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# Potential and Most Promising Second-Life Applications for Automotive Lithium-Ion Batteries Considering Technical, Economic and Legal Aspects

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**Abstract:** Electric vehicle (EV) batteries, i.e., currently almost exclusively lithium-ion batteries, are removed from the vehicle once they no longer meet certain requirements. However, instead of being disposed of or recycled, the removed batteries can be used in another, less demanding application, giving them a "second life". Research in the field of second-life batteries (SLBs) is still at an early stage and, to better understand the "second life" concept and the related challenges, potential second-life applications need to be identified first. Using a detailed study of the scientific literature and an interview with field experts, a list of potential second-life applications was drafted. Afterwards, a technical, economic, and legal evaluation was conducted to identify the most promising options. The findings of this research consisted of the identification of 65 different mobile, semi-stationary and stationary second-life applications; the applications selected as most promising are automated guided vehicles (AGVs) and industrial energy storage systems (ESSs) with renewable firming purposes. This research confirms the great potential of SLBs indicating that second-life applications are many and belong to a broad spectrum of different sectors. The applications identified as most promising are particularly attractive for the second-life use of batteries as they belong to fast-growing markets.

**Keywords:** lithium-ion batteries; second-life batteries; second-life applications; safety; circular economy; electric vehicles

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## 1. Introduction

Lithium-ion batteries (LIBs) are a common solution for powering electric motors in electric vehicles (EVs). During use, the batteries are subject to calendar and cyclic ageing [1,2] which leads to continuous degradation [3]. Therefore, the properties of the battery will change over time, and it will need to be replaced once certain automotive requirements are reached, e.g., 70–80% state of health (SOH) [4–21].

The average lifetime of a battery used in an EV is typically estimated to be between 8 and 15 years [14,17,20,22–33]. Thus, considering the significant increase in the number of EVs sold [34], more than 200 GWh of batteries from EVs will have reached their end of first life (EOFL) by end of this decade and will need to be replaced [35]. Batteries removed from EVs still have a high value, even if they no longer meet automotive requirements. Thus, instead of disposing of or recycling them, the batteries can be reused in another, less demanding application, giving them a second life. Using batteries in a second life is a solution in line with the European Union's (EU) goal of greater sustainability and a more circularly oriented competitive economy [36–38]. This solution is valuable because it prolongs the life of the battery and thus the resources and emissions required to produce the battery are spread over a longer period [39]. As a result, the environmental impact of the battery is reduced [40–44]. In addition to the environmental benefits, using batteries for a second life may also increase their economic efficiency and enable the emergence of new markets and business models (BMs) [41,45–50].

Research in the field of second-life batteries (SLBs) is still in its infancy, and there are still many challenges to be overcome, especially in terms of safety, to enable a successful transition from the first to the second life. As a first step, the potential applications for using SLBs (in this paper referred to as second-life applications) need to be identified and have to be critically assessed not only in technical terms but also by considering the economic and legal aspects.

From an economic point of view, the battery of an EV contributes about one-third of the total value of the vehicle [51]. Therefore, it is important to consider how this expensive component can be used beyond its EOFL. With the increasing number of EVs on the roads, the higher availability of SLBs leads to novel business opportunities that need to be explored, but which are strongly influenced, and in many cases also limited, by political regulations, profitability considerations as well as rising environmental awareness.

From a legal perspective, the issue of the second-life use of LIBs is a global one. The UNECE World Forum for Harmonization of Vehicle Regulations (WP.29), with its Working Party on Pollution and Energy (GRPE), is attempting to create global technical regulations (GTRs) for the standardisation of the legal framework in the automotive sector. In particular, a proposal for mandatory minimum battery durability guarantees for electric and plug-in hybrid vehicles has been published [52].

At the European level, the European Union is planning to enact specific, harmonized legal regulations in the future. In particular, the new European Battery Regulation [53] will be the most important legal text related to the second-life use of batteries. This harmonizing regulation is expected to be directly applicable in all European member states in 2023 (but latest by 2026 [54]) and will represent the central legal regulation. In addition, however, national regulations will also be adapted to second-life use cases. Regarding the UNECE GTRs, the European Union was authorized by the European Council to negotiate and adopt them on behalf of the member states, which gives these regulations—once adopted by the UNECE—a mandatory character for the entire Union [55].

There are several review papers covering the topic of SLBs [41,45,56–61], however, none of them focuses exclusively on potential second-life applications.

Summarising potential second-life applications in a cohesive manner provides a good basis for future studies on SLBs. Therefore, the research task of this paper is to collect potential applications with SLBs and then identify which ones are most promising in technical, economic and legal terms using a specific assessment methodology. The investigation findings not only enable a better understanding of the state of the art but also provide a targeted selection of the most promising applications, which can be analysed in more detail in future investigations.

## 2. Materials and Methods

The purpose of this research is to accomplish two findings. The first one is to draft a list of potential second-life applications, while the second one is to identify the most promising second-life applications. The workflow followed to achieve the purpose of this research is schematically shown in Figure 1. The list of potential second-life applications is derived from in-depth literature research and comprehensive expert interviews in the form of an online survey (see Appendix A). The most promising applications are obtained through the definition of a set of evaluation criteria derived from the literature research.

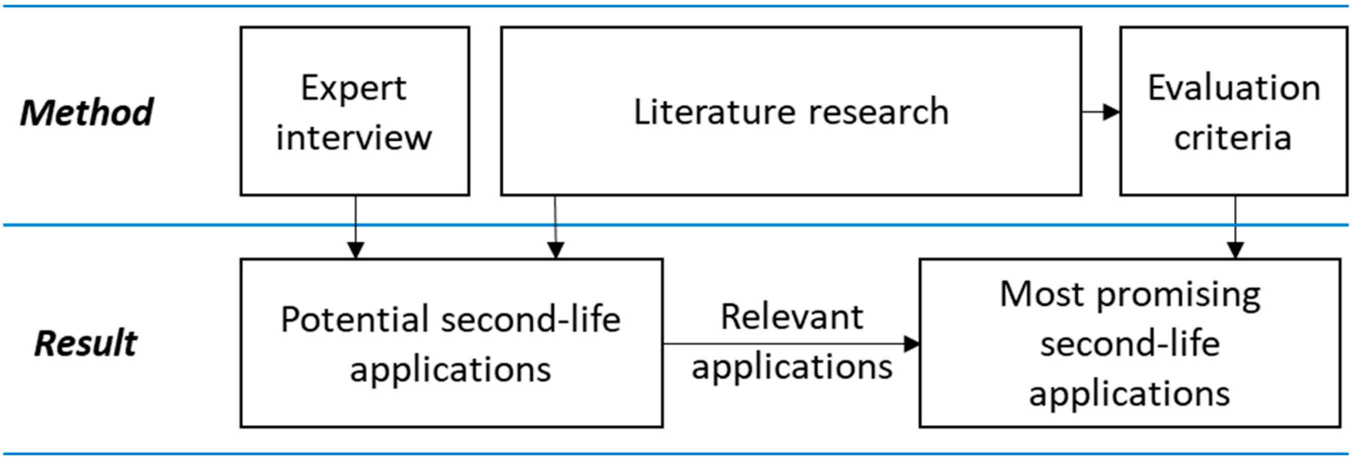

**Figure 1.** Schematic research workflow.

### *2.1. Potential Second-Life Applications*

The literature research laid the groundwork and provided an overview of the second-life applications addressed by the scientific literature, while the interview with experts provided novel second-life applications. The online survey gathered feedback from 70 international experts in the fields of mobility, automotive, electrification and batteries.

A more specific insight into second-life applications was then made by selecting the most relevant applications. The selection was guided by the number of scientific publications concerning the application under consideration and the feedback obtained from the expert interviews in which experts were asked to evaluate the examined applications. The average of the two normalised scores was taken as the final score. After that, all applications that scored above the average of the grades plus a standard deviation were selected. Consequently, the list of potential second-life applications was narrowed down to focus on only eight applications that were currently considered the most relevant by the scientific and industrial actors.

### *2.2. Most Promising Second-Life Applications*

The next step in this research was then to identify the most promising applications. The applications were assessed using an evaluation catalogue containing technical, economic and legal evaluation criteria. The focus of the technical aspects considered as evaluation criteria are on safety. Hence, technical aspects influencing the useful life of the battery (e.g., the number of cycles or state of charge (SOC) range) were not considered, however, they may be relevant for research in which the remaining useful life (RUL) is evaluated. The following criteria were considered to evaluate the applications:

- Maximum discharge rate. This criterion value depends on the type of application and is considered relevant because when the discharge current is too high, this results in lithium plating, capacity fade and internal resistance increase [62–64].
- Maximum charge rate. This criterion directly influences the charging time, which is a crucial aspect for certain applications (e.g., EVs). When the charging rate is too high, this leads to lithium plating, capacity and power fade, faster ageing and, in the worst case, thermal runaway [63–68].
- Required capacity. This criterion is relevant for both practical feasibility and safety reasons. On the one hand, it is inconvenient to use batteries for applications where the required capacity is less than that provided by a single module or even a single cell [69,70]. On the other hand, it is complicated to have a sufficient number of SLBs to meet the demands of applications where the overall capacity required is very high [41]. Furthermore, the safety issues (and consequent maintenance costs) associated with

high energy densities confined to a geographically limited area must also be taken into account [41].

- Degree of mobility (stationary, semi-stationary, mobile). This criterion influences the likelihood of the battery being subjected to mechanical loads (e.g., mechanical shock, indentation) that could eventually lead to catastrophic consequences [71–74].
- Operating and storage temperature. Temperature is a major concern in terms of safety. There is a temperature safety window (25 °C–35 °C) in which the battery is intended to operate [75]. A battery that is thermally abused by elevated temperatures is subject to the decomposition of active material and, in the worst case, exothermic reaction and thermal runaway [63,64,76,77]. If, on the other hand, temperatures are too low, there is a decrease in the reaction rate, metallic lithium depositing, irreversible capacity loss and an increased risk of internal short-circuit [63,64,76,78]. The temperature depends not only on the battery and the cooling system but also on the surrounding environment.
- Applicable BM patterns. The 55 highly successful field-proven BM patterns published by Gassmann et al. [79] have been taken as a basis to build up consecutive analyses and trains of thought. A promising BM pattern in terms of second-life applications can either lead to a successful BM or can be combined with other promising BM patterns into a bundle forming a prosperous BM.
- Legal knock-out criteria. The legal assessment (analysing the thematically pertinent legal texts and case law including broad comprehensive research of the legal literature on European and Austrian/German national level to identify potential problems) was carried out to find possible knock-out criteria that would make certain applications unfeasible.

In order to narrow the scope of the investigation, only the eight most relevant applications were considered for the selection of the most promising applications. The relevant second-life applications determined previously are then assessed using the technical, economic and legal evaluation criteria given above. This evaluation method enables us to rank the investigated second-life applications and identify which applications are most promising. Finally, the most promising applications are validated by comparing the use of LIBs with alternative energy storage technologies.

## 3. Results

### 3.1. Potential Second-Life Applications

SLBs exhibit a higher state of degradation than fresh batteries, so applications with lower requirements than those of the first life must be selected. Potential second-life applications are those where capacity and density are not critical and fast and continuous charging and discharging are not expected. Furthermore, batteries removed from a vehicle at the EOFL can be used in a second-life application at different levels (i.e., pack, module and cell level). Yet, minimising operations to be performed on the battery also reduces costs, so it is generally more cost-effective to use the battery directly at the pack or module level, rather than at the cell level [69,70].

A significant number of potential second-life applications were found with the study of the scientific literature and innovative ideas were also gathered using expert interviews. For simplicity's sake, the applications have been categorised into three categories according to their degree of mobility (i.e., mobile, semi-stationary or stationary). The list of potential second-life applications is summarised in Table 1.

**Table 1.** Potential second-life applications.

| Mobility Degree | Category | | Application | Source |
|---|---|---|---|---|
| Mobile | Commercial EVs | 1 | Short-range EVs | [19,41,45,60,80] |
| | | 2 | Hybrid trucks | [80] |
| | Industrial Vehicles | 3 | Forklifts | [19,20,20,60,81–84] |
| | | 4 | Pallet trucks | [19,20,20,60,82] |
| | | 5 | Tractors | [19,20,20,60,82] |
| | | 6 | Transport trolleys | [19,20,20,60,82] |
| | | 7 | Sweepers | [19,20,20,60,82] |
| | | 8 | Automated guided vehicles (AGVs) | [19,20,20,60,82] |
| | | 9 | Excavators | [19,20,20,60,82] |
| | | 10 | Dumpers | [19,20,20,60,82] |
| | | 11 | Wheel loaders | [19,20,20,60,82] |
| | | 12 | Telescopic handlers | [19,20,20,60,82] |
| | | 13 | Airport pushback tractors | Expert feedback |
| | | 14 | Airport belt loaders | Expert feedback |
| | | 15 | Airport passenger stairs | Expert feedback |
| | Micro-mobility | 16 | E-bikes | [19,20,20,80] |
| | | 17 | E-scooters | [19,20,20] |
| | | 18 | Electric wheelchairs | [19,20,20,81] |
| | Lightweight vehicles | 19 | Golf carts | [19,20,20,80,82,85] |
| | | 20 | Three-wheel vehicles | [19,20,20,82,85] |
| | Lead–acid replacement | 21 | Automotive starting | [86] |
| | | 22 | Automotive lighting | [86] |
| | | 23 | Automotive ignition | [86] |
| | | 24 | Industrial trucks | [86] |
| | Autonomous mobile robots | 25 | Robotic vacuum cleaners | [80] |
| | | 26 | Robotic lawnmowers | Expert feedback |
| | Consumer electronics | 27 | Leisure time gadgets | [80] |
| | | 28 | Kitchen appliances | Expert feedback |
| | | 29 | Working tools | Expert feedback |
| | Marine applications | 30 | Full propulsion | [19,83,85] |
| | | 31 | Hybrid propulsion | [19,80,83,85] |
| | | 32 | Spinning reserve | Expert feedback |
| | | 33 | Load-levelling | Expert feedback |
| | | 34 | Shore-stations | [85] |
| | | 35 | Peak shaving/transient load management | [85] |
| | | 36 | Energy recapture | Expert feedback |
| | Rail transport | 37 | Trams power supply | [87] |
| | | 38 | Trams backup system | Expert feedback |
| | | 39 | Trains power supply | Expert feedback |
| | | 40 | Trains backup system | Expert feedback |
| | FC-based transportation | 41 | Energy buffer for H2FC | Expert feedback |
| Semi-stationary | Mobile power supplies | 42 | Power-stations for construction sites | [20,20,82] |
| | | 43 | Power-stations for major events | [20,20] |
| | | 44 | Power-stations for outdoor camping | Expert feedback |
| | | 45 | Power-stations for outdoor leisure office | Expert feedback |
| | | 46 | Power-stations for outdoor emergency power supply | [20,20] |
| | | 47 | Automotive mobile charging stations | [19,56,82] |
| | Other | 48 | Buffers for stationary traffic signs | Expert feedback |

**Table 1.** *Cont.*

| Mobility Degree | Category | | Application | Source |
|---|---|---|---|---|
| Stationary | Lead–acid replacement | 49 | Telecommunication backup power | [5,85,86] |
| | | 50 | Uninterruptible power supplies | [85,86,88] |
| | EV chargers | 51 | On-grid buffer storages at charging station | [19,20,20,41,44,45,56,60,81,83,87,89–92] |
| | | 52 | Off-grid buffer storages at charging station | [5,18,45,56,83,89,91,93,94] |
| | Special grids | 53 | Micro-grids | [20,20,41,45,56,60,85,88,91,95–97] |
| | | 54 | Smart grids | [11,41,45,56,60,85,88,91,95–99] |
| | Residential ESS | 55 | Residential ESSs with load following purposes | [19,20,20,21,41,45,56,57,60,81,83,85–87,91,92,95,100–106] |
| | | 56 | Residential ESSs connected to a RES | [8,15,16,19,20,20,21,41,43–45,56,57,81,89,92,100–113] |
| | | 57 | Residential ESSs with backup purposes | [19,20,20,41,56,57,60,83,85,90,91,95,111] |
| | Commercial ESS | 58 | Commercial ESSs with peak shaving purposes | [5,19,41,43,45,56,57,60,80,82,83,86,88,90,91,93,95,100–103,111,114–116] |
| | | 59 | Commercial ESSs with load following purposes | [5,20,20,21,41,45,46,56,57,60,86,88,104,105,111,116] |
| | | 60 | Commercial ESSs with backup purposes | [19,20,20,41,45,57,60,80,90–92,95,111] |
| | Industrial ESS | 61 | Industrial ESSs with load levelling purposes | [5,19,20,20,21,41,45,57,60,82,111,117,118] |
| | | 62 | Industrial ESSs with renewable firming purposes | [5,7,20,20,21,41,45,56,57,60,80–82,85,88–92,95,100,102,103,108,111,113,114,119–123] |
| | | 63 | Industrial ESSs with spinning reserve/area regulation purposes | [5,7,19,21,41,44,45,60,86,89–91,95,103,111,114,124] |
| | | 64 | Industrial ESSs with peak shaving purposes | [5,19,41,44,45,56,60,80,82,83,86,88,91,93,95,101–103,111,114,115] |
| | | 65 | Industrial ESSs with transmission stabilisation purposes | [7,20,20,21,41,45,56,60,80,86,88,91,95,114,118] |

The first major category of possible second-life applications is "mobile applications", i.e., applications where the battery is expected to move during use. One possible application is to reuse the batteries in a short-range EV. In fact, although EOFL is commonly defined as when the battery reaches 70–80% capacity retention, the range provided by the battery is sufficient for most daily trips. For example, a battery with 60% capacity retention is able to meet the daily travel needs of over 75% of drivers [12,41]. Furthermore, this is a cost-effective solution as reprocessing the battery is hardly, or not at all, necessary [20]. Similarly, SLBs can be installed in hybrid trucks operating in urban areas to provide power at low speeds before the internal combustion engine (ICE) starts up and recharges the battery. Another possibility is to use the batteries for the propulsion of micro-mobility vehicles (e.g., e-bikes, e-scooters, electric wheelchairs), lightweight vehicles (e.g., golf carts, three-wheel vehicles) and industrial vehicles (e.g., forklifts, pallet trucks, tractors) or for the internal energy management of some vehicles [83] (e.g., food trucks).

The ability to withstand partial electrochemical cycles without degrading excessively and the higher energy density in terms of both weight and volume result in LIBs being more appealing than conventional lead–acid batteries. The main obstacle to using LIBs rather than lead–acid batteries is the difference in cost, which makes the use of lead–acid batteries more widespread than LIBs for certain types of applications. However, when considering the case of SLBs, the price difference flattens out, leaving room for the emergence of new second-life applications linked to the replacement of lead–acid batteries [60]. Possible replacements for mobile applications may be the batteries used for automotive starting, lighting and ignition or the ones used in industrial trucks.

Other examples of mobile second-life applications include the use of SLBs as buffer storage in fuel cell (FC) vehicles or different types of transportation technologies, e.g., rail (e.g., trams and trains propulsion) or marine applications (e.g., propulsion, backup, load levelling).

Another category of potential mobile second-life applications includes all consumer electronic applications (e.g., mobile home robots, household appliances, working tools, laptops and other leisure time gadgets) as further potential mobile second-life applications. However, it is not always considered an optimal solution because, in most applications, the battery provided by a single large-format automotive cell has a higher capacity than required for the specific consumer electronics application [86].

Second-life applications in which the batteries are not intended to operate while moving but are expected to be relocated frequently are defined as "semi-stationary". Examples are power generators or power stations used in remote areas and automotive mobile charging stations [19,56,82].

Another major category of second-life applications includes stationary use cases, i.e., the battery is not expected to move during its operational cycle. In addition to the degree of mobility, the difference between stationary and mobile (or semi-stationary) second-life applications is that they tend to have less stringent weight and volume limits. Moreover, they have a reduced possibility of being mechanically abused, which could allow for less stringent safety requirements than those applied in the case of mobile applications. The first macro-category for stationary second-life applications is energy storage systems (ESSs). ESSs can be subdivided into smaller categories depending on the type of consumer, whether attached to the grid or not, and the functions to be fulfilled. In this paper, the first mentioned classification method is utilised.

The first type of consumer is at the residential level and therefore concerns individual households (e.g., private houses, flats). Residential second-life battery energy storage systems (SLBESSs) are a viable solution in terms of performance as the required power and capacity are provided by most SLBs extracted from EVs. Residential SLBESSs can store energy when consumption is low and release energy when higher consumption is reached, which results in smoothing the load and gives the possibility of participating in the energy arbitrage business; this not only provides economic benefit but also a more environmentally sustainable solution and reduces the strain on the electric grid. Furthermore, they can be used in combination with renewable energy sources (RESs), for example, photovoltaics (PV), encouraging RES use and promoting the decentralisation of the electricity production system. The SLBESSs can also act as an energy backup in the event of a power failure or blackout. Depending on the purpose, the scenarios to which the ESS is subjected are different. Considering a typical residential demand load profile (LP1—Urban Domestic 24-h [125]), in the case of load-following, a capacity of at least 3–4 kWh is required [111]. The expected load profile is characterised by one deep discharge and several small discharges during the day, and a typical discharge rate of C/3 (The C-rate refers to the current at which the battery is charged (or discharged) with respect to its nominal capacity. For example, a discharging C-rate of C/3 indicates that it ideally takes 3 h to discharge the battery from 100% to 0% SOC). In the case of the backup system, the capacity required is 25 kWh (in the case of an off-grid application) and moderate daily discharges are expected (depth of discharge < 50%) [41,111]. The use of SLBs also tackles the problem of the high costs of using new batteries, which is the main limitation for the installation of domestic ESSs [102]. Nevertheless, there are other limitations to consider, e.g., the needed amount of space and the high maintenance requirements, which suggest that residential ESSs are often not the best solution [85]; furthermore, the risk due to the proximity of the residence and people should also be addressed [41].

ESSs may also be intended for larger applications at the commercial or industrial level. These types of applications require a greater investment in storage size and tighter safety standards [41].

The commercial-level consumer is broad and includes different types of businesses and light industries. Commercial businesses, where the presence of ESS could be beneficial, are, for example, telecommunication companies, large offices and fresh food distribution centres. The commercial load is on average higher than the domestic load, making it more suitable for applications such as load following and peak shaving. When considering a typical commercial load (LP5—Non-Maximum Demand Non-domestic 24-h [125]), in the case of peak shaving, the required capacity is about 3000–4000 kWh, thus a considerable number of batteries is needed (approximately 178–238 reconditioned Nissan Leaf batteries [111]), which is why a hybrid solution with both new and SLBs is commonly chosen. The expected discharge rate ranges between C/2 and C and occurs daily. In the case of load following, the required capacity is 75–100 kWh (approximately 4–6 reconditioned Nissan Leaf batteries [111]), considerably less than that required by peak shaving, making this application more likely to be fully managed with SLBs [41,111]. In addition, a deep discharge and many small discharges are expected on a daily basis. The C-rate required for load following is typically C/3, which is easily sustained using LIBs. Another possible application concerns the use of SLBs as a backup system that comes into operation in the event of unusual scenarios, in this case, the expected discharge rate is approximately C/5 [41,111].

The power demand for industrial ESS applications (e.g., heavy industry) is even higher than for residential and commercial applications [41]. In the case of industrial ESS, there are several possible purposes: load levelling, renewable firming, spinning reserve or area regulation, peak shaving and transmission stabilisation.

When considering a typical industrial load (LP8—MD Load Factor > 30 to 50% [125]), the capacity required for industrial load levelling is around 100 MWh (approximately 6000 reconditioned Nissan Leaf batteries), the high number of batteries required makes this application impractical with SLBs [41,111]. A lower number of batteries is required in the case of renewable firming (1–10 MWh, approximately 60–595 reconditioned Nissan Leaf batteries), spinning reserve/area regulation (5–7.5 MWh) and peak shaving where the capacity required is similar to the one seen in the commercial sector (75–100 kWh, i.e., 4–6 reconditioned Nissan Lead batteries) [41,111]. Renewable firming is characterised by frequent discharge cycles with an intensity of C/5, spinning reserve/area regulation and peak shaving by discharge cycles varying from C/2 up to C, all of which are suitable for SLBs. Another application worth mentioning is transmission stabilisation (140 kWh, 500 MW), where short bursts of power are used for voltage and frequency regulation; however, the C-rate required in this application is higher than the capabilities of LIBs [41,111]. Another promising application is to replace grid-connected combustion turbine peakers with ESS to provide peak shaving services and thus improve the system efficiency [86,124].

SLBs can also be used in microgrids and smart grids to provide localised support for the production and distribution of energy from alternative power sources. Microgrids can be either attached to the main grid (on-grid) or belong to a stand-alone system (off-grid). Microgrids promote the decentralisation of energy storage and allow energy to be supplied in remote areas in combination with renewable energy production systems, ensuring increased stability and providing backup power [41,85,91].

EV batteries can also be used as buffer storage at charging stations to reduce the power demand while charging and to relieve the load on the public grid or decentralised buffer storages in combination with energy production from renewable sources allowing the charging of vehicles in remote areas where the public grid does not reach. The use of new batteries, however, is not cost-effective. In contrast, SLBs, in addition to meeting the required technical expectations, have a lower cost [41]. Furthermore, for this type of application, assuming the battery is used from 80% to 60% SOH, the estimated lifespan is 15 years [44].

Finally, as in the case of mobile applications, there are stationary examples of SLBs replacing lead–acid batteries in stationary applications. For example, for telecommunication backup power or uninterruptible power supply (UPS).

### *3.2. Most Promising Second-Life Applications*

From the list of potential second-life applications, four mobile and four stationary applications were selected to be analysed in more detail. As mentioned above, the selection of these eight applications was based on their relevance in the scientific literature and the feedback obtained from the expert interviews. The selected applications are listed in the first column in Table 2. The table was then filled with the technical data from real cases or the scientific literature (see Appendix B). The comparison and ranking of the application were performed using an evaluation system (see Appendix C) which assigns a score (++, +, o, -, –, x) based on the value in brackets.

**Table 2.** Filled evaluation matrix with real values linked to the applications under investigation.

| Application | Max Discharge [C-Rate] | Max Charge [C-Rate] | Required Capacity [kWh] | Degree of Mobility [-] | Min T [°C] | Max T [°C] | Promising BM Patterns * [-] | Legal Knockout Criteria [-] | Score |
|---|---|---|---|---|---|---|---|---|---|
| **Forklift** | +<br>(0.71) | ++<br>(0.89) | ++<br>(34) | ++<br>(Mobile) | -<br>(0) | o<br>(40) | o<br>(6) | o<br>(None) | **5** |
| **Pallet truck** | +<br>(0.56) | -<br>(3.33) | ++<br>(2) | ++<br>(Mobile) | o<br>(10) | o<br>(30) | o<br>(6) | o<br>(None) | **3** |
| **AGV** | ++<br>(0.13) | ++<br>(0.50) | ++<br>(10) | ++<br>(Mobile) | o<br>(10) | o<br>(30) | o<br>(6) | o<br>(None) | **7** |
| **Golf cart** | x<br>(6.90) | ++<br>(0.35) | ++<br>(3) | ++<br>(Mobile) | -<br>(0) | o<br>(40) | o<br>(6) | o<br>(None) | **Discarded** |
| **On-grid buffer storage at charging station** | -<br>(2.29) | +<br>(1.22) | +<br>(140) | +<br>(Stationary) | x<br>(−30) | -<br>(50) | +<br>(7) | o<br>(None) | **Discarded** |
| **Commercial ESS with peak shaving purposes** | o<br>(1.00) | +<br>(1.00) | o<br>(4000) | +<br>(Stationary) | +<br>(20) | o<br>(30) | +<br>(7) | o<br>(None) | **5** |
| **Industrial ESS with peak shaving purposes** | o<br>(1.00) | +<br>(1.00) | o<br>(4000) | +<br>(Stationary) | +<br>(20) | o<br>(30) | +<br>(7) | o<br>(None) | **5** |
| **Industrial ESS with renewable firming purposes** | ++<br>(0.20) | ++<br>(0.20) | -<br>(10000) | +<br>(Stationary) | +<br>(20) | o<br>(30) | +<br>(7) | o<br>(None) | **7** |

* The list of the promising BM patterns for each application is shown in Appendix E.

The analysis of the legal framework yielded that there is no law prohibiting the applications under investigation. Therefore, all applications are valid to be used with SLBs in the same way. For more details concerning the legal framework, see Appendix D.

The last column of Table 2 summarises the scores of the eight applications under investigation. Golf carts and on-grid buffer storage at charging stations were discarded because one of the parameters was outside the limits imposed by the evaluation knock-out criteria. All the remaining applications scored between three and seven. Due to their overall score, AGVs for mobile applications and industrial ESSs with renewable firming purposes for stationary applications are considered as most promising.

## 4. Discussion

The literature research combined with the expert interviews yielded a wide spectrum of possible stationary, semi-stationary and mobile applications that can be powered with SLBs. The fields of application vary extensively from transport to home applications, from buffer storage to ancillary services on the public power grid. This demonstrates the potential for SLBs to be versatile in a plethora of application areas, to serve existing markets and open new markets using the associated application of a wide range of BMs.

The subsequent analysis indicated two applications with different degrees of mobility as “most promising”, again suggesting that the complexities of the transition to second life are many and involve multidisciplinary studies.

### *4.1. Validation*

AGVs and industrial ESS with renewable firming purposes are considered the two most promising second-life applications. However, it is necessary to consider that different types of energy storage technologies could be more advantageous than LIBs. It is therefore necessary to analyse the possible energy storage technologies for the two selected applications and confirm that LIBs are a viable solution.

In the case of AGVs, the main alternative to LIBs is lead–acid batteries [126]. Currently, the best solution depends on the type of application. Yet, as LIBs offer several advantages over lead–acid batteries (e.g., lighter and more compact, suitable for fast charging, longer runtimes and battery life) the AGV market is witnessing a gradual shift from lead–acid to LIBs. This is also connected to the fact that in most scenarios where AGVs are involved, high round-trip efficiency is required [127].

In the case of industrial ESS with renewable firming purposes, in addition to the use of batteries (e.g., LIBs, lead–acid batteries, high-temperature batteries, flow batteries), mechanical energy accumulators can also be utilised (e.g., pumped-storage hydroelectric, compressed air energy storage, flywheels). An analysis conducted by the International Renewable Energy Agency (IRENA), in which all these different technologies are compared, shows that the use of LIBs is the best solution [128]. In addition, another comparative study revealed that the cost-effectiveness of lithium-ion batteries is greater than that of lead–acid and flow batteries [129].

As a result, it emerged that in the case of both AGVs and industrial ESS with renewable firming purposes, the use of LIBs is not only a viable solution but is currently the best solution.

### *4.2. Limitations*

More than 60 potential applications have been identified; however, the applicability must be studied on a case-by-case basis as there are some parameters (e.g., extreme geographical latitude and environmental conditions) that may result in an application being unprofitable or even unfeasible. The analysis of the most promising applications was conducted on eight specific second-life applications. However, the method used is suitable for studying a larger number of applications that could also be promising. Furthermore, it is important to consider that second-life applications belong to a rapidly evolving market that may witness significant changes in the coming years.

## 5. Conclusions

A multidisciplinary study was conducted to identify potential and relevant second-life applications of automotive lithium-ion batteries using a comprehensive study of the scientific literature and consultation with experts in the relevant fields of application, and to subsequently evaluate their basic feasibility/implementation potential (“most promising applications”) according to a specific set of evaluation criteria, taking into account economic and legal criteria as well as technical ones, ensuring that the study was not limited to a purely technical analysis.

From the investigation, more than 60 potential second-life stationary, semi-stationary and mobile applications were identified, with AGVs and industrial ESSs with renewable firming purposes being the most promising considering economic, legal and technical aspects.

The results show that SLBs can be used in a multitude of potential applications. In addition, novel second-life applications, not addressed in the scientific literature, emerged from the feedback obtained from the expert interview. The applications evaluated according to the evaluation criteria received different scores which allowed them to be ranked, thus demonstrating the importance of analysing each second-life application on a case-by-case basis given the variety of each application.

The findings obtained are of interest as they provide a valuable and informative summary of the potential and most promising second-life applications. The method used for the identification of the most promising applications can be adapted and used in similar research. The identified applications can be further researched by the scientific community or developed into novel products in the industry.

The authors are currently continuing research in the field of SLBs by analysing in more depth the applications identified as most promising to understand the actual feasibility of SLB use from an economic, legal, technical and safety perspective.

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## Appendix A

The expert interview was used for collecting novel potential applications and assessing which are most relevant. For the identification of novel potential second-life applications, the list of the potential second-life applications obtained from the study of the literature was provided and then the following question was asked:

- What other possible second-life applications, apart from the already mentioned ones, could be interesting?

To determine the most relevant second-life applications, the experts were asked to assess all the applications extracted from the literature by assigning a mark between 1 (not promising) and 5 (extremely promising).

A total of 70 experts were involved in this interview; the experts were selected according to their possible interest in SLBs mainly on the technical side but also on the economic and legal side; see Figure A1. The experts come from both the SafeLIB consortium and the major European clusters of mobility, automotive, electrification and batteries.

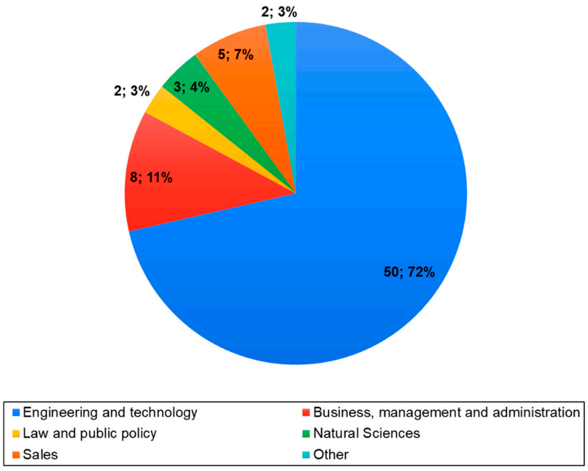

**Figure A1.** Professional field of the experts involved in the interview.

## Appendix B

The references listed in Table A1 were used to assess the absolute values of the parameters attributed to the applications investigated. These are either real applications or references to the scientific literature.

**Table A1.** List of references used to collect the absolute values of the parameters considered for the applications under investigation.

| Application | Reference |
|---|---|
| Forklift | Hyster E60XNL |
| Pallet truck | Jungheinrich EJE M15 |
| AGV | KUKA KMP 1500 |
| Golf cart | ClubCar Onward® 2 Passenger |
| On-grid buffer storage at charging station | HPC-Booster–StoraXe |
| Commercial ESS with peak shaving purposes | [41,111] |
| Industrial ESS with peak shaving purposes | [41,111] |
| Industrial ESS with renewable firming purposes | [41,111] |

## Appendix C

The evaluation of the applications is conducted utilizing thresholds set for each evaluation criterion. Applications are rated between “++”, “+”, “o”, “-” and “–”. “++” represents an extremely positive evaluation, “–” represents an extremely negative evaluation and “o” represents a neutral evaluation. Finally, if an application is rated “x” for a category, it is outside the acceptable window of the project and is excluded from the analysis regardless of the result obtained using the other evaluation criteria.

The conversion table in which the scoring decreases as the charging and discharging rates increase is shown in Table A2. If the discharging rate is higher than 5 C or the charging rate is higher than 8 C, then the application is immediately rejected, regardless of the scores obtained with the other evaluation criteria, since using an excessively high discharging rate leads to accelerated lithium plating, higher capacity fade and increased internal resistance [62–64]. Similarly, when the charging rate is too high, the cell is characterised by accelerated lithium plating, increased capacity and power fade, irreversible thickness increase, faster ageing and, in the worst-case scenario, thermal runaway [63–68,130].

**Table A2.** Conversion table used for discharging and charging rates.

| Evaluation Scoring | Discharging [C-Rate] | Charging [C-Rate] |
|---|---|---|
| ++ | $0 < x < 0.5$ | $0 < x < 1$ |
| + | $0.5 < x < 1$ | $1 < x < 2$ |
| o | $1 < x < 2$ | $2 < x < 3$ |
| - | $2 < x < 3$ | $3 < x < 5$ |
| – | $3 < x < 5$ | $5 < x < 8$ |
| x | $x > 5$ | $x > 8$ |

For the required capacity in kWh, the rating decreases with increasing size for two main reasons. The first, purely practical, is the difficulty of finding a large number of SLBs for a second-life application; the second is related to the safety concerns arising from a high concentration of energy in a small space, as small incidents can lead to catastrophic situations [41]. On the other hand, too low a capacity is also inefficient because of the problems associated with dismantling the modules, especially in terms of safety. The conversion table is shown in Table A3. Applications requiring a capacity of more than 100 MWh are automatically discarded.

**Table A3.** Conversion table used for the required capacity.

| Evaluation Scoring | Required Capacity |
|---|---|
| ++ | 2 kWh < capacity < 100 kWh |
| + | 100 kWh < capacity < 1 MWh |
| o | 1 MWh < capacity < 10 MWh |
| - | 10 MWh < capacity < 50 MWh |
|  | 0.2 kWh < capacity < 2 kWh |
| – | 50 MWh < capacity < 100 MWh |
|  | 0 kWh < capacity < 0.2 kWh |
| x | capacity > 100 MWh |

Another monitored critical parameter is the operating and storage temperature range. If the temperature is too high, then decomposition of the active material occurs and, in the worst cases, exothermic reactions can be triggered, leading to thermal runaway [63,64,76,77]. If the temperature is too low, then there is a decrease in the reaction rate, an increase in metallic Li depositing and, therefore, an irreversible capacity loss and an increased risk of internal short-circuit [63,64,76,78]. The optimal temperature range is between 25 and 30 degrees Celsius and—the further it is away from this—the less favourable it is (as shown in Table A4). If the temperature is above 80 °C or below −30 °C, then the application is immediately discarded.

**Table A4.** Conversion table used for the operating and storage temperature range.

| Evaluation Scoring | Operating and Storage Temperature Range [°C] |
|---|---|
| ++ | 20 < temperature < 30 |
| + | 15 < temperature < 35 |
| o | 0 < temperature < 50 |
| - | −10 < temperature < 60 |
| – | −30 < temperature < 80 |
| x | temperature ≤ −30 or temperature ≥ 80 |

The degree of mobility is assessed; mobile applications are more prone to mechanical abuse than stationary ones. Thus, stationary applications, as shown in Table A5, scored higher than mobile applications.

**Table A5.** Conversion table used for the degree of mobility.

| Evaluation Scoring | Operating and Storage Temperature Range [°C] |
|---|---|
| ++ | Stationary |
| + | Mobile |

The number of BM patterns applicable to the investigated second-life applications is also considered. A greater number of viable BM patterns indicates greater versatility in bringing the respective application to market and thus a more promising application in general. The applied scoring is shown in Table A6.

**Table A6.** Conversion table used for the number of promising BM patterns.

| Evaluation Scoring | Number of Promising BM Patterns |
|---|---|
| ++ | BM patterns ≥ 10 |
| + | 7 ≤ BM patterns <10 |
| o | 4 ≤ BM patterns < 7 |
| - | 2 ≤ BM patterns < 4 |
| – | BM patterns = 1 |
| x | BM patterns = 0 |

Finally, for legal aspects, there is no such unambiguous assessment in advance because here, too many different factors have an influence. Thereby, it always depends on the individual use, the national legal system and the design of the specific application. For example, failure to comply with a minor legal condition for a specific application may prevent its use, meanwhile, the abidance makes a use unproblematic. However, if there is any legal or economic knock-out criterion that causes the application to be unfeasible, then the application is discarded immediately.

## Appendix D

From a legal perspective, neither the national nor the European legislators have enacted specific legal texts for second-life use at the national level. As a result, there is currently no unified legal framework for battery law in Europe. Although there is a directive from 2006 [131], which is intended to align the national legal texts with each other and to at least harmonise their objectives. However, since a European directive must always be transposed into national law to become legally valid, the national legal frameworks of the member states must currently be analysed in detail to determine the legal framework for batteries. Due to the importance of the issue, the European Commission has initiated an amendment of the “battery law” within the framework of the “European Green Deal” and has presented a draft for a European battery regulation in 2020 [53]. If the regulation is implemented, then it will be directly applicable to every European member state. This is intended to create at least an initial unified legal framework for batteries within the European Union. However, certain details within the regulation will only be regulated later by means of implementing acts. In addition to this urgently needed harmonization of the European battery law, the individual national provisions remain valid in principle, which means that these must also continue to be observed and makes a legal investigation even more important.

Neither the Austrian nor the German legislators have enacted specific legal texts for second-life use at the national level. The given national regulations can only provide tangential regulations and do not prevent second-life use. Their primary focus is set on the regulation of first-life use and recycling and less for a concrete second life. For example, the Austrian and German legal texts for waste and recycling management can be cited as standards of this kind of regulation [132–136]. In addition, there are general safety regulations (in Austria, for example, the Produktsicherheitsgesetz [136], the Elektrotechnikgesetz [137] and the Elektrotechnikverordnung [138]) as well as product liability law [139], which must also be observed in second-life use. Since legislation cannot always keep pace with technological developments and therefore the current “state of the art”, technical standards (which reflect the current state of the art) can often specify safety and liability provisions, without containing the direct legal character.

Although no law prohibits the secondary use of LIBs, there are various product requirements for batteries and the potential second-life applications arising from national legal texts. This applies to environmental and circular economy requirements [132–135] as well as, e.g., the aforementioned Product Safety Act [136] and the Product Liability Act [139], which set out general requirements for product safety and liability. Depending on the specific second-life application and the second-life battery used, this may require new product certification (CE marking) to meet all product law requirements of the second-life system. Although technical standards have no direct legal value, they have an essential influence on second-life use. In product safety law, for example, there is a presumption of conformity if harmonised European technical standards are complied with [140,141]. Such harmonised EU standards, which are developed by experts, must be instructed by the European Commission and published in the Official Journal of the EU. If such a technical standard is complied with, it is presumed that the battery or second-life application meets the safety requirements. In general, however, an evaluation is required on a case-by-case basis in order to be able to classify the fulfilment of the legal claims of the respective second-life product.

## Appendix E

Table A7 shows the promising BM patterns for the investigated second-life applications. The identified BM patterns are in any case of interest for several of the listed applications.

**Table A7.** Summary of which BM patterns are associated with the investigated application.

| | **Pay-per-Use** | **Performance-Based Contracting** | **Rent Instead of Buy** | **Fractionalised Ownership** | **Guaranteed Availability** | **Two-Sided Market** | **E-COMMERCE** | **Direct Selling** | **Mass Customisation** | **Total** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Forklift** | | x | | | x | x | x | x | x | **6** |
| **Pallet truck** | | x | | | x | x | x | x | x | **6** |
| **AGV** | | x | | | x | x | x | x | x | **6** |
| **Golf cart** | x | | x | | | x | x | x | x | **6** |
| **On-grid buffer storage at charging station** | | x | | x | x | x | x | x | x | **7** |
| **Commercial ESS with peak shaving purposes** | | x | | x | x | x | x | x | x | **7** |
| **Industrial ESS with peak shaving purposes** | | x | | x | x | x | x | x | x | **7** |
| **Industrial ESS with renewable firming purposes** | | x | | x | x | x | x | x | x | **7** |

The analysis of the investigated applications regarding potential BMs or BM patterns showed a strong dependency on the degree of mobility. "Pay-per-use" and "Rent instead of buy" were only taken into account for the mobile application golf cart as this, unlike the others, is not an industrial application and therefore quite different priorities arise, e.g., regarding operational reliability and consequences of downtimes. Forklifts and other industrial applications are used on a daily basis and thus the pattern "Performance-based contracting" is much more suitable than "Pay-per-use". "Performance-based contracting" is a possibility to use SLBs without the need to purchase them and thus minimises the risks of new types of batteries disrupting the market and the uncertainties regarding durability or the battery's history in the first life. "Fractionalized ownership" deals with joint ownership including its advantages and drawbacks in terms of acquisition, operation, maintenance and further utilisation. "Guaranteed availability" is a BM pattern that suits all listed applications except "golf carts" and gives the applying company the certainty of permanent and unrestricted usage of the SLBs application as it very often also incorporates repair and maintenance services. The highly promising "Two-sided market" pattern focuses on platforms as a prerequisite, whereas the "Mass customization" pattern has individualisation with simultaneous mass production at its core. "E-Commerce" and "Direct Selling" are two BM patterns that are very likely to be combined with others to develop a suitable and innovative BM in the field of SLBs.

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139. In This Context, National Provisions such as the Austrian or German Product Liability Act Are Largely Based on European Law Directives; cf. Council Directive of 25 July 1985 on the Approximation of the Laws, Regulations and Administrative Provisions of the Member States Concerning Liability for Defective Products, Abl L 210/29. Available online: https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:31985L0374&from=HU (accessed on 14 March 2023).
140. § 5 para 1 and 2 Austrian Produktsicherhreitsgesetz, BGBl I 16/2005 as Amended by BGBl I 32/2018. Available online: https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=20004009 (accessed on 14 March 2023).
141. Art 7 Directive 2006/42/EG of the European Parliament and of the Council of 17 May 2006 on Machinery, and Amending Directive 95/16/EC, OJ L 157/24. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32006L0042 (accessed on 14 March 2023).