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Procedure for Assessing the Suitability of Battery Second Life Applications after EV First Life

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Abstract: Using batteries after their first life in an Electric Vehicle (EV) represents an opportunity to reduce the environmental impact and increase the economic benefits before recycling the battery. Many different second life applications have been proposed, each with multiple criteria that have to be taken into consideration when deciding the most suitable course of action. In this article, a battery assessment procedure is proposed that consolidates and expands upon the approaches in the literature, and facilitates the decision-making process for a battery after it has reached the end of its first life. The procedure is composed of three stages, including an evaluation of the state of the battery, an evaluation of the technical viability and an economic evaluation. Options for battery configurations are explored (pack direct use, stack of battery packs, module direct use, pack refurbish with modules, pack refurbish with cells). By comparing these configurations with the technical requirements for second life applications, a reader can rapidly understand the tradeoffs and practical strategies for how best to implement second life batteries for their specific application. Lastly, an economic evaluation process is developed to determine the cost of implementing various second life battery configurations and the revenue for different end use applications. An example of the battery assessment procedure is included to demonstrate how it could be carried out.

Keywords: second life; Lithium-ion battery; battery life cycle; battery assessment; energy storage system; electric vehicle



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1. Introduction

The goal to mitigate global climate change has resulted in strong policies aimed at reducing greenhouse gas emissions, decoupling economic growth from resource use and more equitable distribution of cost and impacts related to energy. This has been galvanized with large investments to support these objectives including through the EU Green Deal [1] and the recovery plan for Europe, which includes large public investment to aid in the substitution of combustion vehicles for the electric vehicle [2].

With rapid growth in battery markets, particularly the EV market, reductions in the cost and environmental impact of batteries can greatly improve their ability to help achieve energy and environmental goals. The use of batteries in second life applications after reaching the end of life for their initial use is one way to reduce environmental impacts and the costs of storing energy.

The use of batteries in second life applications is starting to gain traction, with several companies commercializing second life storage systems; however, the decision-making process for transitioning from primary, first life applications to second life applications is not well understood. Several studies have been performed that consider the benefits of reusing EV batteries before recycling in various applications [3–6]. There are some studies and

standards that propose tests to evaluate the state of the battery after its first life [7,8]. Two other studies establish the stages between first life and second life, but do not consider the different possibilities of end of life and the different possible configurations [9,10]. Lastly, there is one study that, while it does propose a general process for assessing the second life of batteries, focuses on the disassembly process and does not explore the implications for use in various end-use applications [11].

Uncertainties related with the state of the battery, the different ways and requirements for adapting the battery to a new application, and difficulties in analyzing the economic and environmental benefit, complicates the transition from the first life to the second life. There are multiple potential pathways for the batteries when they reach their end of life (EOL). The more common pathway nowadays is to build a refurbished battery from used modules to perform, for instance, time shifting in an industry [12] or to stack used EV battery packs to provide services at the utility scale [13]. The above-mentioned uncertainties represent a barrier to the replicability and scalability of the implementation of second life batteries.

The aim of this work is several fold: (1) to consolidate and expand upon the battery assessment approaches in the literature by developing a framework for assessing the suitability of battery second life applications. This framework should be well-structured and complete enough to use today, but flexible enough to accommodate evolutions in battery chemistry, topology, regulations, etc. (2) While general frameworks for a second life transition assessment has been developed previously, there are many specific considerations that are not considered, but which are essential to perform a functional assessment. As such, this paper develops a table of specific advantages and disadvantages to consider during the transition process that will guide the user's decision-making, thereby enabling a more practical and actionable assessment to be performed. (3) This work brings together several layers of the battery evaluation process including an assessment of the state of the battery, a technical viability assessment considering potential second life applications, and an economic assessment. This process can be integrated into the life cycle of the battery and can start as early as the design stage of the battery pack. Additionally, based on the battery assessment process presented, there is the possibility that part of the assessment can be automatized to further accelerate the process of transitioning to second life applications.

Ultimately, the goal of this work is to streamline the decision-making process used to assess EV batteries after their first life with a detailed and actionable assessment tool. This can enable a more rapid, replicable and scalable transition of batteries from first life to second life.

This article is organized as follows: Section 2 summarizes the overall framework of the battery assessment, with Sections 3–5 providing a detailed description of the three main steps in the battery assessment including “Evaluation of the State of the Battery”, “Technical viability of different solutions,” and “Economic evaluation of each potential solution”, respectively. Section 6 provides an example of the proposed battery assessment procedure. Section 7 contains a concluding discussion and a description of future work.

2. Framework for the Battery Assessment after First Life

The total vehicle stock of EVs on the market is projected to increase through 2050 [14]. Now, each manufacturer designs their own battery pack so the number of different models with a variety of characteristics, management, controls, and thermal management systems will continue to increase. This issue will affect the second life analyses, since the preferred second life strategies depend on the specific characteristics of the EV battery. This is further complicated by variations of the degradation levels derived from the first life use, that results in batteries reaching EOL with different aging conditions. In addition, the battery state at EOL must be matched to the most suitable and/or profitable second life end use application considering duty cycle, size requirements, market size and revenue potential.

In order to analyze and evaluate these uncertainties, a procedure is proposed to aid in the decision-making process regarding battery reuse (depicted in Figure 1). The battery assessment procedure is placed inside a simplified scheme of the battery life cycle. This

assessment is recommended to be performed during the first life, even before removing the battery from the vehicle. This is to avoid incurring unnecessary expenses if a second life solution is not recommended as an output of the analysis. To this end, the assessment is proposed in a way that it can be used by any battery manufacturer, EV manufacturer, distributor, specialist workshop or the vehicle owner. It is comprised by three stages that should be performed.

1. Battery state evaluation: The degradation conditions of the battery (energy, power, external wear) are analyzed.
2. Technical viability of different solutions: Requirements for different applications and possible configurations of the EV batteries are analyzed.
3. Economic evaluation: The economic viability of the possible solutions is analyzed.

With the structure proposed for the battery assessment, it could be possible to automate part of the assessment to even further accelerate the decision process after first life. The feedback of the assessment could be saved in the battery passport that the EU dictates for future batteries [15].

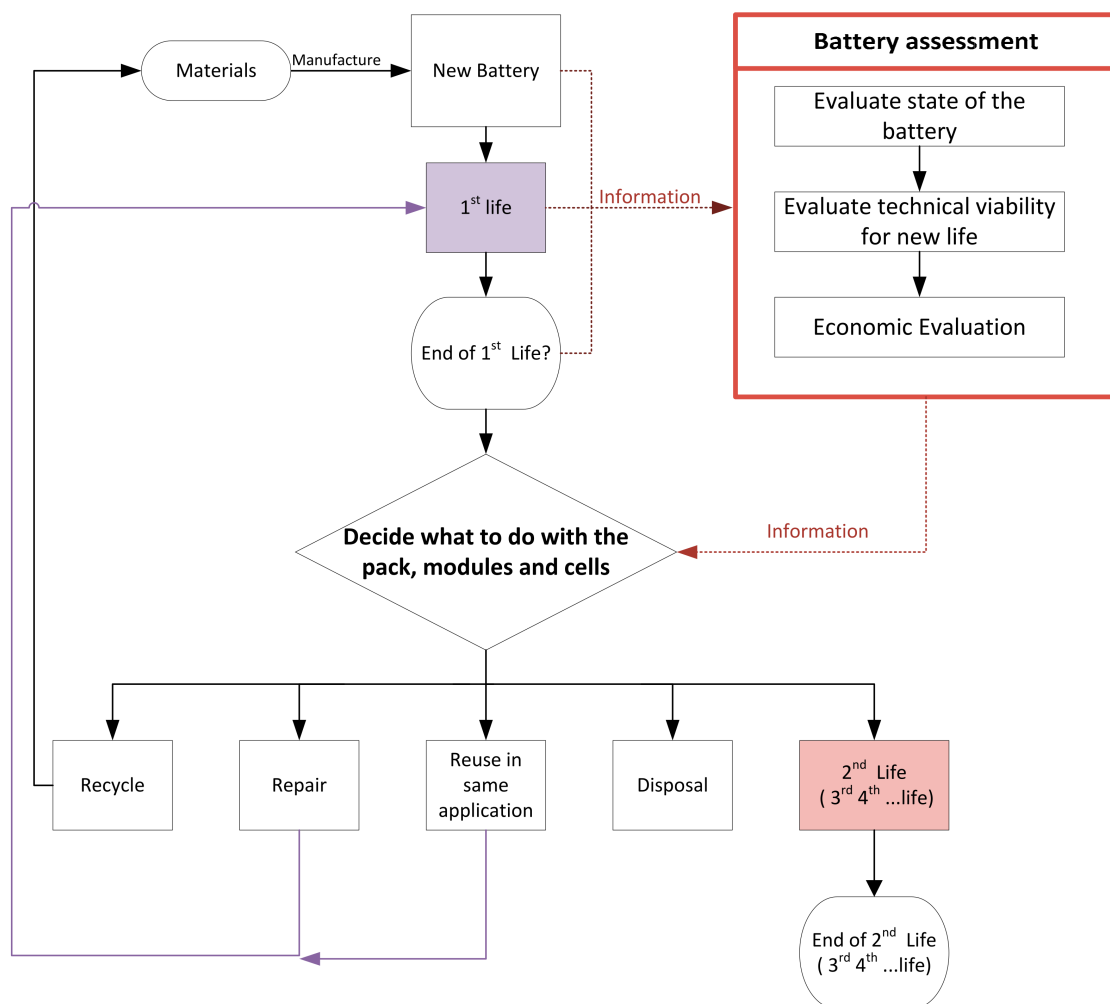


Figure 1. The proposed battery assessment as part of a simplified battery life cycle.

Depending on the information available, after each stage of the battery assessment there is an opportunity to determine what should be done with the battery. The available options include the following:

- **Recycle/disposal:** If the battery is not repairable, it can be recycled or disposed of. If the technology is not available, there is not sufficient recycling capacity or there is no

obligation to recycle the battery, and a second life is not possible, disposal immediately after the first life is a potential option.

- Repair/reuse: Depending on the battery architecture and financial considerations, the battery pack or individual modules can be repaired and continue first life in the same vehicle or in another.
- Study second life: If the battery is still in good condition or can be repaired but does not have enough remaining life to meet its first life requirements, the battery assessment can be performed to explore potential options for second life applications.

3. Evaluation of the State of the Battery

The first stage of battery assessment is to not only analyze the health conditions of the battery, but also the accessibility and veracity of the information needed for the following stages. This stage can begin before the battery reaches its EOL, if desired. Batteries will reach EOL at different states since they have undergone different degradation conditions including temperature, C-rates, average state of charge (SoCm), and depth of discharge (DoD) and there may be several reasons for reaching EOL. This step is the first filter to decide what to do with the battery (repair, recycle, disposal or analyze for second life).

To begin this evaluation, the information available about the battery should be collected. Some information may come from the cell manufacturer which may include cell format, chemistry, operating conditions for voltage and current, capacity, expected number of cycles. Datasheets from the pack manufacturer or assembler may include the number of modules, number of cells, internal pack design, warranty, other pack properties and operating conditions. A battery assessment can be performed with a subset of this data; however, the inclusion of limited data will affect the accuracy of the results. Available data can be supplemented with open source [16] or private databases.

The next step is to obtain indicators of the battery health or data that helps to calculate the life in the new possible application. Two different categories are identified:

1. Continual estimation of battery health:

Either on-board or through the cloud, relevant health indicators can be calculated throughout the first life of the battery. These can be direct measurements of important factors including the distance driven, age of the battery, ambient temperature, depth of discharge, battery charging and discharging rate, or more sophisticated calculations such as the State of Health (SOH).

The accuracy of the SOH is dependent on the algorithm or process implemented. A variety of different solutions have been developed to estimate SOH [17–25], so specific techniques will not be addressed in this paper. However, generally, the use of data to develop the SOH estimation could be based only on a subset of data (periodic health estimates) or even recording of the full life of the battery in the cloud, as some manufacturers are starting to do [26,27]. Additionally, the SOH can be based on data from an individual vehicle or multiple vehicles. In the case that these data are shared, it could make second life rollout and also vehicle-to-grid (V2G) technology more effective [18,28].

2. **Testing of the battery pack:** Obtaining indicators of the battery health after the first EOL is currently the most common technique for advising second life decisions. The typical tests performed are capacity and internal resistance. These tests may last 2 days and can be carried out at the pack level, module level or cell level [29]. There are standards that can be followed during the test process, for example, UL 1974 [7]. There is also the chance that the testing of the battery is performed periodically during the first life of the battery as part of the maintenance of the vehicle, which might make the data available for consideration during second life. Also, some strategies to estimate the remaining useful life (RUL) can be use with the data obtained by the tests [30].

The last step of the evaluation stage is to ascertain the reason for reaching the EOL. In general, EOL can be defined as the point in the time when the battery can no longer

provide enough power or energy to safely accomplish its intended function [31], which depends on the application and the resulting battery requirements [32]. In EVs, the EOL is commonly established when the discharge capacity drops to a certain value relative to its initial value [33]—typically fixed at 80% [34,35] or 70% [36,37]. There are also some other cases where the EOL is defined by the relative internal resistance instead of the relative capacity. In these cases, the EOL is typically set to 200% of the initial internal resistance of the battery [38,39]. The relative capacity is commonly linked to high-energy EV applications and the relative resistance threshold is normally related to high-power EV applications [10]. However, these definitions do not cover all scenarios that may lead to the EOL of a battery. In general, there are three main reasons for reaching EOL:

- **Vehicle reaches EOL:** In this case, the vehicle is reaching its EOL while the battery is still functional. For example, the vehicle is retired or damaged either with or without damage to the battery. Depending on the condition and health of the battery, the battery can be used directly as a pack or disassembled into modules or cells along with the accompanying balance of plant to proceed to the next step in its lifecycle, as depicted in Figure 1.
- **Battery reaches EOL:** There are a broad set of reasons that a battery can reach EOL—most notably, the battery can no longer meet the needs of the driver. This could be because the driver's needs have changed, or because the battery has degraded rendering it unable to achieve the same level of performance as it once could. This scenario is the most common when the battery cannot fulfill the requirements of the driver in terms of range or power due to a decrease of the energy capacity or an increase of the internal resistance, respectively. Additionally, there could be a failure in the battery pack that prevents its use, while the rest of the vehicle systems are still functional.
- **Warranty or legal limitation:** There can also be reasons outside of the owner's control that affect the ability to operate the vehicle. For instance, there can be stipulations in the warranty that require certain actions for the vehicle or the battery pack at a specific age or mileage. Lastly, there could be laws passed in a given country or region that limit usage of vehicles that achieve certain milestones (e.g., age, or mileage). This has been done in many cities in the European Union to limit emissions, by encouraging vehicle stock turnover and movement to more efficient and less polluting vehicles.

4. Technical Viability of Different Solutions

Following the first stage of the assessment, the battery now enters the technical evaluation stage. This stage is focused on exploring requirements for different end use applications and the battery configurations necessary to meet those requirements.

4.1. Second Life Applications: Requirements

Batteries, and storage systems in general, can be used in a broad number of applications. The most discussed applications for second life batteries are: time-shifting (energy arbitrage) [40], peak shaving [41], grid services [42], renewables integration [43], support EV charging stations [44], capacity reserve, personal e-mobility [45] and small electronic devices. The above-mentioned applications require different characteristics for the battery and can vary, even within the same application. That is why, for each specific case, the following requirements should be analyzed:

- **Capacity:** The maximum energy storage capacity to be installed in each application is limited by several factors such as maximum initial investment, energy demand or desired power. Some applications have to follow regulations or consumer requirements to choose the most suitable capacity. The future income of the installation is dependent on the installed capacity, so an economic study is needed to optimize the sizing. If future degradation is taken into consideration during the optimization, it can affect the sizing of the system as well as its economic feasibility. In Figure 2, the

identified second life applications are classified in terms of capacity and are matched with the end user of the installation.

- **Max power:** This depends on the maximum C-rate that the battery can deliver. For Li-ion batteries, it typically varies from 0.5C (Energy Cells) to 5C (Power Cells). Moreover, higher C-rates (25C) can be delivered in small pulses (a few seconds) [46]. Despite that, battery energy storage systems (BESS) oftentimes offer max C-rates of 1C [47–49]. Because of the battery design, the power requirement is often interrelated with choosing the most suitable capacity.
- **Weight:** To obtain the same capacity with second life cells (80% SoH) as with first life cells, 25% more cells are needed and therefore, 25% more net weight of cells will be installed. In stationary applications this does not influence the performance. However, in mobile applications, the weight affects the power and the range of the vehicle. Despite this, in small mobility applications the performance reduction does not appear to be significant. For example, the difference in performance between a scooter with first life batteries (2 kg [45]) and one with second-life batteries (2.5 kg) is equivalent to the difference between the performance of a scooter driven by a 75 kg person and another driven by a 75.5 kg person, that is negligible for the final customer.
- **Volume limitations:** In mobility applications and small electronic devices, volume is always a limiting factor. For example, the design of the vehicle or the device is greatly affected by the volume and shape of the battery, and therefore it affects the final quality of the product. In contrast, for stationary applications the volume occupied by the battery has a much less significant effect on the capacity installed. However, there are some exceptions such as industries, buildings, or individual houses where the space available may not be enough to install the desired capacity.
- **Energy Management system (EMS):** The EMS is in charge of controlling the flow of energy in the installation between the different components. The complexity depends on the optimization algorithms included. For example, algorithms to improve the life of the elements of the system, or algorithms to optimize the revenue of the system. It is worthwhile to highlight that the EMS is different from the Battery Management System (BMS), which has the unique objective of ensuring that the battery functions safely. Depending on the new second life application, a new EMS has to be implemented. The communication between the BMS of the old battery or the power converter should be addressed, and may be an impediment as discussed in Section 4.2.
- **Thermal management:** There are different ways of managing the temperature of the batteries. There are passive techniques and active techniques. The most common active techniques to maintain temperatures in the optimal range are forced air and liquid refrigeration. Depending on the ambient temperature and the working conditions, an appropriate thermal system should be chosen and the degradation of the batteries will be reduced. The decision to include thermal management in the possible second life application should consider the economics of the alternatives (e.g., the ability to reuse a pack or module thermal system, the cost of purchasing a new system, and the performance reduction from not including a thermal management system).
- **Possible configurations:** Depending on the design of the EV battery pack, it could be adapted to second life applications through different configurations. The main configurations identified in this document are: stacking battery packs, refurbishing used modules and refurbishing used cells. In Figure 2, second life applications are matched with different possible configurations vs capacity. For stationary applications, the three configurations are possible. For low-capacity applications, due to the form factor and capacity requirements, the only practical configuration is to use refurbished cells. This will be explained in detail in the next subsection.

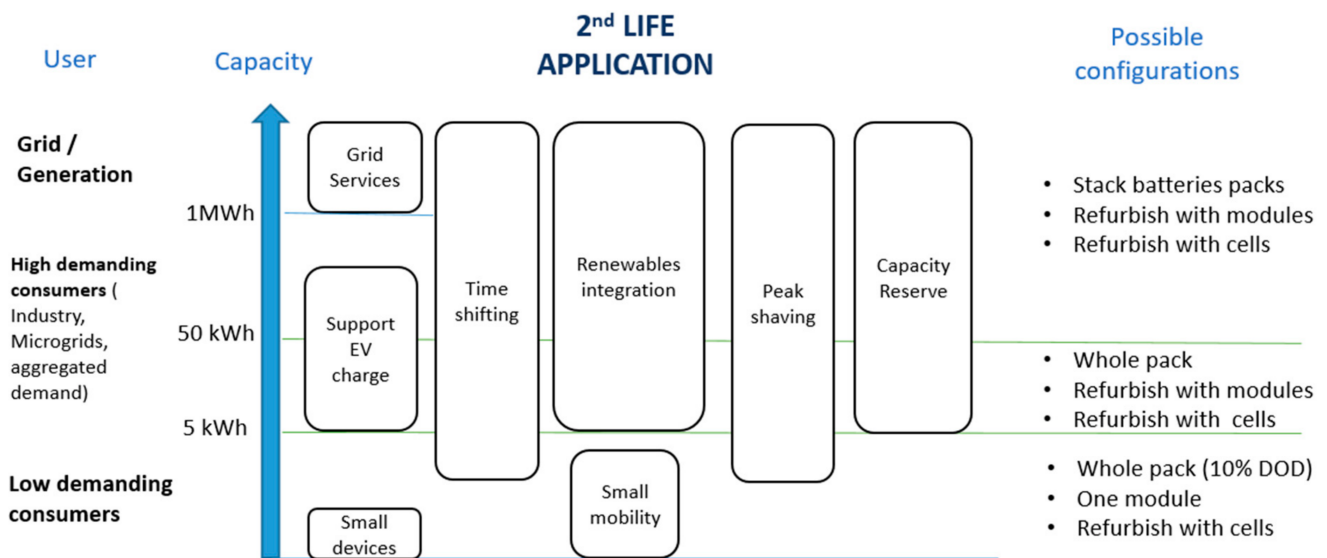


Figure 2. Possible configurations and applications depending on the desire capacity.

4.2. Second Life Applications: Potential Configurations

Consideration of different battery configurations when deciding on the appropriate second life application is an important part of the battery assessment process. Many battery packs are not designed for a potential reuse; however, more manufacturers are beginning to integrate concepts of eco-design for their battery packs that will aid in the reuse and refurbishing processes—thus lowering costs and complexity [50]. In this section, the possible configurations are analyzed, including the advantages and disadvantages, which are summarized in Table 1.

Table 1. Summary of main advantages and drawbacks of the second life application configurations.

Second Life Application Configurations	Advantages	Disadvantages
Stacking battery packs	<ul style="list-style-type: none"> The module distribution within the battery pack does not affect the performance for the second life applications, so pack designs that are more integrated and less modular are acceptable when stacking battery packs. The thermal control can use the internal heating and cooling of the battery packs. Stacking batteries could result in lower costs, complexity, and more rapid transition because the disassembly steps are removed, any required redesign steps are removed and internal components of the battery packs are used. Reusing internal components and even the battery housing has the potential to reduce waste generated by a new battery that would otherwise be used in this application. This strategy is more accepted by car manufacturers as their product is less manipulated, thus having less risk of failure [46]. This could mean that the BMS from the original equipment manufacturer (OEM) could be leveraged, potentially lowering the cost of implementation. 	<ul style="list-style-type: none"> The pack operates beyond the warranty offered from the OEM which could shift risk to the owner in the event of a failure, as opposed to the alternative of purchasing a remanufactured product that comes with a new warranty. The performance of the whole system is affected by the worst performing module/cell. While the pack will be compact and lightweight for stationary applications, the shape of the pack cannot be modified without additional costs. The thermal management system will require modification too, particularly if the systems rely on vehicle radiators. Limited flexibility in sourcing components for repair and periodic maintenance. When connected in parallel, unexpected current flows may develop between the battery packs. DC/DC power converters have to be used to connect the EV battery packs in parallel.

Table 1. Cont.

Second Life Application Configurations	Advantages	Disadvantages
Refurbished battery made from used modules	<ul style="list-style-type: none"> The best module(s) of the pack can be selected, and the worst can be discarded. Greater flexibility in terms of dimensions of the new battery size with respect to stacking full packs. The BMS of the new battery is designed for the new application, and it can communicate directly with the power converter. Simpler to repair than an entire battery pack. If a module fails, it can be substituted for another one. 	<ul style="list-style-type: none"> Module performance is affected by the worst performing cell. The thermal management system will require modification too, particularly if the systems rely on vehicle radiators. Limited flexibility in sourcing components for repair and periodic maintenance. If the cells within the pack are not subdivided into modules, then this configuration is not possible. Some components of the EV battery pack are not used and must be discarded/recycled sooner. New components should be added, which adds cost and complexity to the product compared to using packs directly.
Refurbished modules made from used cells	<ul style="list-style-type: none"> The best cells of the pack can be selected and the possibilities of introducing damage cells are considerably reduced. Flexibility in designing the size and shape of the remanufactured system. 	<ul style="list-style-type: none"> Higher cost to disassemble the pack to the cell level. Difficult to disassemble the EV battery pack without damaging cells. Disassembly to the cell level means that there will be higher waste of components that are unable to be reused during the remanufacturing process. High cost for provision of new housing, busbars, sensors, BMS and re-assembly process.

4.2.1. Stacking Used EV Battery Packs

Stacking battery packs consists of connecting battery packs with the least possible modifications. Combining battery packs can be useful for applications where the energy required is greater than that offered by a single battery pack. Interoperability between battery packs from the same and different manufacturers presents challenges, because EV batteries are not designed with the idea of stacking batteries for second life applications.

Due to the high voltages of the EV battery packs, the connection between them may be done in parallel to avoid isolation problems. This has the advantage of allowing the disconnection of one battery pack in case of failure while maintaining system operation (with lower capacity and power capabilities). On the other hand, when connecting batteries in parallel, some unexpected current flows may develop between batteries with different voltages. To solve this problem, in most of the projects with second life batteries, a power converter is added to the battery. This solution raises the cost, as the DC/DC power converters usually have to be designed especially for each battery type and project [51]. Moreover, if the BMS of the battery pack is not able to communicate with the power converter, a specific gateway has to be developed [52]. EV battery packs with similar characteristics (e.g., capacity, voltage, internal resistance) facilitate the implementation of this type of configuration [51,53].

4.2.2. Refurbished Battery Made from Used Modules

This configuration requires disassembly of the battery pack to the module level. It requires assessing the exterior of the modules, performing characterization tests, certifying that the modules meet the second-life standard, and lastly, integration to form a new battery pack that fits the new application [54]. For applications with high-energy demands, this is an alternative to stacking batteries packs. Similar to the configuration of stacking battery packs, modules with similar characteristics that are able to communicate with a superior BMS should be used in this type of configuration.

4.2.3. Refurbished Modules Made from Used Cells

Refurbishing used cells is similar to refurbishing modules, but the battery pack is disassembled to the cell level. The cells are then packed into new modules and new battery

systems. This is particularly valuable when pack or module dimensions are not suitable for the application. Based on the required energy capacity and dimensions, some small mobility and small electronic devices are only able to use cylindrical cells, meaning that if the battery pack is made using prismatic or pouch cells, then the owner can immediately remove these second life applications as potential options.

The outcome of the technical evaluation stage of the battery assessment is to identify suitable end use applications and pack configurations, based on the design and state of the battery pack being assessed.

5. Economic Evaluation of Each Potential Solution

From the technical evaluation, several eligible solutions may have emerged. Each solution is a match to the possible configuration of the battery and the final application. The third stage of the battery assessment is to perform an economic evaluation to find the most profitable application.

The economic evaluation requires an estimation of costs and potential revenues. In subsequent subchapters, important considerations for making this assessment will be described. An example of data from the literature has been provided; however, it is recommended that battery-specific and application-specific data be gathered when performing this analysis.

5.1. Cost of Each Potential Solution

The cost of each solution can be divided into two categories: the cost of the battery, including disassembly, and the cost of the installation into the possible application.

The cost of second life batteries varies widely depending on the configuration chosen. Stacking used EV battery packs or using a whole pack will always have a lower cost than refurbishing modules from used cells. The more it is disassembled, the higher the associated costs. This is due to, on one hand, the cost related with disassembling and, on the other hand, the costs associated with the new equipment needed that can increase the cost around 30% with non-cell related materials (connectors, BMS, case, etc.) [55].

Not all batteries packs have the same internal design, and that makes the cost of disassembly different for each battery. There are different methodologies [56–59] that can be followed to estimate the cost before disassembling the battery. These methodologies provide deeper insights into which disassembly tasks are the most time-consuming, and provide feedback on how the battery design could be improved to facilitate faster and lower cost disassembly [60].

In [11], the costs associated with removing a battery from the vehicle and disassembling it to the module level and cell level were evaluated. In Table 2, these costs are shown as a reference for manually disassembling a battery pack. This cost will decrease with economies of scale and the use of automatic methods like robots.

Table 2. Cost of disassembling battery packs. Reprinted from Ref. [11].

Cost of Dismantling	Battery Pack	Module	Cell
Battery removal from EV	117 €	117 €	117 €
Disassembly to modules	—	500 €	500 €
Disassembly to cells	—	—	275 €
TOTAL	117 €	617 €	892 €
COST/kWh	6.68 €	35.26 €	50.97 €

Table 2 only considers the disassembly cost. The cost of the second life battery acquisition should also be included, which ranges from 40 to 165 €/kWh [61]. The cost of the battery acquisition varies, depending on remaining life and how much disassembly and testing has been done after the first life.

The cost of the battery is not the only cost of the new second life application that needs to be evaluated. For grid services, the installation is usually called a Battery Energy Storage

System (BESS). In Table 3, a brief summary of the costs associated with the installation of BESSs are shown. These costs can be used as a reference, but using data specific to the installation that is being studied will improve reliability of the results of the assessment.

Table 3. Cost associated with the installation of a BESS.

Concept	Description	Cost
Storage Block	Includes the battery module, rack, and battery management system.	185–450 €/kWh [62–64]
Storage-Balance of System	Container, cabling, switchgear, flow battery pumps, and heating, ventilation, and air conditioning (HVAC).	25–45 €/kW [62–64]
Power Equipment/Power Control system	Includes bidirectional inverter, DC-DC converter, isolation protection, alternating current (AC) breakers, relays, communication interface, and software.	66–150 €/kW [62–64]
Controls & Communication	Includes the energy management system for the entire ESS and is responsible for the ESS operation.	13–40 €/kWh [62–64]
System Integration	Price charged by the system integrator to integrate sub-components of a BESS into a single functional system. Tasks include procurement and shipment to the site of battery modules, racks with cables in place, containers, and power equipment. At the site, the modules and racks are containerized with HVAC and fire suppression installed and integrated with the power equipment to provide a turnkey system.	33–46 €/kWh [62,63]
Engineering, Procurement, and Construction (EPC)	Includes non-recurring engineering costs and construction equipment as well as shipping, siting and installation, and commissioning of the ESS.	45–58 €/kWh [62,63]
Project Development	Costs are associated with permitting, power purchase agreements, interconnection agreements, site control, and financing.	54–67 €/kWh [62,63]
Grid Integration	Direct cost associated with connecting the ESS to the grid, including transformer cost, metering, and isolation breakers (could be a single disconnect breaker or a breaker bay for larger systems).	20–28 €/kW [62,63]
Operations & Maintenance (O&M)	Includes costs to keep the storage system operational throughout the duration of its economic life that do not fluctuate based on energy throughput, such as planned maintenance, parts, labor and benefits for staff.	5–20 €/kW-year [62,64]
Decommissioning Costs	Disconnection, disassembly/removal and disposal	200 €/kW [64]

In summary, the total cost to prepare a battery for second life includes acquisition of the battery, disassembly, possible refurbishing and installation of the new system. Representative costs have been provided for each of these items.

5.2. Revenues

The revenue obtained in consumer-orientated applications (e.g., scooters) comes directly from the price of selling the replacement battery, but in most applications, the amount of revenue obtained depends on how the battery is used during the new life (e.g., time shifting).

For the applications whose source of revenue depends on the use, an optimization algorithm is needed for both analyzing the viability of the project and during the execution of the project to provide operational support (with an EMS). Depending on the quality of this algorithm, the profits of the application can be increased [6]. One of the biggest challenges with developing accurate optimization algorithms is the consideration of bat-

tery degradation during the optimization process. The battery degradation is nonlinear, depending on one or more independent variables, and some variables are very difficult to calculate in the same time domain as the other variables of the application. For example, battery degradation is highly affected by the DOD which has to be calculated when the discharge ends, and it is possible that the discharge continues in different periods. This issue makes it difficult to compute the degradation for a single period and the profitability of discharging the battery in that period.

Different authors have proposed many solutions to obtain the optimal use of the battery in different applications and calculate possible revenues. Some of them completely ignore battery degradation [65–67] and, in others, the degradation is calculated post-optimization [3]. As a result, the operation strategy is shortsighted and does not consider the battery as a time-limited and costly resource [68]. However, two other approaches do consider battery degradation:

- The constraint-based approach [69,70]: one or more of the following variables are constrained: power, DOD, number of cycles per day, and maximum and minimum state of charge SOC. Such approaches that do not model the degradation behaviour at all return non-optimal results [71].
- The objective-based approach [72,73]: the cost of battery degradation is included as an economic cost in the objective function. The degradation can be expressed using the Ah throughput method [73,74] that assumes that the battery can deliver a certain amount of energy before its end of life without considering the working conditions. Another way of expressing the degradation of the battery is using the number of cycles vs DOD power functions [69,72], where it is assumed that the number of cycles that a battery can perform is inversely proportional to the amplitude of DOD given by a simple power function [71].

Revenue potential for energy storage systems in the U.S. was analyzed in detail by Balducci et al. in 2018 [75]. The minimum, mean and maximum values for each application is presented in Table 4. The highest mean values were registered for frequency regulation (\$123/kW-year), capacity or resource adequacy benefits (\$106/kW-year), and demand charge reduction (\$104/kW-year). Additionally, there is the potential to participate in multiple markets, thereby allowing for stacking of revenues [54].

Table 4. Minimum, mean and maximum values of different applications in the US markets. Reproduced from Ref. [75].

	MIN \$(/kW (Installed)-Year)	MEAN \$(/kW (Installed)-Year)	MAX \$(/kW (Installed)-Year)
Capacity or resource adequacy	10	106	196
Energy arbitrage	1	52	163
Regulation	1	123	359
Spin/non-spin reserve	1	20	67
Frequency response	37	54	81
Voltage support	3	22	60
Black start service	8	8	8
Transmission congestion relief	12	72	260
Transmission upgrade deferral	24	124	233
Distribution upgrade deferral	9	93	177
Power reliability	2	77	283
TOU charge reduction	2	65	266
Demand charge reduction	12	104	269

The high variability of the values is due to the inclusion of different markets, different years, and different ways of implementing the battery. In [5], the following factors are identified as sources of uncertainty when the revenue of an application is calculated: (i) Revenue streams: target market, rate structures, electricity prices and ancillary service

payment structures, etc. (ii) Technical parameters: second life battery lifetime, power and energy capabilities, efficiency, heterogeneity, etc. (iii) Policies and market-specific conditions: environmental initiatives, subsidies, legal requirements, etc.

Moreover, apart from the great uncertainties of each application, the market size also needs to be considered. Many applications have a limited market size that can become saturated. Frequency regulation markets are particularly susceptible due to their relatively high value and limited size [76–78].

Additionally, there may be other factors that can affect the profitability of second life applications including incentives for battery reuse, or credits for greenhouse gas emissions reductions through a carbon market.

If none of the possible applications and configurations are profitable, the owner should consider recycling or disposing of the battery after this assessment.

6. Example Battery Assessment

In order to show the functionality of the battery assessment procedure, an application example is shown in this chapter. For this, realistic assumptions will be used to observe how the extracted information is analyzed and used to find the optimal pathway for a particular battery.

To begin with, it is assumed that the evaluation is carried out by the car manufacturer. This is a convenient situation as it is the one with extensive knowledge of the battery. It is also a realistic assumption, as European regulations require that the vehicle OEM or battery manufacturers cover expenses related to battery collection and recycling.

The example deals with a vehicle that is no longer capable of fulfilling the driver's requirements.

6.1. Evaluate State of the Battery

The first step is to assess the condition of the battery. Several pieces of information are needed to evaluate the state of the battery. In the procedure, two options are mentioned: continual estimation of the battery health through vehicle monitoring or through battery tests. This example begins by compiling the available information that does not require any special operation. It will be assumed that the following battery information is available (Table 5):

Table 5. Information available for assessing the condition of the battery.

Feature	Value
SOH estimation	75%
IR increased	30%
Initial capacity	54 kWh
Condition of battery pack	The battery still works but does not fulfill the requirements of the driver.
Condition of Modules/cells	There is not a significant difference between the performance of modules.
Battery lifetime model is available?	No
Age of the battery	8 years
Total vehicle mileage	300,000 km
Maximum vehicle range	400 km

In the case of the study, a lifetime battery model is not available to predict the possible estimated life for other applications. However, with the mileage of the vehicle, some calculations (Equations (1) and (2)) can be made to aid in a lifetime estimation.

It is assumed that 1 cycle of the battery is equivalent to the range of the vehicle, by dividing the total km by the range; an estimated value of the total full equivalent cycles (FEC) of the battery can be obtained:

$$\text{Estimation of number of cycles during first life} = \frac{300,000 \text{ km}}{400 \frac{\text{km}}{\text{cycle}}} = 750 \text{ cycles} \quad (1)$$

Another assumption is that the life of the vehicle can be linearized [79] and a similar degradation rate can be established for the second life application, as shown in Equation (2).

$$\text{Degradation rate} = \frac{25\%}{750 \text{ cycles}} = 0.03\% \frac{\text{capacity fade}}{\text{cycle}} \quad (2)$$

With these values, the battery assessment can be continued without the need to carry out any test or removal of the battery pack from the vehicle. Moreover, after this first stage, it is known that the battery works correctly, so it could be used without requiring any repair in a second life application.

6.2. Technical Viability

The objective of the technical feasibility study phase is to check if the battery pack can have a second life, and in what type of configuration it would be. To do this, the necessary information is compiled based on Section 4 (see Table 6).

Table 6. Information available for the technical feasibility part of the case study.

Feature	Value
Number of battery packs	1
Number of modules	8 series
Number of cells	12 series
Cell format	Prismatic
Available Energy	$0.75 \times 54 \text{ kWh} = 40.5 \text{ kWh}$
Max Power	25 kW
Weight	300 kg
Volume	Unknown
Thermal management	The thermal management system can be reused with an external pump
Safety of disassembling modules and cells	Modules and cells can be disassembled without damaging them
Battery pack: Possibility to stack or connect to battery converter	The battery packs are not designed to be connected. The BMS is available, and a gateway can be developed to use the battery with a power converter
Modules: Possibility to stack, work alone Communications, safety	The external case of the module does not meet the safety requirements (e.g., penetration, insulation) to function outside the battery pack. It needs a superior BMS to work
Cells: Possibility of building a new module	The cells should be characterized if a new BMS is planned to be used

Looking at the available information in Table 6, the following possible solutions can be assessed:

- Stacking battery packs: This configuration is viable and can be implemented easily using power converters. In this case, only one battery pack is available, so it would be a standalone battery pack application.
- Refurbished battery pack made from used modules: a new battery pack or rack of modules should be built with a BMS available to communicate with the module control units (MCU) of the modules. It is unable to work alone.
- Refurbished modules made from used cells: the battery pack can be dismantled to the cell level so it is possible to refurbish a new pack/module using the used cells. The inconvenience is that in order to use the cells with a new BMS, they should be characterized and a minimum of cells should be wasted in some previous tests.

After analyzing the technical viability of the different configurations, all of these options are possible. However, a priori, refurbished modules made from used cells, and

refurbish battery packs made from used modules implies more tasks than using the battery pack directly.

At this point in the battery assessment, a decision must be made from the different options for the purpose of economic analysis. The following options shown in the Table 7 will be explored:

Table 7. Options to be explored in the economic analysis, based on the information identified in the technical feasibility and battery evaluation steps of the battery assessment.

Configuration:	Use the whole pack battery pack
Power:	25 kW
Energy:	40 kWh
Possible applications:	Support EV charge, time shifting, renewables integration, peak shaving, capacity reserve

6.3. Economic Analysis

For the economic analysis of this example, the costs and revenues shown in Section 5 will be used as a reference. A simplified example is shown here, but a more detailed economic analysis should be carried out when making a financial decision.

Several applications are possible. Table 4 contains reference revenue values. For this exercise, it will be assumed that the mean revenue is 50 €/kW-year for energy arbitrage.

To estimate the duration of the battery, we can assume the end of life of the second life application at 50% SOH [80]. This means that 750 FECs can be performed with the battery. Assuming that the battery is cycled every day, the lifetime of the battery before reaching end of life would be around 2 years. Table 8 contains the example assessment of the cost of installation of the second life battery pack.

Table 8. Example cost assessment of the battery's transition to second life.

	Unit Cost	Units	Amortization	Total Cost/Year
Removal from EV	6.68 €/kWh (Table 2)	40 kWh	2 years	133.6 €
Power equipment	66 €/kW (Table 3)	20 kW	10 years	132 €
Controls & communication	13 €/kWh (Table 3)	40 kWh	10 years	52 €
System Integration	33 €/kWh (Table 3)	40 kWh	10 years	132 €
Engineering, Procurement, and Construction (EPC)	45 €/kWh (Table 3)	40 kWh	10 years	180 €
TOTAL COST/year				629.6 €

The results for the economic analysis are shown in Table 9.

Table 9. Results of the economic analysis for the example battery assessment.

Concept	Value
Costs	629.6 €/year
Revenues	1000 €/year
Benefits	370.4 €/year

6.4. Decision

With the analysis done, a second life application seems viable. When this analysis is done before the battery has been removed from the vehicle, the following steps can be decided (dismantling, transport to the place of installation, etc.) and the calendar ageing due to the storage of the battery is avoided.

The following list contains considerations for improvement that should be taken into account based on the presented example:

- The scrap value (i.e., the price that must be paid to the old owner) of the battery pack has to be subtracted from the mentioned revenues.

- The operation predicts a relatively short lifetime (i.e., two years), after which a new battery would need to be acquired to continue operation.
- Real costs of the required power converter and other equipment should be used, as opposed to the general cost items identified from the literature.
- A deeper analysis of the revenues and optimization of the battery use could be done, to consider the potential for stacked values and the opportunity for enhancing operation decisions by internalizing degradation into the optimization. The assumption that the battery will have a linear degradation until 50% SOH is unlikely if the battery reaches a point of rapid increase in degradation before the 50% SOH level (i.e., the ageing knee).

7. Conclusions and Future Work

This article develops a procedure for the assessment of batteries when transitioning from first life to second life applications. First, the framework for the battery assessment is established with the main uncertainties and challenges identified. The procedure is divided into three stages including: state of the battery, technical viability to transition to a new end-use application, and economic viability.

The first stage gathers information to understand the condition and expectation of performance for the battery. The second stage explores various end use applications, their requirements and using the information gathered in the first stage. It also explores the benefits and weaknesses of different battery configurations to meet those requirements. The third and final stage of the battery assessment outlines the development of an economic evaluation to compare the revenue from different end uses with the cost of implementing the battery configurations outlined in the second stage. The main goal is to establish combinations of second life applications and battery configurations that are profitable.

The main highlights from this work are summarized below:

- This work develops a framework for assessing the suitability of battery second life applications that can be used today, and which has the ability to evolve with changes in the future. Some of the changes envisioned are related to an increase in the volume of recorded data points, advancements in battery modeling and digital twins, as well as improvements to the optimization algorithms in energy management systems to internalize degradation in their objective functions.
- Building on the previous literature, the paper discusses the reasons for transitioning to EOL, the decisions that must be made, and identifies a quantifiable process for determining the most suitable use for batteries as they reach EOL (including repair, reuse, recycle, or disposal).
- This paper explores options for battery configurations (direct use of pack, stack of packs, direct use of modules, refurbish with modules, and refurbish with cells). Uniquely, by comparing those configurations to the technical requirements for second life applications, a reader can rapidly understand the tradeoffs and gain practical knowledge on how best to implement second life batteries for their specific application. This discussion includes a table of advantages and disadvantages to guide the decision process.
- This work develops a method for evaluating the economic impacts of reusing second life batteries compared to purchasing a new battery pack. There are provided default values for costs and revenues. However, with limited data available, it is acknowledged that there is high variability in these data. It is therefore recommended that additional studies need to be performed that capture the cost of transitioning batteries into second life applications.
- Minimizing the costs, accurately predicting battery health and remaining lifetime, and proper sizing for the application are the keys to maximizing the profit from second life batteries.

The next step to consolidate this procedure is to apply it for the assessment of second life batteries in relevant EU projects. Several candidates include the Albatross, COBRA, MARBEL, and HELIOS projects.

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