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Circular Economy-Based Alternatives beyond Second-Life Applications: Maximizing the Electric Vehicle Battery First Life

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Abstract: Electric vehicle battery second-life applications are gaining attention as a way to minimize the environmental impact and increase economic profits. However, the demand for stationary energy storage is expected to be saturated in the near future with these second-life batteries. This fact, in addition to the several technical and economic challenges of second-life batteries, promotes exploring other alternatives. This work analyses and compares these possible approaches in terms of battery degradation and economic profit. The results show that for large batteries, intensive Vehicle to Grid does not cause an early retirement of the battery and allows reducing the underuse of the battery. In addition, for the same battery size, Vehicle to Grid provides more economic profit than second-life applications. Nevertheless, only in a few cases does this appear to be more profitable than simply utilizing the battery for driving. Importantly, this study has shown how the assessment of the second-life tends to be too optimistic as a consequence of assuming a fixed End of Life threshold for the batteries.

Keywords: battery ageing; electric vehicles; second-life application; V2G (Vehicle to Grid)

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1. Introduction

The fast growth of the Electric Vehicle (EV) market goes hand in hand with a large R&D effort to improve the technology, reduce the cost of the vehicles, especially of their Lithium-ion (Li-ion) batteries, and to lengthen their lifespan.

Degradation is a key issue surrounding these batteries. As a consequence of usage and time, batteries lose the abilities to provide energy and power [1], which can intensify the range anxiety of the drivers. To avoid this, EV manufacturers have taken two actions: first, thanks to their cost reduction, the battery capacity is constantly being increased. While early EV models counted on a battery of 16 or 24 kWh, current EV batteries have capacities of 40, 70, 90 kWh, or even higher. Secondly, in order to avoid excessive levels of degradation that could jeopardize meeting the driver's day-to-day requirements, the End-of-Life (EoL) of the battery for traction purposes was set to 70–80% of the State of Health (SoH) [2].

Considering this threshold, especially in recent models, EVs are expected to reach the EoL with a large residual capacity. To extract value from this residual capacity, second-life applications gained presence in the research field and have started to be deployed in real life. Through the deployment of second-life applications, instead of sending batteries to be recycled or disposed, they can first be used in less demanding applications, providing economic revenue and extending the total lifetime of the battery [3].

However, second-life applications present several technical, economic and environmental uncertainties. From the technical point of view, the main challenges are using the Battery Management System (BMS) outside its original purpose [4] and using batteries after important levels of degradation [5]. From the economic side, it is unclear whether these applications are as profitable as some authors have suggested due to the additional costs of battery refurbishment and equipment purchase [6]. In terms of the environmental impact, most studies argue that the Greenhouse Gas (GHG) emissions saved by deploying second-life applications can be over 25% [7,8]. However, the estimations are based on the assumption that the second-life battery replaces a new one, which may not be realistic as the purchase of a new battery for providing grid services may not have taken place due to their high cost [9].

In addition, the growth of EV sales also means that the same number of batteries will be reaching EoL at some point. Considering the forecasted demand for energy storage, several sources point out that the needs of this market will be saturated with second-life batteries close to 2030–2035 [10,11]. Therefore, many of the retired batteries will not be able to reach second-life markets.

In view of these uncertainties, other solutions are required to increase economic revenue and reduce the environmental impact of EV batteries. In this sense, the circular economy can be considered as a valuable framework to obtain guidelines. The circular economy aims to decouple economic activity from environmental degradation by promoting the practices that maintain the value of the resources for longer.

This study explores circular economy-based alternatives beyond second-life applications, which follow the principles of sharing and enlarging the lifespan to maximize the use until the EoL, considering that it is better to totally use a device in the first place than to not do so and reuse it afterwards to reach the same end-point [12]. The alternatives considered are:

(a) the reduction in the battery capacity to the minimum size that can cover the driving requirements,
(b) redefining the EoL threshold to avoid early retirement and,
(c) counting on Vehicle to Grid (V2G) as the tool for value extraction based on sharing instead of the second-life applications.

Reducing the battery capacity is based on the idea of narrowing resource loops. Considering the range requirements of most of the population, batteries over 40 kWh have the risk of being underused, which does not help minimize the environmental impact of the EV [13]. Therefore, if the nominal capacity of the battery is reduced, all its value can be extracted during the first life, without the need for other cycles, such as a second life, which require additional resources to implement.

Regarding the battery EoL, a few authors have started to question the commonly assumed threshold of 70–80% SoH, arguing that the battery can be functional at higher degradation levels [14,15]. A universal threshold does not take into account the nominal battery capacity or the actual driving requirements. Therefore, in many cases, the EoL could be pushed further, which affects the duration of the first life, as estimated by the Remaining Useful Life (RUL) algorithms, and the state of the battery at retirement, which directly affects the evaluation of the battery reuse.

Finally, V2G enables EVs to provide a bi-directional flow of energy when they are connected to the EV supply equipment. In this way, the battery not only serves the automotive application but can additionally provide services to the grid by discharging energy into it. V2G adds additional cycling which intensifies the usage of the battery during its first life to avoid the potential underuse that has been mentioned previously.

The three alternatives proposed aim to give a higher weight to the battery's first life to avoid having to count on a second life to make sure that the battery does not reach the recycling facilities with residual value. This idea is backed by the circular economy, which promotes prioritizing cycles at the first stages of the lifecycle over those at later stages.

In particular, this study aims to obtain a general EoL range requirement that batteries should meet to cover common driving trips and to evaluate whether the current batteries found on the market are able to arrive at the EoL at the same time as the vehicle, while providing the required functionalities. Based on the results, the potential place for providing V2G services is analysed and, the different circular economy-based approaches are compared in terms of the economic cost to evaluate which strategies should be prioritized.

In addition, the impact of considering the fixed EoL threshold over the functional one is discussed, with a special focus on the implications on the economic analysis of the second-life applications.

2. Methodology

This study starts by estimating the requirements that EoL batteries should meet to cover the range requirements of most drivers. According to [16], the daily mileage can be represented using a Weibull distribution in which 90% of the daily trips consist of less than 60 km. Considering this conservative daily mileage and the fact that the consumption suffers from seasonal variations (up to 60%) due to the difference in ambient temperature [17], it is estimated that the EoL battery should be able to provide at least 14.85 kWh to cover 90% of all the trips all year round.

2.1. Degradation Model

A degradation model is used to estimate the ageing of batteries with different nominal capacities and usage patterns to understand their SoH at EoL. The model combined the degradation caused by driving the EV (D1) and the one caused by a specific application such as the V2G profile or the second-life application (D2).

2.1.1. Degradation Model D1

To model the degradation caused by driving, the mileage completed through their entire first life is assessed. The lack of retired EVs forced us to adopt assumptions to evaluate this EoL mileage. It was considered that EVs will be retired and sent to dismantling facilities having a similar distribution of mileage and years as diesel vehicles. Considering this assumption and the open data provided by the MOT (Ministry of Transportation) on regular inspections of vehicles driving in the UK [18], the mileage of EoL vehicles has been analysed. Depending on the year of retirement, the distribution of the EoL mileage is significantly different. However, to make a conservative estimation, the distribution corresponding to a retirement age of 20 years has been obtained. This mileage can be best represented by a normal distribution with a mean of 227,264 km and a standard deviation of 91,505 km. Considering 90% of all vehicles retired, the EoL mileage obtained through this distribution is 344,532 km.

The degradation model used to estimate the SoH after the defined EoL mileage was presented by the authors in a previous publication that provides a detailed explanation [19]. In summary, the model was built based on the degradation patterns found in UK fleet vehicles obtained from the EV Battery Degradation Comparison Tool provided by Geotab [20]. The data show the evolution of the SoH for different EVs over time.

The ageing tendency found using Geotab is relatively linear and could be represented by Equation (1), where α is the parameter that relates the ageing of the battery through time. This ageing tendency was transformed into Equation (2), considering that the average mileage is 28,175 km per year as published by the UK department of transport statistics. The β parameter is related to the ageing of the battery depending on the mileage. Both α and β depended on the EV battery capacity and were the result of using linear regression on the Geotab data. The coefficients for both regressions are shown in Table 1. For more details, the reader can refer to the original publication [19].

$$\mathrm{SoH}_{\mathrm{D1}} = 100 - \alpha \cdot \mathrm{age} \tag{1}$$

$$\mathrm{SoH}_{\mathrm{D1}} = 100 - \beta \cdot \mathrm{km} \tag{2}$$

Table 1. D1 degradation model parameters according to battery size.

Battery Capacity (kWh)	α	β
16	3.64	0.000227
24		0.000161
30		0.000129
40	2.24	0.000097
70		0.000083
90		0.000064

This degradation model is used to estimate the battery SoH after 20 years of driving the EV. It should be noted that each EV battery could have a different degradation level even for the same mileage, depending on the driving conditions. However, using a degradation model based on the analysis of the ageing tendencies of different EVs allows us to cover several driving conditions simultaneously and therefore, it can be used for generalizing.

2.1.2. Degradation Model D2

An empirical degradation model is used to estimate the additional degradation D2 caused by the V2G or second-life profiles that can not be captured through model D1. In this case, it is assumed that the battery performs discharging at constant currents unlike during driving conditions. The model developed by Olmos et al. for NMC cells is employed for this purpose [21]. Following the assumption from model D1, a linear relationship is considered between the Full Equivalent Cycles (FEC) and SoH. In addition, all the cycling is considered to take place at 25 °C, 1 C-rate for charge and discharge and starting at 100% State of Charge (SoC). The average SoC ($\mathrm{SoC_m}$) is defined by the desired Depth of Discharge (DoD) of the duty cycle. The degradation model D2 is represented by Equation (3) and its parameters are shown in Table 2.

$$\mathrm{SoH_{D2}} = 100 - \mathrm{a} * \exp(\mathrm{bDoD} + \mathrm{c}) * \left(1 + \mathrm{dSoC_m}\left(1 + \frac{\mathrm{SoC_m}}{\mathrm{e}}\right)\right) * \mathrm{FEC} \tag{3}$$

Table 2. D2 degradation model parameters.

D2 Parameters	
a	0.001673
b	0.022
c	0.4124
d	−0.0212
e	84

2.2. Use Cases

Four different use cases have been defined to analyse their technical feasibility considering the battery degradation and to evaluate, from the economic point of view, which alternative is the most profitable:

- 1—No grid services: aims to represent the baseline where the battery does not provide any grid services and is only used for driving until the functional EoL (20 years) is reached. This use case allows for evaluating which is the minimum capacity that would provide the required functionalities during the entire EV lifespan.
- 2—V2G: considers the functional EoL and different grid services provided through V2G, as explained later in this section.

- 3—Second-life: considers the functional EoL and different grid services provided through a second-life application instead of V2G, as explained later in this section. To evaluate the impact of assuming the fixed threshold in the second-life assessment studies, the same use case has been defined considering the EoL at 80% SoH, instead of the functional one.

There are several grid services that EV batteries can provide. In this study, the residential (R) use, peak shaving (PS), and participation in the demand response (DR) actions have been considered. In this section, the assumptions made regarding the V2G profiles are presented. It should be noted that the approach in this study is to consider V2G as an important source of value extraction, exploiting the battery's first life as much as possible. Other works, however, may view V2G as an opportunistic behaviour and therefore may reduce the frequency of the service to lower values.

- Residential (R): EV batteries can be used to provide energy to households while parked to support renewable energy sources or perform load balancing or energy arbitrage strategies. This study considers that the battery provides 50% of the load of the home which is around 4000 kWh yearly for European households [22]. This means that the battery provides 5 kWh daily regardless of its capacity.
- Peak Shaving (PS): this service aims at reducing the power consumed by a building by providing energy from batteries during peak times and charging them during low-demand hours. It is expected that several EVs will provide this service by aggregating the energy discharged by each one. Therefore, the profile selected in this case is not calculated by a fixed amount of energy, but instead, by a value of the DoD that should not be exceeded to avoid the range limitations of the driver. This value is set to 25% and the frequency of the service is assumed to be 5 times per week.
- Demand Response (DR): in this case, the goal of the service is to solve particular constraints that may appear on the grid, such as congestion or frequency deviations caused by an imbalance between supply and demand. Batteries are considered to be ideal for providing primary and secondary frequency control services due to their fast response time [23]. These services are only activated during a short period of time. For this study, 30 min of discharge at 1C are considered for each activation, the frequency of the service is assumed to be 3 times per week, and the battery availability is set to 5 h/daily.

These same services can be provided by a second-life battery. Considering that in the second life the automotive restrictions are not present, the operating conditions are redefined to be more extreme, as presented in Table 3.

Table 3. Grid service parameters considered.

Grid Service	V2G		Second-Life	
	Energy Provided	Frequency (Times/Year)	Energy Provided	Frequency (Times/Year)
Residential	5 kWh	365	8 kWh	365
Peak Shaving	25% DoD	260	80% DoD	365
Demand Response	30 min at 1C	156	45 min at 1C	365

2.3. Battery Lifecycle Costs

The different use cases defined are compared in terms of the cost over the lifecycle of the battery. The goal of this study is not to provide an accurate estimation of the cost of each of the use cases, but to compare them. For that reason, the activities that are common for all use cases are not analysed (e.g., EV manufacturer or battery disassembly from the EV).

Figure 1 shows the main activities during the entire lifecycle of the EV battery. The first step is the raw material extraction and manufacturing process. The cost of these processes depends on several factors such as the location, which affects the energy mix, the chemical composition of the cells, or the methods used for raw material extraction and component manufacturing. The cost of battery manufacturing is not considered as it is common for use cases with the same battery size. However, it will be necessary for estimating the cost of battery degradation, which takes into account the battery purchase, as explained later on. Therefore, the cost of the battery purchase (C_{bat}) is set to 120 €/kWh [24].

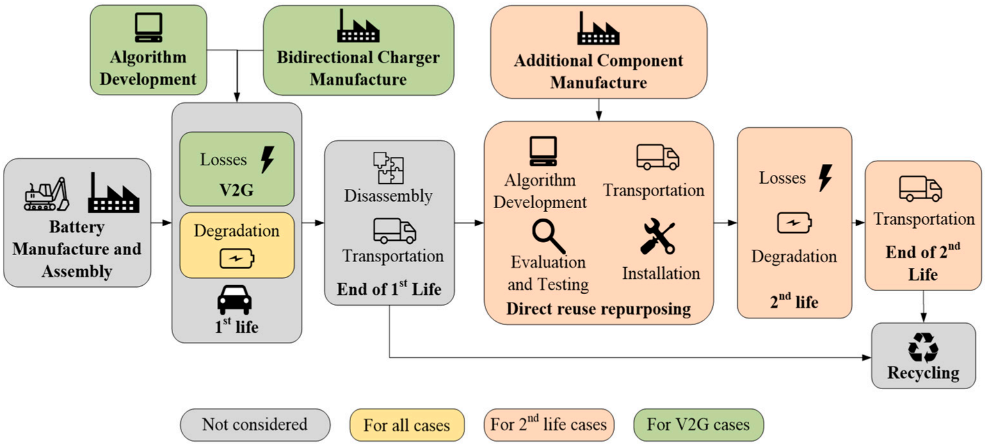

Figure 1. Lifecycle of the EV battery.

The battery then serves its main purpose by providing energy to the EV during its first life. The costs during this stage (e.g., battery charging) are common for all the use cases and therefore were not considered. For the cases where the battery is employed for V2G, additional costs should be considered (C_{V2G}). First, a bidirectional charger should be purchased instead of a standard Level 2 charger. This impact has been estimated by comparing the cost of commercial bidirectional chargers with standard ones for the same company [25]. The estimated additional cost is 5200€. Additionally, the algorithm development for providing V2G services is estimated to be 27 €/kWh, equal to the one that will be assumed for the second life [26].

Once the battery reaches the EoL it should be disassembled from the EV and transported to the second-life repurposing or recycling facilities. It is assumed that the distance to each facility is similar and therefore the cost of this stage is common for all use cases.

If the battery is reused in a second life, additional steps are required, which entail an additional cost ($C_{2nd\text{-}life}$). In this study, it is assumed that the retired battery will be directly reused, without the need to dismantle the pack at the module level or develop a new battery management system. The activities related to the repurposing are the development of algorithms for the control, evaluation and testing of the battery, and the transportation and installation of the battery at the end-use location. The cost related to the testing and transportation is assumed to be 87 €/kWh for a direct reuse approach [27]. The cost related to the algorithm development is estimated at 27 €/kWh and the final installation and commissioning are assumed to cost 52 €/kWh [26]. Additionally, new components are needed for the second life, which includes power electronics converters and electrical safety elements. The power considered in the inverter is set to 40 kW for the peak shaving and DR services and 5 kW for the residential one. The cost of the power electronics and the additional electrical equipment is considered to be 80 €/kW [28].

Additionally, for the cases providing grid services either during a first or a second-life, the additional cycling of the battery must be translated to a cost, as it implies some energy losses due to the efficiencies of the EV charger or the second-life power electronics (C_{loss}). The efficiency of the charger is assumed to be 87% when working at the maximum power [29] and the second-life inverter efficiency is assumed to be 90% [30]. The value of this cost was obtained from Equation (4) that considers the efficiency of the charger or inverter (η), the energy provided as grid services during the entire lifespan ($E_{grid\ services}$), and an average cost for the electricity consumed (C_{av}). The cost of electricity is obtained as an average of different available tariffs reviewed for residential or industrial consumers (peak shaving and demand response) in Spain [31]. The values considered are 0.287 €/kWh and 0.101 €/kWh, respectively.

$$\mathrm{C_{loss}} = \eta\ \mathrm{E_{grid\ services}}\ \mathrm{C_{av}} \tag{4}$$

The last cost to be considered is related to battery degradation. Depending on the use case, the battery suffers different levels of degradation, which should be translated into a cost to reflect the fact that the value of the battery deprecates with degradation. The assumed degradation cost ($\mathrm{C_{degr}}$) follows Equation (5) and considers the replacement of the battery that depends on the capacity loss ($\mathrm{Q_{loss}}$), the cost of the new battery per kWh ($\mathrm{C_{bat}}$), and the assumed EoL, which has been set to 60% of the SoH [32].

$$\mathrm{C_{degr}} = \frac{\mathrm{Q_{loss}}}{60\%}\ \mathrm{C_{bat}} \tag{5}$$

Providing grid services entails revenues ($\mathrm{R_{grid\ services}}$) depending on the application. The benefits derived from the residential service are obtained from energy arbitrage strategies which are based on charging the batteries during off-peak periods and using this stored energy to provide electricity to the loads during peak periods, in which the cost is higher. Considering residential 3-level tariffs from different electrical companies, the difference in the cost between peak and off-peak periods is estimated at 0.13 €/kWh [31].

Similarly, peak shaving reduces the energy consumed during peak periods to reduce the power consumed at these times. In this case, it is considered that peak shaving is provided to an industry or larger consumer. The associated revenue comes from the energy arbitrage considering a tariff for a large consumer above 15 kW (0.035 €/kWh in the reduction from peak to off-peak periods), from avoiding exceeding the contracted power at a penalty of 1.4 €/kW and from shifting the contracted power at peak periods to off-peak ones, which reduce the annual cost by 369 €/kW [31]. The excess power penalties are assumed to take place only 6 times per year, consuming 10% more than the contracted power.

The economic retribution from the demand response services comes from the availability and utilization concepts. The first is related to the time during which the power is available for providing frequency regulation and the second considers the actual energy provided. The values considered were 4 €/MW/hour for the availability [33] and 0.023 €/kWh for the utilization obtained from the Spanish capacity market prices in 2021 [34].

The last step in the battery lifecycle for all cases is recycling. It is assumed that all the batteries would be recycled using the same processes and therefore their cost is not considered.

A summary of the cost and revenue considered for this study is given in Table 4.

Figure 2 shows the calculation of the costs for each of the use cases defined. As mentioned, the first life of the battery is assumed to be 20 years and the second life is defined to end at 60% SoH. An additional restriction is set for the second-life lifespan, considering the fact that batteries cannot be employed forever and that they eventually become obsolete. For this reason, the second life can not exceed 15 years beginning from the battery retirement of the EV.

Table 4. Costs and revenues considered.

Concept			Value	Reference
Costs	Energy Losses (C_{loss})		See Equation (4)	-
	Electricity (C_{av})	Residential	[31]	[31]
		Industrial	0.101 €/kWh	
	Degradation (C_{deg})		See Equation (5)	[32]
	Battery (C_{bat})		120 €/kWh	[24]
	V2G (C_{V2G})	Components	5200 €	[25]
		Software	27 €/kWh	[26]
	Second-Life ($C_{2nd\text{-}life}$)	Testing and Transportation	87 €/kWh	[26]
		Installation and Commissioning	52 €/kWh	[26]
		Software	27 €/kWh	[26]
		Components	80 €/kW	[28]
Revenues ($R_{grid\ services}$)	Residential Arbitrage		0.13 €/kWh	[31]
	Peak Shaving	Arbitrage	0.035 €/kWh	[31]
		Excess Power Penalties	1.4 €/kW	
		Contracted Power Shift	369 €/kW	
	Demand Response	Availability	4 €/MW/h	[33]
		Utilization	0.023 €/kWh	[34]

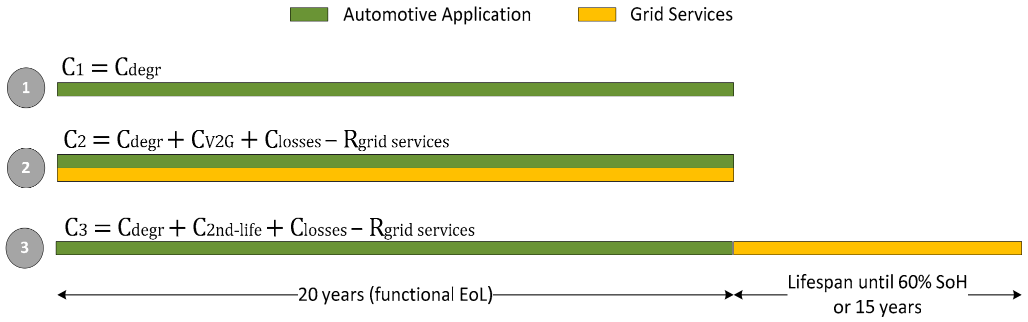

Figure 2. Cost calculation for each use case.

3. Results

Figure 3a shows the EoL battery capacity and SoH for different sizes considering the fixed threshold. All batteries, except those having 16 kWh, reach the EoL while being able to cover the required range. However, the mileage performed by the EVs is, in all cases, lower than the assumed mileage of the EoL vehicles, especially for the small-capacity batteries. Figure 3b shows a more realistic scenario where the functional EoL is considered, meaning that the battery and EV reached the EoL at the same time, with the previously derived mileage of 344,532 km after 20 years.

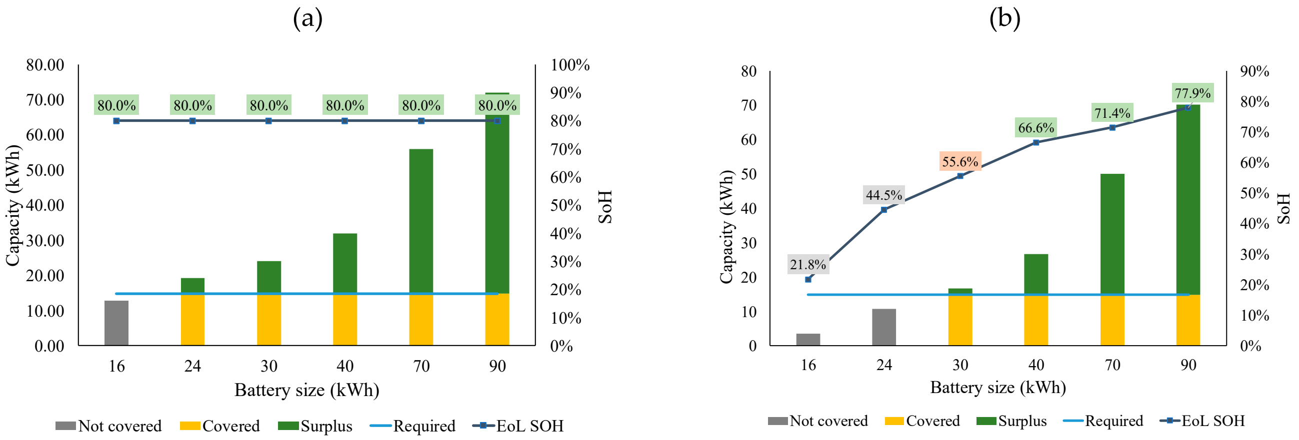

Figure 3. EoL capacity for 16 to 90 kWh batteries considering: (**a**) a fixed threshold and (**b**) a functional threshold.

Considering the 20-year lifespan, batteries with 16 and 24 kWh of capacity are not able to reach the EoL alongside the EV while providing the required driving range. The 30 kWh batteries, on the other hand, hold enough capacity but reach the EoL with an important level of degradation (55.6% SoH), with potential safety and underperformance issues linked to this state. Batteries of 40 kWh and above exceed the required capacity while maintaining a relatively healthy state, over 60% SoH, indicating that a capacity of 40 kWh would be enough to meet the requirements of most drivers (1—No Grid Services).

Larger batteries are able to reach the EoL with a large residual capacity and with SoH values over 70%. Therefore, these batteries could either extend their use during their first life by providing V2G services (2—V2G) or serve a second-life application after the EoL (3—Second-life).

If V2G is used during the first life of these larger batteries, the degradation increases, ending with more aged batteries at the EoL, as shown in Figure 4 for the different V2G profiles.

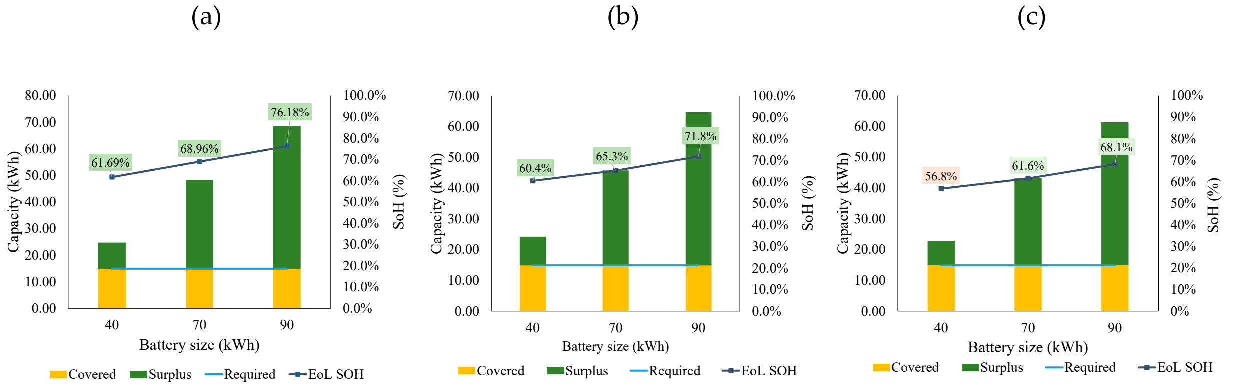

Figure 4. EoL capacity for 40, 70, and 90 kWh batteries considering V2G services: (**a**) residential, (**b**) peak shaving and (**c**) demand response.

In all cases, except for the DR service with the 40 kWh battery, EV is able to provide V2G services while reaching the EoL in a healthy state and being able to provide the required range. In fact, the largest battery of 90 kWh still holds an important residual capacity and reaches the EoL with SoH close to or over 70%. Therefore, it is possible to extend the use of these batteries by stacking different V2G services or through a second life. The most demanding V2G application is the DR one, which increases the capacity fade by 9.8% over the 20 years, followed by peak shaving with a 6.1% increase, and the residential one with an increase between 1.8% and 4.9% depending on the battery capacity.

3.1. Economic Analysis

Considering the previous results, it is possible to compare the different use cases that guarantee that the driving requirements are not compromised. This involves batteries of 40 kWh and higher for all use cases except for the V2G DR one. This analysis serves to understand which strategy is more beneficial from an economic point of view.

The cost for each case over the battery life can be observed in Figure 5. The reader is reminded that for the Case 1—No Grid Services, the cost was related to the degradation of the battery, and for the Case 2—V2G and Case 3—Second-life, the cost and revenues of providing grid services are additionally considered.

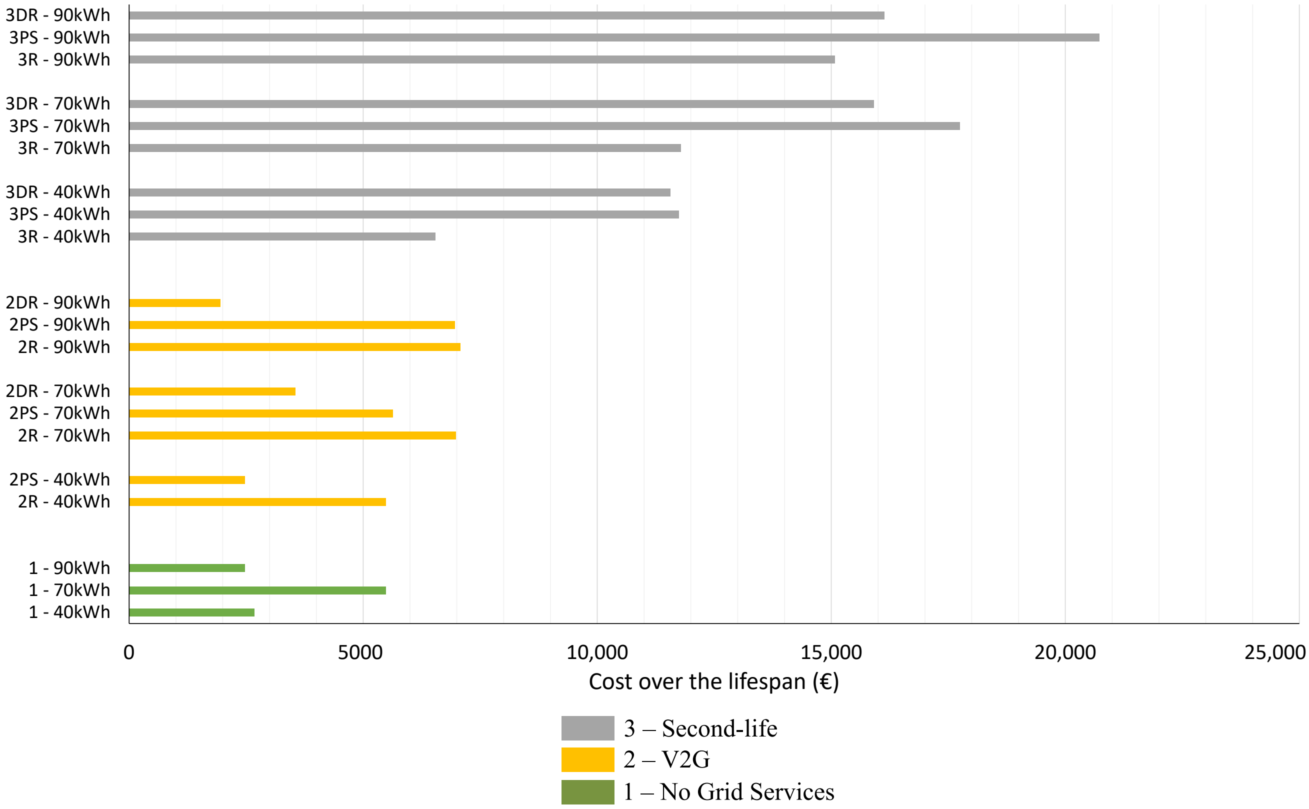

Figure 5. Cost over the battery lifetime for the different use cases: 1—No grid Services, 2—V2G, and 2—Second-life (R: residential, PS: peak shaving, DR: demand response).

It can be seen how the cost of Case 3—Second-life cases are the highest except for the 40 kWh providing residential services, which is slightly less costly than the other alternatives. The lowest cost comes from the use case 2DR-90 kWh. However, the reader is reminded that the purchase of the battery is not considered in the total cost and, therefore, the comparison should be made for the same battery sizes.

To provide a clearer representation, the previous costs are grouped by battery capacity in Figure 6. Notice how for the 40 kWh battery (Figure 6a), the DR case provided by V2G is discarded due to technical feasibility issues. The first thing to highlight is that few use cases allow for a reduction in the cost compared to Case 1—No Grid Services. Especially, not a single Case 3—Second-life scenario appears to be economically beneficial. As mentioned in the introduction, the additional costs that are required for second-life applications hinder their profitability. In all services, Case 2—V2G entails a lesser cost than the same services provided through a second life. However, only some use cases prove to be profitable compared to simply using the battery for driving (Case 1—No Grid Services). These profitable cases are PS provided by the 40 kWh battery and DR with the 70 or 90 kWh ones.

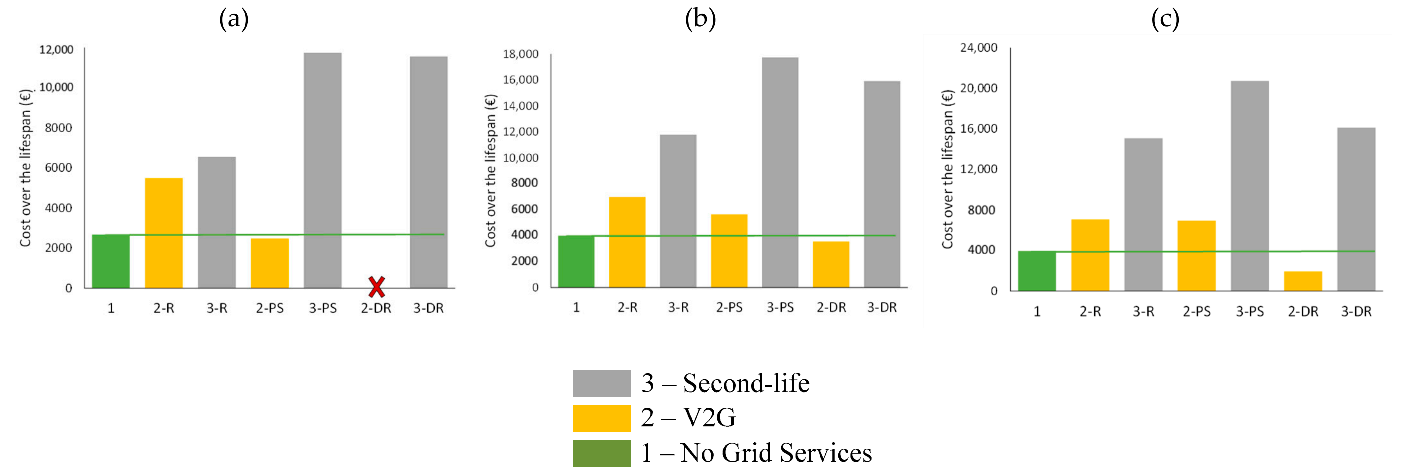

Figure 6. Cost over the battery lifetime for (**a**) 40 kWh batteries, (**b**) 70 kWh batteries, and (**c**) 90 kWh batteries.

Therefore, V2G appears to be more beneficial than second-life applications. Nevertheless, the previous results are absolute cost values and do not consider the energy provided to the grid as a service. For that reason, the specific cost (€/kWh of grid services provided) is represented in Figure 7. Even if the specific costs of the second life become closer to the ones of V2G, in all cases the latter still appears more beneficial.

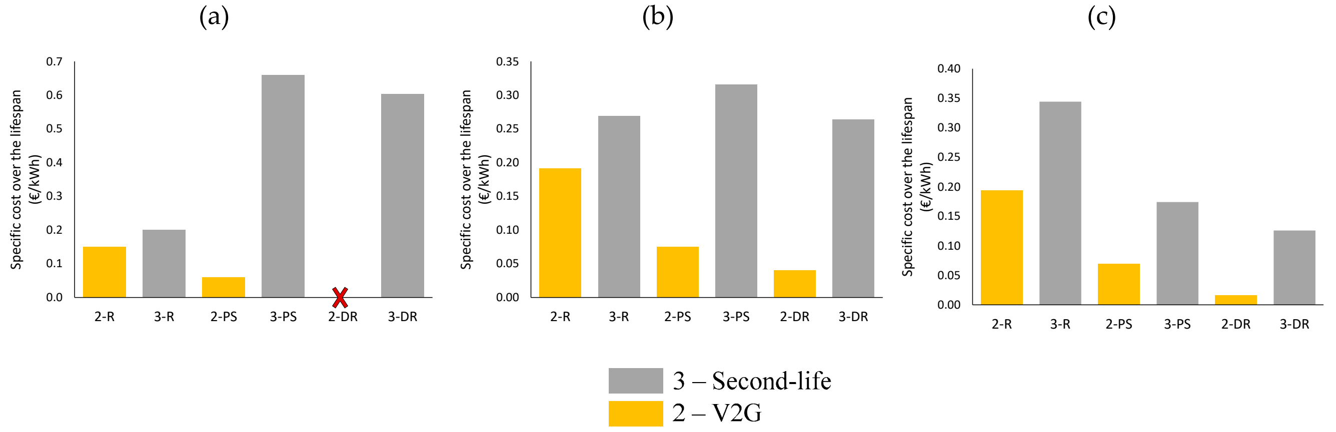

Figure 7. Specific cost over the battery lifetime, considering the provided kWh as grid services, for (**a**) 40 kWh batteries, (**b**) 70 kWh batteries, and (**c**) 90 kWh batteries.

3.2. Implications of the Fixed Threshold

In this study, the criterion employed assumes a functional EoL that extends the use of the battery until the vehicle EoL. However, as mentioned in the introduction, most of the second-life assessments and RUL algorithms in the literature rely on the fixed EoL threshold of 80% SoH. This section analyses the implications of using the fixed threshold instead of a functional one in terms of the battery's first-life and second-life evaluation.

Considering the fixed EoL threshold implies, except for the 16 kWh battery, assuming an early battery retirement from the EV. As shown in Figure 3b, 24 kWh and 30 kWh batteries are not able to reach the EV EoL, however, they can still provide the required range below the 80% SoH threshold. For these batteries, the EoL should be defined based on functional requirements such as not providing the required range, having limited power, or due to safety considerations. As shown in Table 5, if the EoL is calculated using the fixed threshold, which is the current state of the art for RUL algorithms, the battery is assumed to be retired between 0.5 and 7.1 years early.

Table 5. Functional EoL and assumed early retirement from the EV.

Battery Capacity (kWh)	Functional EoL SoH (%)	EoL Reason	Early Retirement (Years)
24	61.9%	Not able to cover range requirements	2.7
30	60.0%	Other functional limitations	1.3
40	67%	EV reaches EoL	7.1
70	71%	EV reaches EoL	4.9
90	78%	EV reaches EoL	0.5

Besides the implications in the estimated first-life duration, the fixed threshold also affects the evaluation of the second life. Since the EoL batteries are considered to have a higher SoH than the functional one, the estimated lifespan of the second life is higher, which increases the economic interest in battery reuse.

First of all, the low-capacity batteries (the 16, 24, and 30 kWh ones) are considered technically viable for a second life assuming the fixed EoL. In fact, for the applications defined, a second life for these batteries would be economical. However, the reality is that these low-capacity batteries reach the EoL with high levels of degradation and therefore cannot be used for a second life. Furthermore, if they were to be retired early from the EV, the replacement cost of the battery for driving would need to be considered, which would reduce the consumer's interest in selling the battery for reuse.

For batteries above 30 kWh, a second life is technically possible considering the functional EoL. Nevertheless, battery reuse is much less profitable than commonly assumed in the literature. Depending on the application and battery capacity, the lifespan of the second life considering the functional EoL can be up to 5.7 years shorter than considering the fixed one. This has an important impact on the cost assessment. In fact, assuming 80% SoH at the EoL implies an underestimation of the cost between 2.5 and 33% depending on the use case, without taking into account the additional replacement cost due to the early retirement.

4. Conclusions

This work has presented a study of degradation and lifetime costs for EV batteries under different usage strategies, with the goal of promoting the most profitable actions.

In accordance with other studies in the literature, the minimum battery capacity that covers the required range throughout the EV lifespan has been shown to be 40 kWh. Many of the current EV models on the market are way above this value, suggesting that batteries may remain underused. Considering guidelines on the sustainable material usage, additional cycling is required to maximize the value of the batteries during their lifetime. This may come both in the form of V2G during the first life or through a second life. Both strategies require additional resources to be put into practice, especially for second-life reuse. For this reason, this study has shown how V2G is always more profitable than battery reuse, even considering a direct reuse approach which is the least costly. Nevertheless, only in a few cases have the revenues provided by V2G allowed counteracting the additional costs. This promotes the idea that it is better to reduce the battery capacity as much as possible to avoid having to rely on additional services. This study has focused on analysing the circular-economy approaches in terms of cost. However, an environmental impact assessment is required to fully understand which strategy should be pursued.

This work has also highlighted an important issue regarding current assumptions in the literature. Almost every study dealing with EoL EV batteries assumes that they should be retired from the vehicle at 70–80% SoH. The use of this fixed threshold implies that batteries are considered to be retired earlier and in better conditions than in reality. In fact, this study has shown how different functional aspects cause the EoL, but for all battery capacities, the EoL is found to be below 80% SoH.

This study has provided a general guideline for the best practices for EV batteries. However, driver requirements and degradation trends change from case to case and an individual analysis should be performed to find the optimal pathway for each battery. Understanding each driver's requirements and driving conditions is key for accurately defining the EoL and for decision-making on whether V2G can be provided without compromising their needs.

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