organization types currently share similar positions on the topic of KPIs.

3.2.2. Reference Values. Since KPIs are measurable values that must be achieved for a successful market launch and supply of SLB applications, it is important to have reference values. For four of the KPIs listed in Table 3, no reference values were collected: For SCR and RR_{BR}, qualitative rather than quantitative units of measurement are to be used. For the SCR, the scale ranges from “low” to “medium” to “high” and must be low. The RR_{BR} is a “yes” or “no” indicator, which must be answered with “yes.” The other two indicators, the TCO and IRR, are newly added KPIs from the online survey and were therefore not included in the collection of reference values. For all other KPIs, reference values were collected, and the descriptive statistics of this data set are presented in Table 4.

Starting with the technical and safety-related KPIs, the calculated median for the SoH is 75.0% of the remaining capacity. For the SoS, which is currently under definition, the median is 95.0%. According to the survey participants, safety is the highest priority and must be properly managed and monitored. It needs to be ensured that SLBs are no less secure than FLBs. Overall, an accurate calculation of the SoH

Table 4: Descriptive statistics for the KPI reference values.

KPI category	KPI	Unit	*N*	Median	Std. deviation
Technical and safety-related KPIs	SoH	%	$23^{b,c}$	75.0	14.77
	SoS[a]	%	$23^{b,c}$	95.0	14.93
	RUL	Cycles	$15^{b,c}$	1,000.0	1,243.38
	RUL	Years	$21^{b,c}$	5.0	2.74
Economic KPIs	CR2to1	Ratio	$20^{b,d}$	0.7	0.20
	CR2toR	Ratio	$15^{b,d}$	0.7	0.22
	AMT	Years	$21^{b,c}$	4.0	4.10
Environmental KPIs	$CO_{2\text{-sav}}$	%	10	41.5	31.52
	R_{sav}	%	9	50.0	37.20

Abbreviations: AMT, amortization period; $CO_{2\text{-sav}}$, CO_2-eq savings compared to first-life; CR2to1, cost ratio second-life to first-life; CR2toR, cost ratio second-life to recycling; KPIs, key performance indicators; R_{sav}, resource savings compared to first-life; RUL, remaining useful life; SoH, state of health; SoS, state of safety.

[a] Currently under definition; it will most likely be a %-value (0 = sure thermal runaway; 100 = completely inert).

[b] For "greater/smaller than XY," indicated min./max. values were used.

[c] For "value ranges" the mean value was used.

[d] Possible values = "1"; "0.9"; "0.8"; "0.7"; "0.6"; "<0.5."

and SoS is regarded as key. In terms of the RUL, the calculated median for the expression of this KPI in cycles is 1,000.0 and in years 5.0. Several survey participants emphasized that this KPI depends heavily on the usage and cycling conditions as well as the SoH of the LIB (cf., Figure 3). Further influencing factors are the application and LIB type, according to experts. They expect a longer remaining lifetime for lithium-iron-phosphate (LFP) than for lithium-nickel-manganese-cobalt-oxide (NMC) SLBs. One survey participant reported practical experience with a system that has been in operation for more than 2000 cycles and is still running. A look at the literature shows that currently available values for the expected RUL also depend on the application and the LIB type. A study of Gaines [61] presents values ranging between 5 and 10 years for SLB applications like utility load leveling. Casals et al. [62] speak of a possible RUL of around 6 years in area regulation grid services and about 30 years in fast EV charge support applications. They base their results on models analyzing four stationary application scenarios. Tong et al. [63] applied an accelerated cycle test on an LFP SLB cell used for a photovoltaic (PV) EV charge system. The results indicate a possible RUL of 1,435 cycles for the SLB cell investigated. If the results are extrapolated to an entire battery pack, the RUL is 5.5 years, according to the authors. In general, the possible RUL values from the literature correspond well with the reference values collected in the online survey.

As far as the reference values for the economic KPIs are concerned, the median for the CR2to1 and the CR2toR is 0.7 in each case. This means that an SLB application must be 30% cheaper than an FLB application or recycling. According to one survey respondent, the cost target window is defined by the price of an FLB (possibly minus a discount) at the upper end and the recycling value at the lower end. The technical KPIs, as well as the application and LIB type, have an influence on these two KPIs (cf., Figure 3). Values from verbal sources and literature on CR2to1 correspond well with the online survey values. In two presentations, the speakers referred to cost savings of up to 30% when using SLBs [64, 65]. This is consistent with the content of an expert interview in which the interviewee mentioned that they are able to offer their customers a CR2to1 of 0.7. Moreover, a cost-benefit analysis (CBA) on home storage systems, comparing an FLB and SLB system, showed a cost reduction of around 20% [49]. In terms of the KPI AMT, the calculated median is 4.0 years, as can be seen in Table 4. The literature reports values between 1.5 and 10 years. In this context, Debnath et al. [66] applied a system model in which grid-compatible vehicles (i.e., EV and plug-in hybrid EVs (PHEV)) and SLBs were combined to provide backup energy. Their simulation results show a payback period of 1.5 years for the SLBs. A techno-economic analysis of the use of SLBs from plug-in EVs (PEV) reveals expected AMT from 7 to 10 years [67]. Interviewees mentioned an estimated AMT of around 6 years. One online survey participant highlighted a possible similarity to industrial plants, which are supposed to pay off after 2 or 3 years. For the newly added KPI IRR, one survey respondent mentioned a reference value of at least 20% to get into the market. According to this expert, the IRR may decline to 10% in the future, depending on the level of experience and the development of inflation and its influence on the weighted average cost of capital (WACC).

At the level of environmental KPIs, the calculated median for $CO_{2\text{-sav}}$ is 41.5% and for R_{sav} is 50.0%. Most of the currently available values for savings in CO_2 and resources originate from life cycle assessments (LCAs) and product environmental footprint (PEF) calculations, which are, however, based on more holistic and complex calculation methods than those suggested for the KPIs. For $CO_{2\text{-sav}}$, the values calculated for the reduction of the global warming potential (GWP), which are expressed in kg CO_2-eq, can be used as a rough orientation. However, according to experts, it is difficult to find comparable values in the literature, as most of the analyses use different system boundaries, LIB types, use cases, and service lifetimes. Consequently, the values from the literature presented below can only serve as a rough guide and must be analyzed in detail with regard to the underlying assumptions

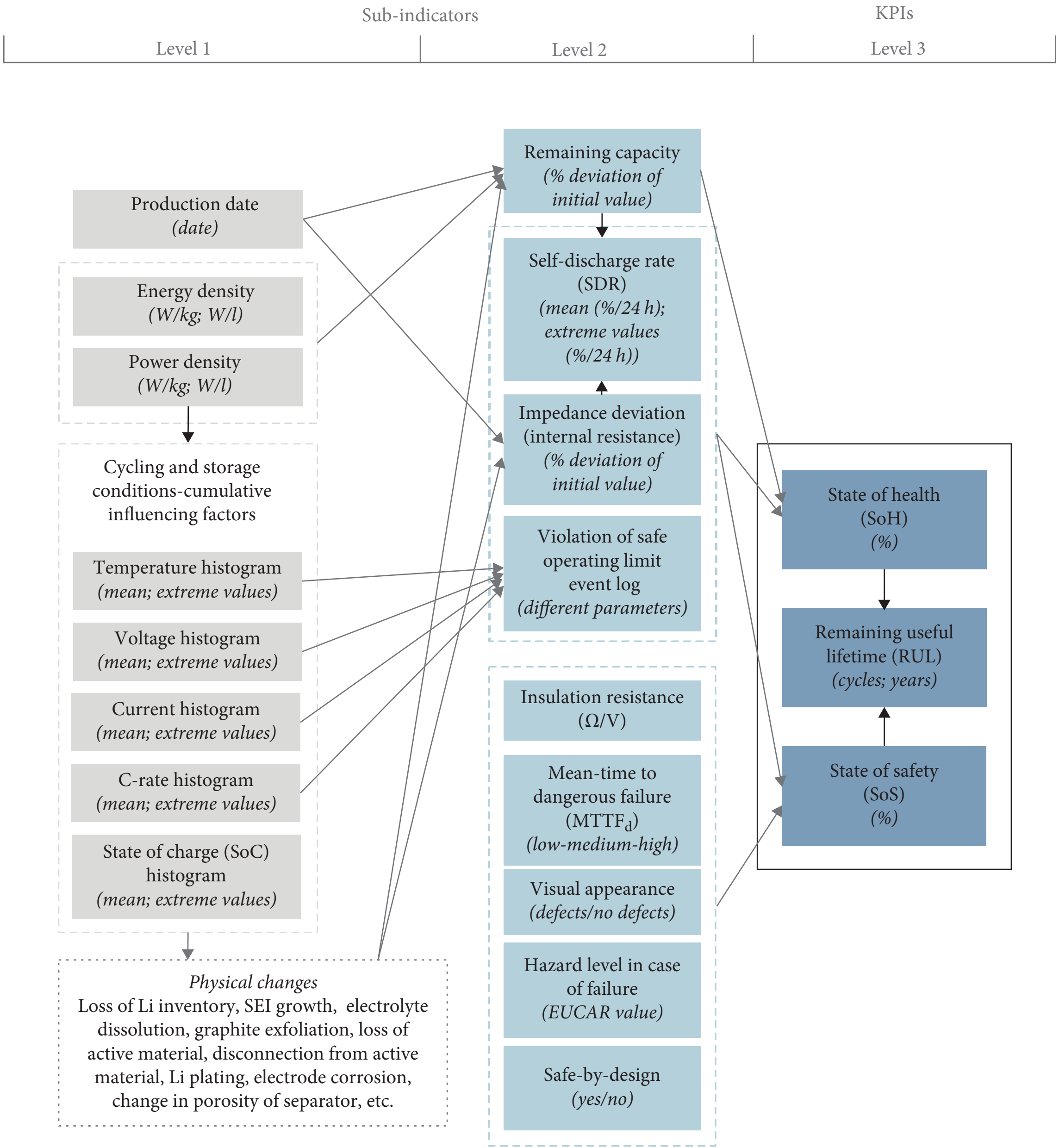

Figure 3: Underlying sub-indicators and determining factors to calculate the three technical and safety-related KPIs for the successful market launch of SLB applications, including the visualization of interlinkages and different indicator levels. KPIs, key performance indicators; SLB, second-life lithium-ion battery.

and specifications for the respective use case. For example, different LCA studies investigated CO_2-eq savings when using repurposed EV LIBs for PV-coupled home storage systems. Two studies show similar results with CO_2-eq savings of around 16% [23] and 15% [25], whereas another study presents results of 34 or 39% CO_2-eq savings depending on the recycling scenario [49]. A further study examined a PV-coupled SLBESS for a residential building that is connected to the grid. In this case, CO_2-eq savings of about 31% were calculated [26]. In a presentation, a possible 48% reduction of CO_2-eq was stipulated without any further information on the specific use case [65].

Overall, the data for all KPI reference values in Table 4 show a large variance, which shows how difficult it currently is for experts to define reference values in this emerging technology area. This is also reflected in the literature, where no applicable reference values could be found for some of the KPIs (i.e., SoS, CR2toR, R_{sav}). As far as the technical and safety-related KPIs are concerned, figures from the battery passport may serve as reference values in the future.

3.2.3. Structure and Sub-Indicators of the Technical and Safety-Related KPIs. Already existing technical and safety-related KPIs with different objectives and focussing on FLBs can be found in the literature. For example, Armand et al. [34] define performance indicators for automotive applications; Dühnen et al. [14] describe "safety," "lifetime," "fast charging," "power density," and "energy density" as relevant FLB performance indicators. Safety KPIs from the end-user point of view concerning the operation of an LIB can be found in a report by Batteries Europe [37]. In this report, "heat," "pressure," "hazardous gas emission," "onset temperature oxygen evolution," "propagation (cell-to-cell) temperature (outside the system)," and "entering in thermal runaway" are defined as KPIs for FLBs on material, cell, and pack level. A further study from Batteries Europe defines a set of technical KPIs for the different segments of the LIB value chain [36]. However, no technical and safety-related KPIs for the successful market launch of SLB applications have yet been defined. Building on the results from the literature, findings from the qualitative interviews, and the quantitative online survey, technical and safety-related KPIs for SLB applications were developed within this study. Figure 3 shows these KPIs, the sub-indicators required to calculate the KPIs, as well as the links between the various indicators.

The indicators required to calculate the technical and safety-related KPIs can be categorized into two different sub-indicator levels: The first level for the calculation of the technical and safety-related KPIs contains the cycling and storage conditions, which are, according to interviewees, decisive indicators for cell development and battery aging. Values in the form of histograms are recommended for these determining factors, as histograms require less data than other approaches, such as time traces. Specifically, histograms are needed for "temperature," "current," "voltage," "C-rate," and "state of charge" (SoC). The data for these indicators is measured by the BMS. According to an expert, an application-specific safe operating temperature range for SLB applications can be defined based on the values of the temperature histogram. As far as the C-rate and the current histogram are concerned, both are linked to each other via the capacity. The cycling and storage conditions are in further consequence responsible for physical changes within the LIB, like, for example, the loss of lithium inventory (LLI), solid electrolyte interphase (SEI) growth, electrolyte dissolution, lithium plating, or loss of or disconnection from active material. Besides the cycling and storage conditions, the "production date" as well as "energy density" and "power density" are located at the first level. The production date is included in the first registration. In this respect, the rapidly developing battery technology may have an impact on SLB applications, according to experts.

At the second level, several indicators were identified that are linked in different ways to the sub-indicators of the first level (cf., Figure 2). The "remaining capacity" of an EoFL EV LIB is in principle at least 70%, a value that is guaranteed by most European car manufacturers [9]. Interviews revealed that the capacity of EoFL EV LIBs is currently often above 90%, resulting from contracts with OEMs who provide LIBs from test vehicles, "B-cells," or unused LIBs. In general, the remaining capacity is strongly influenced by cycling and storage conditions. The "self discharge rate" (SDR) indicates the rate at which an LIB loses its charge when not in use. Another important sub-indicator in the view of experts is the "impedance deviation," which contains information related to changes in the internal resistance of an LIB or the intercalation process that may indicate abnormal changes. The "violation of safe operating limit event log" contains different parameters like the total number of events, their order and duration, or combinations of events. The UL/ANSI/CAN Standard for Safety [17] introduces limits for the total number of error messages above which an EoFL LIB may no longer be used for repurposing unless dedicated tests prove its safety. Regarding "insulation resistance," this indicator is only applicable for pack and module level. The "mean time to dangerous failure" ($\mathrm{MTTF_d}$) should be the same for SLBs as for FLBs in the view of experts, and thus, high values are preferrable. According to DIN EN ISO 13849–1:2023 [68], values range from low ($3\ \text{years} \leq \mathrm{MTTF_d} < 10\ \text{years}$), over medium ($10\ \text{years} \leq \mathrm{MTTF_d} < 30\ \text{years}$), to high ($30\ \text{years}$ $\mathrm{MTTF_d} < 100\ \text{years}$). Complete failures occur due to mechanical, electrical, or thermal influence and may result in a thermal runaway. The "visual appearance" refers to external abnormalities such as cracks, swellings or burn marks that can be detected by visual inspection [17]. For repurposing, no visual defects may be present. Furthermore, the "hazard level in case of failure" needs to be assessed, for example, using the well-established European Council for Automotive R&D (EUCAR) levels. These hazard levels range from 0 to 7, where 0 stands for "no effect" and 7 for "explosion" [69]. Finally, it was regarded as important to guarantee a "safe-by-design battery structure," addressing the inclusion of propagation mitigation systems at different levels. At cell level, for example, early venting or charge disconnection functions are possible safety factors. At module level, spacings or heat traps can be implemented, and at pack or rack level, insulation, cooling systems, or specific housing materials are safety factors that can be included to mitigate propagation, according to experts. Ultimately, an existing probability of failure or thermal runaway at the cell level can be acceptable if it is proven that it will remain a local event and not propagate to neighboring modules.

The sub-indicators on levels one and two determine the KPIs on the final KPI level, which comprises the SoH, SoS, and RUL. According to the UL/ANSI/CAN Standard for Safety [17], the SoH describes the ratio of the original energy capacity of the LIB (in Ah) to the current one and is expressed as a percentage. It thus serves as a quantification of the battery's condition and expected performance level for repurposing [17]. For repurposing, it was recommended to have cells/modules with a similar SoH due to economic reasons, as the weakest cell/module determines the total capacity. However, modular multilevel converter (MMC) technologies can help to overcome this barrier [31]. An issue is the lacking standardized definition and calculation method for the SoH. According to a survey participant, each OEM calculates the SoH in a different way, which leads to difficulties in comparing LIBs from different OEMs. Like the SoH, the SoS is dependent on several sub-indicators and specified as a percentage (cf., Figure 3). In this case too, a standardized definition and calculation method would be crucial, but this is not yet available. However, a common definition is currently being developed for the SoS. In terms of testing, according to one survey participant, OEMs and/or designers have an advantage as they have a higher level of knowledge to qualify and test the EoFL LIBs and propose them for a second life. Besides laboratory testing, AI, ML, and digital twins offer promising opportunities for the development of prediction tools for the SoH and SoS. Both of these KPIs, the SoH and the SoS, are necessary to determine the RUL, according to experts. The RUL can be expressed in cycles or years and is dependent on the LIB type (i.e., cell format and chemistry) as well as the second-life application and the use [62]. Survey participants highlighted the RUL not only as important for a successful market launch but also as an important indicator on the customer side for a purchase decision.

3.2.4. Structure and Sub-Indicators of the Economic KPIs. In the literature, economic KPIs are only available for FLBs, for example, from Armand et al. [34] and Dühnen et al. [14]. These authors describe "costs" as an economic KPI. Furthermore, a study from Batteries Europe defines a set of economic KPIs for the different segments of the LIB value chain [36]. For the successful market launch of SLB applications, however, no economic KPIs have been defined so far. Based on this starting point, the findings from the qualitative interviews and from the quantitative online survey, this study developed economic KPIs for a successful market launch of SLB applications. Figure 4 presents these KPIs, the sub-indicators required to calculate the KPIs, and the interlinkages between the various indicators. Costs are also reflected in several of the second-life indicators.

The indicators required to calculate the economic KPIs can be categorized into three different sub-indicator levels: The first level for the calculation of the economic KPIs contains the sub-indicators "labor costs" and "energy costs." According to interviews and the literature, these sub-indicators include the "LIB-removal for the vehicle," "disassembly," "evaluation and testing" of the EoFL LIB, "installation of new components," "assembly of the SLB application," and "commissioning" [8, 36]. Repurposing costs decrease at module and pack level compared to cell level. This is, according to experts, because manual labor is one of the major cost drivers. However, robotic disassembly, as offered by a few companies, has a cost-reducing effect but is currently limited to relatively large EV LIB packs. Standard LIB sizes and types as well as a unified European denomination on each unit (cell, module, pack) would facilitate the disassembly and assembly in the view of survey participants. With regard to evaluation and testing, according to interviewees, it requires more effort if no BMS access is granted by the OEM. Finally, depending on where the repurposing facility is located, country-specific hourly rates and energy costs are required for the calculation.

At the second level, capital expenditure (CAPEX) and operational expenditure (OPEX) are the overarching categories of the different costs. Starting with the CAPEX, apart from labor and energy costs, there are several other indicators building the basis for the "costs for repurposing" and the "costs for SLB applications." The "market price of an EoFL LIB" is dependent on the LIB type but also technical and safety-related KPIs such as the SoH, SoS, and RUL and their determining sub-indicators (cf., Figure 3). The market price for EoFL LIBs is substantially affected by the availability and costs of raw materials, political decisions regarding incentives, import duties, or penalties for disposal of LIBs, and other economic factors like, for instance, economies of scale or market competition. The decline in the price of FLBs over the last 10 years is currently slowing down, with buyers of EoFL LIBs being seen as buyers of future assets. One interviewee suggested introducing an SoH-cost matrix for flexible pricing. Depending on how much capacity can still be utilized, the prices would be higher or lower (i.e., lower costs with less SoH). However, the market for EoFL LIBs is not well developed, as most OEMs do not want to have SLBs on the market due to several reasons, such as not wanting to disclose data with the LIBs or fearing a loss of reputation due to potential safety issues [31]. This unwillingness to transfer data may also result in data having to be purchased from OEMs, which is reflected in the indicator "transfer costs for BMS data from OEMs". The battery passport will provide a small remedy here, as it will require a minimum of data access. However, most likely no proprietary aspects and detailed dynamic usage data will be provided [31]. Further indicators are the "costs for new components" like, for example, for a BMS, an energy management system (EMS), or connectors, as well as "disposal costs for unsuitable LIB components." Disposal costs are a newly added sub-indicator resulting from the online survey, which, according to experts, are country-specific values and arise for LIBs that are not suitable for a second life. In addition, "costs for recertification and re-standardization" must be considered. These costs are dependent on the type of certification and standard. Recertification is particularly relevant in the view of experts when dismantling is carried out down to cell level, as some certifications may lose their validity (e.g., the European conformity CE marking) [31]. Economic incentives arise through governmental interventions such as subsidies, tax reductions, or sustainability regulations imposed by governments and are reflected in the indicator "direct and indirect governmental interventions." Another major cost driver, in the view of experts, is "warranty costs." These costs are dependent, like the market price, on the LIB type and the technical and safety-related KPIs (cf., Figure 3). In the case of FLBs, the manufacturers bear a certain risk, depending on the contract, if the LIBs are operated within the specifications and an incident occurs. In the case of SLB applications, the repurposer bears the risk and provides guarantees for potential safety incidents. These potential safety incidents are also reflected in the indicator "discount for safety concerns and decreased capacity," which was newly added as a suggestion from a survey participant. "Costs for the transport of dangerous goods" are country-specific and depend on the average haul distance, with short distances being preferred, according to experts. Regarding OPEX, costs for "insurance" and regular "maintenance" were identified [49].

The third level for the calculation of the economic KPIs includes the indicators "costs for an FLB application" and "costs for an SLB application." These prices depend on the LIB and application type as well as on the previously

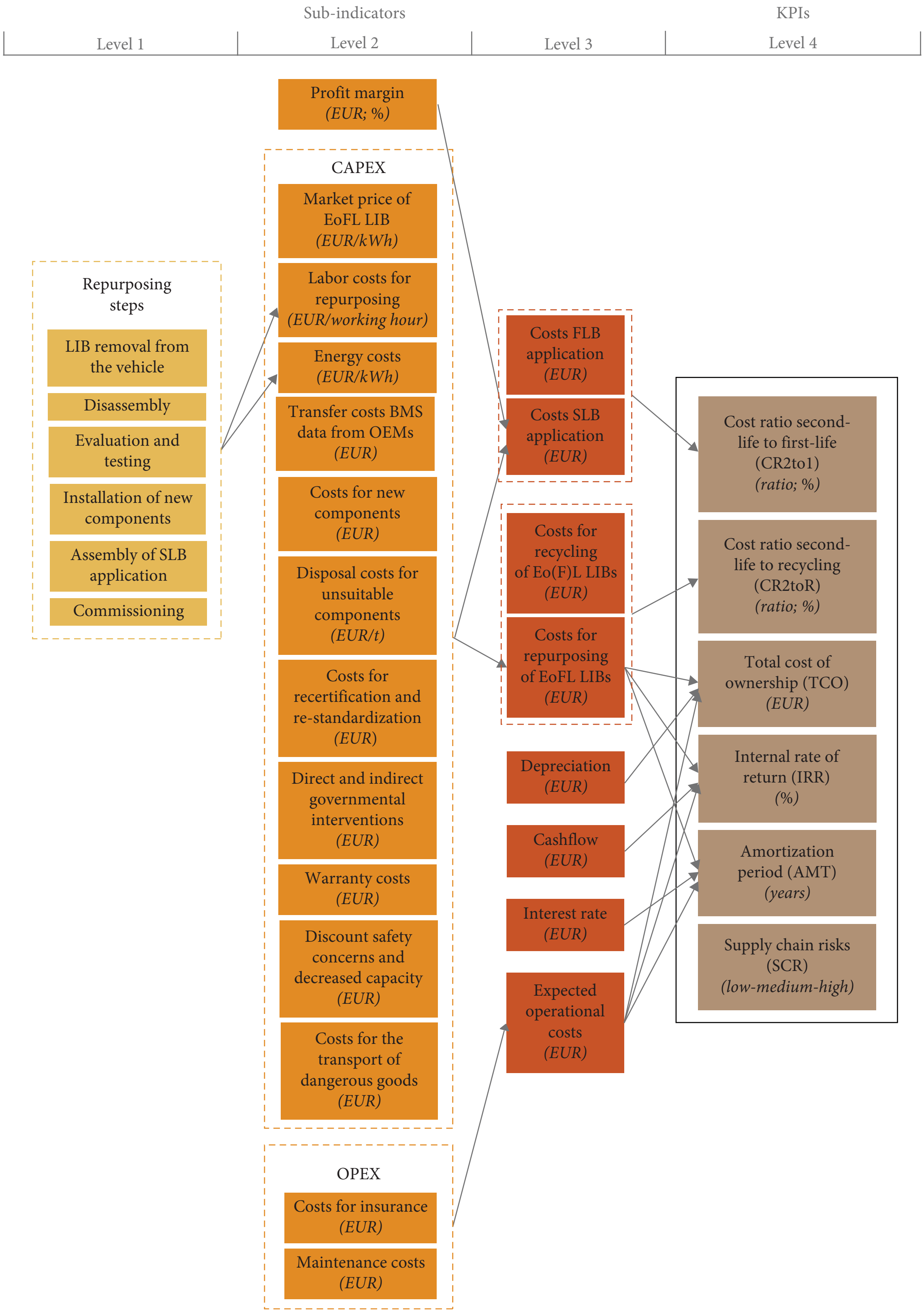

Figure 4: Underlying sub-indicators and determining factors to calculate the six economic KPIs for the successful market launch of SLB applications, including the visualization of interlinkages and different indicator levels. KPIs, key performance indicators; SLB, second-life lithium-ion battery.

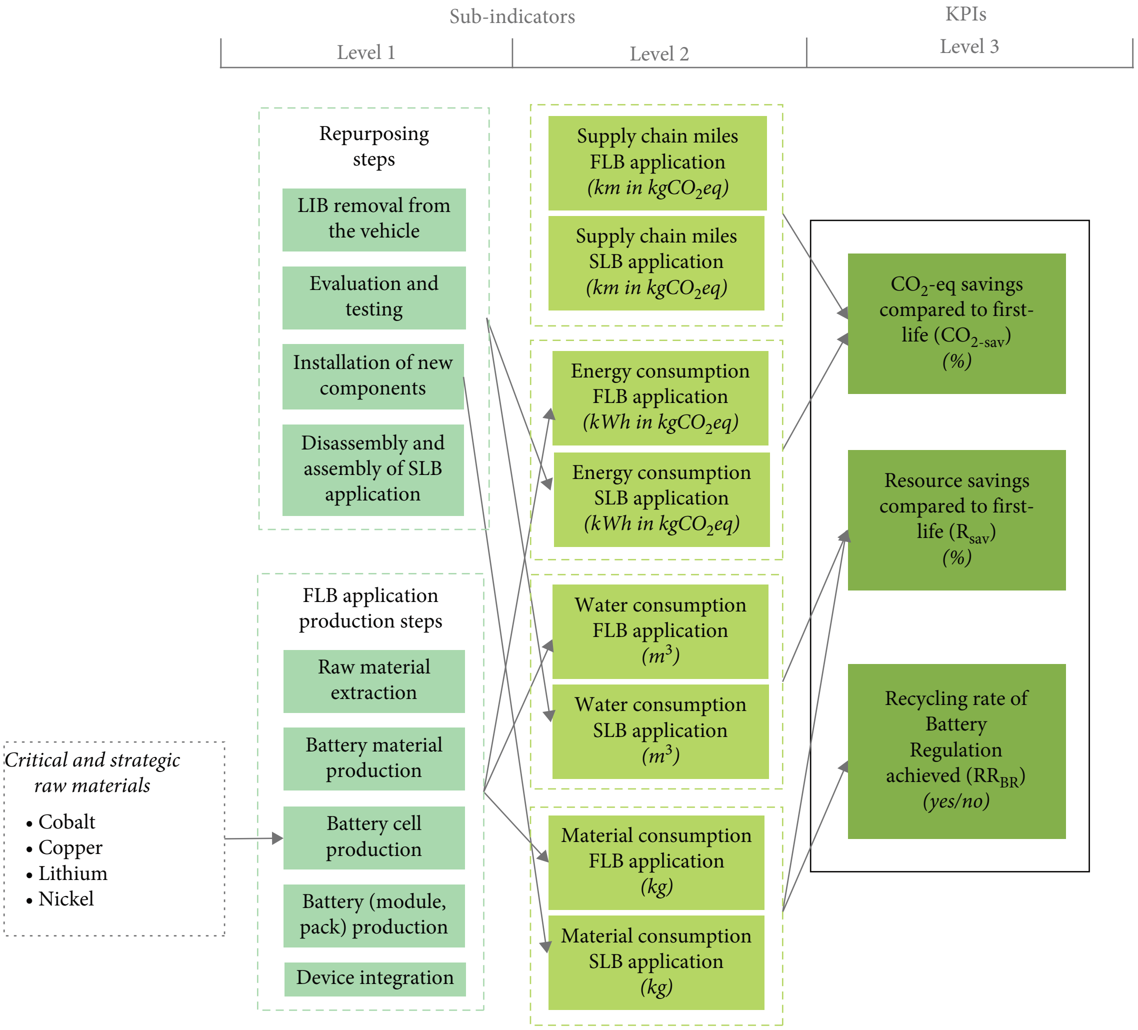

Figure 5: Underlying sub-indicators and determining factors to calculate the three environmental KPIs for the successful market launch of SLB applications, including the visualization of interlinkages and different indicator levels. KPIs, key performance indicators; SLB, second-life lithium-ion battery.

described sub-indicators. Furthermore, “costs for recycling of an EoFL or EoL LIB” is an indicator at this level. According to experts, these costs depend on the type of recycling process (i.e., pyro- or hydrometallurgical recycling, including thermal or mechanical pretreatment) and are country-specific. The indicator “costs for repurposing of EoFL LIBs” differs from the cost for an SLB application only in that it does not include a profit margin, which is retailer-specific. Additional indicators resulting from the online survey and serving as a basis for calculating the KPIs are “expected operational costs,” which depend on the usage and final application, “depreciation,” “cashflow,” and the “interest rate.”

The sub-indicators on these three levels determine the KPIs on the final KPI level, which comprises the CR2to1, CR2toR, TCO, IRR, AMT, and SCR. The CR2to1 reflects the price competition of SLB applications with first-life ones and is expressed as a ratio or percentage. SLB applications should offer about the same functions and cost less than FLB applications, in the view of experts. The CR2toR reflects the same problem as before, but now the question arises as to whether it is economically advantageous to include an additional R-principle in the form of repurposing before a final recycling. This KPI is also specified as a ratio or percentage. The newly added KPIs from the online survey include the TCO, which is the sum of the initial costs plus maintenance costs minus residual value and expressed in Euro (or any other currency), and the IRR, which is widely used for long-term investments in the energy sector and specified as percentage. The AMT reflects the time required to fully recover the initial cost of the system through savings, revenues, or other financial benefits associated with the operation of the SLB application and is expressed in years. Finally, the KPI SCR was mentioned by experts, which depends on factors such as the main global producers or import reliance and must be low [29].

3.2.5. Structure and Sub-Indicators of the Environmental KPIs. Existing literature contains environmental indicators with different objectives focussing on FLBs. For example, Armand et al. [34] define ”recycling targets” for automotive applications. Moreover, Dühnen et al. [14] describe “second-life," "renewable resources," "carbon footprint," "recyclability," "element abundancy," and "material accessibility" as relevant performance indicators. A study from Batteries Europe defines a set of environmental KPIs for the different segments of the LIB value chain [36]. For a successful market launch of SLB applications, however, no specific environmental KPIs have been defined so far. Building on the findings from the literature, results from the qualitative interviews, and the quantitative online survey, environmental KPIs were developed as part of this study. Figure 5 shows these environmental KPIs, the sub-indicators required to calculate the KPIs, and the links between the various indicators. Although there are similarities with some of the indicators used in LCA and PEF calculation, the environmental KPIs and sub-indicators of this study are independent indicators. Since conducting an LCA or PEF is often a complex and time-consuming task, the identified environmental indicators should allow for relatively easy performance measurement of a successful market launch of SLB applications.

The sub-indicators required to calculate the environmental KPIs can be categorized into two different levels. At the first level, according to experts, the production steps are decisive indicators for the "energy and water consumption" needed to produce FLB applications. These steps of the FLB value cycle include "raw material extraction," "battery material production," "battery cell production," "battery (module, pack) production," and "device integration." On the contrary, for the "energy and water consumption" needed to produce SLB applications, the repurposing steps "LIB removal from the vehicle," "evaluation and testing," "installation of new components," as well as "disassembly and assembly of the SLB application" from the SLB value cycle are perceived as important by experts. As far as "material consumption" is concerned, the production of LIB cells, modules, and packs for the manufacture of FLB systems and the use of new components for the production of SLB systems are relevant. In this regard, the critical and strategic raw materials, including "Cobalt," "Copper," "Lithium," and "Nickel," which are further used to produce the cathode material for LIB cells, are important. All other materials used for cell, module, and pack production (e.g., anode material, housing, cables) are not listed as they differ from LIB to LIB and must be specified by the expert using this KPI overview. Although this also applies to the critical raw materials, they are still included as their relevance for LIBs and for greater sustainability in terms of reduced impact on the biosphere, less waste generation, and increased security of supply is highlighted in the European Commission's report on "Critical Raw Materials and the Circular Economy" [70].

The indicators at the second level differ in their focus on the production of FLB or SLB applications. Values for "energy consumption" and "supply chain miles" need to be converted into CO_2-eq. In this regard, short transport distances are preferable. "Water consumption" and "material consumption" are further indicators, according to experts. These indicators were regarded as the most important ones by the experts in terms of resource consumption during the production of FLB and SLB applications. For material consumption, different levels of detail are possible for the assigned sub-indicators. For FLBs, this depends on factors such as the LIB type or the housing used. For SLBs, the application specifications are crucial, e.g., whether entire packs or modules are used for repurposing. In this case, the focus is on the material used for newly installed components. For both FLB and SLB systems, the available information is a decisive factor.

The sub-indicators from the first and second levels determine the KPIs at the KPI level, which are the $CO_{2\text{-sav}}$, R_{sav}, and RR_{BR}. These indicators cover CO_2 and material savings that are possible due to the extension of the service life by a second life and the recovery of materials, in particular critical metals, by recycling. The KPI $CO_{2\text{-sav}}$ reflects the differences between FLB and SLB applications in terms of the CO_2 emissions generated during transportation and through production-related energy consumption. These two sub-indicators do not claim to be exhaustive for LIB-related CO_2 emissions but were selected because, according to experts, they account for the largest share of CO_2 emissions and are relatively easy to calculate. The KPI $CO_{2\text{-sav}}$ is expressed in percentage. The R_{sav} also reflects the differences between FLB and SLB applications and is specified as percentage. In this context, one expert pointed out that this indicator may not be applicable when compared to recycling. This is due to the fact that more new-generation LIBs could be produced with the materials obtained from recycling, as they require fewer materials, which represents an ecological advantage and would favor recycling over repurposing [49]. However, this study assumes that recycling takes place after repurposing anyway as a "chain of reasoning" in the sense of a functioning circular economy. This means that the production of new LIBs from recycled materials is merely delayed. Finally, the KPI RR_{BR} must be met. This corresponds mainly to the specified recycling rates and recycled content of the critical and strategic raw materials to be used [18].

4. Conclusions

In line with the principles of the circular economy, the repurposing of EoFL EV LIBs as an intermediate step before recycling is a key strategy for improving sustainability. To promote the repurposing of EoFL EV LIBs and facilitate manager and investor decisions, this study defines and analyses necessary preconditions and KPIs for the successful market launch of SLB applications. If all preconditions are met, the repurposing can start, and KPIs need to be applied to manage and monitor the performance of the market launch of SLB applications. The findings highlight:

- Twelve preconditions, which can be used as a checklist to ensure the technical, economic, and legal feasibility of repurposing. The "availability of information on battery specification" and "compliance with standards and regulations" were considered very important preconditions.
- Twelve KPIs with reference values as an initial guide for repurposing facilities. In this regard, the KPIs "SoS" and "R_{sav}" were rated as highly important.

However, future research needs to refine these initial findings and establish generally recognized reference values. Therefore, a follow-up survey should extend and strengthen the data to obtain more comprehensive insights. In this process, the unevaluated preconditions and KPIs suggested in the online survey should be rated according to their importance. In addition, reference values for the newly added KPIs and their determining sub-indicators should be collected. An introduction of bandwidths would be advantageous for the final reference values. Moreover, the study does not distinguish between different types of LIBs and does not include non-lithium-ion–based chemistries such as sodium-ion batteries (SIBs), which could have an impact on the applicability of the results. Future research should, therefore, address this gap by exploring the differences between different battery technologies and end-use applications of SLBs. Regarding the ongoing efforts to define the SoH and SoS, the KPIs with their determining sub-indicators presented in this study may serve as an orientation. It is stressed that standardization of the SoH and SoS on an international level would be very important to minimize the risks of SLB applications.

Besides repurposing, it is essential to also integrate other R-principles and design strategies at multiple levels, including research, industry, and policy-making, to advance the circular economy. This includes, for example, enhancing the repairability and applying design-for-reuse, design-for-disassembly, design-for-recycling, or safe-and-sustainable-by-design concepts. For this, collaborations among all stakeholders in the entire battery value network are needed. This study offers a contribution to one R-principle by providing critical insights and performance measurement guidance for companies and investors involved in the repurposing of EV LIBs. By effectively leveraging the preconditions and KPIs, companies can enhance their ability to build successful and circular business models for SLB applications, contributing to the circular economy objectives. Moreover, regulators and decision-makers can utilize the findings to develop supportive legal and economic frameworks that facilitate the growth of this emerging market. Hence, the findings of this study not only support innovation and resource optimization at the company level but also align with global efforts to achieve a more sustainable and resilient future.

Nomenclature

AI:	artificial intelligence
AMT:	amortization period
BEPA:	batteries European Partnership Association
BESS:	battery energy storage systems
BMS:	battery management system
BoL:	begin-of-life
CAPEX:	capital expenditure
CBA:	cost-benefit analysis
CO_2-eq:	CO_2-equivalent
CO_2-$_{sav}$:	CO_2-equivalent savings compared to first-life
CR2to1:	cost ratio second-life to first-life
CR2toR:	cost-ratio second-life to recycling
EMS:	energy management system
EoFL:	end-of-first-life
EoL:	end-of-life
EPR:	extended producer responsibility
EUCAR:	European Council for Automotive R&D
EV:	electric vehicle
FLB:	first-life LIB
GWP:	global warming potential
IEA:	international Energy Agency
IRA:	inflation Reduction Act
IRR:	internal rate of return
KPI:	key performance indicator
LCA:	life cycle assessment
LFP:	lithium-iron-phosphate
LIB:	lithium-ion battery
LLI:	loss of lithium inventory
ML:	machine learning
MMC:	modular multilevel converter
$MTTF_d$:	mean time to dangerous failure
N/A:	not available
NMC:	lithium-nickel-manganese-cobalt-oxide
OEM:	original equipment manufacturer
OPEX:	operational expenditure
PEF:	product environmental footprint
PEV:	plug-in EVs
PHEV:	plug-in hybrid EVs
PLI:	production Linked Incentive
PMM:	performance measurement and management
PV:	photovoltaic
R&D:	research and development
$RR_{BR:}$	recycling rate of Battery regulation achieved
$R_{sav:}$	resource savings compared to first-life
RUL:	remaining useful life
SCR:	supply chain risks
SDGs:	sustainable Development Goals
SDR:	self discharge rate
SEI:	solid electrolyte interphase
SIB:	sodium-ion battery
SLB:	second-life LIB
SoC:	state of charge
SoH:	state of health
SoS:	state of safety
SPIN:	situation-Problem-Implication-Needs
TCO:	total cost of ownership
WACC:	weighted average cost of capital.

Data Availability Statement

The data that supports the findings of this study are available in the article and in the Supporting Information in this article.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Stefanie Prenner: conceptualization, data curation, formal analysis, investigation, methodology, visualization, and original draft. Florian Part: conceptualization, funding acquisition, methodology, project administration, supervision, visualization, validation, and review and editing. Aleksander Jandric: formal analysis, validation, and review and editing. Arnaud Bordes: visualization, validation, and review and editing. Robert Leonhardt: visualization, validation, and review and editing. Sabine Jung-Waclik: methodology, supervision, validation, and review and editing. Marion Huber-Humer: supervision, validation, and review and editing.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. (*Supporting Information*) The Supporting Information includes (1) additional information on the applied methodologies: Literature analysis: details on the keywords, search strings, topics, and sources of information. Qualitative interviews: interview guide. Quantitative survey: full questionnaire, sampling steps, information on the distribution channels. Explorative online workshop: presentation materials used. Qualitative data analysis: Mayrings framework, developed categories, and category groups. (2) and additional information on the results from the quantitative survey: Demographic data: descriptive statistics. Preconditions: Kruskal–Wallis test, additional preconditions and statements from the author team, statements by the authors on open questions. Key performance indicators (KPIs): changes of terminology between the indicators in the online survey and the final version, Kruskal–Wallis test, Dunn-Bonferroni post hoc Kruskal–Wallis test, reference values for the KPIs incl. data corrections, additional KPIs and statements from the author team.

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