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Reconsidering the current trends in the Electric Vehicle market: alternatives beyond second-life applications

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Summary

Electric Vehicle battery second-life applications are gaining attention as a way to minimize the environmental impact and increase the economic profit. 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, that go from battery capacity reduction, redefining the End-of-Life requirements to focusing on Vehicle to Grid actions. In accordance with circular economy notions, this work suggests that larger efforts should be put into first-life profit extraction, instead of blindly counting on second-life applications, and into defining a reliable End-of-Life threshold according to the driving requirements.

Keywords: battery ageing, *EV (electric vehicle), Second-life battery,* V2G (vehicle to grid)

1 Introduction

The growth of the EV market comes hand to 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 enlarge their lifespan. Ageing is a key issue surrounding these batteries. As a consequence of usage and time, batteries lose 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 being constantly increased, as shown in Figure 1 [2]. While early EV models counted on a battery of 16 or 24 kWh, current EV batteries have capacities of 40, 70 or even 90 kWh. 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 State of Health (SoH) [3].

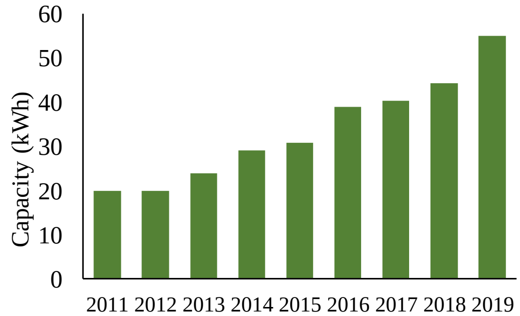

Figure 1. Evolution of the average EV capacity 2011-2019

Considering this threshold, especially in recent models, EVs 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 start to be deployed in real life. However, second-life applications present several technical and economic 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]. For the economic side it is unclear whether these applications are as profitable as some authors have suggested [6].

In addition, the growth of the EV sales also means that the same amount 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 [7,8]. Therefore, many of the retired batteries will have no place for a second life.

In view of these uncertainties, other circular economy based solutions are required to increase the economic revenue and reduce the environmental impact of EV batteries. 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 not doing so and reusing it afterwards to reach the same end-point [9]. The alternatives considered are: a) Reduce the battery capacity as a way to use less natural resources while reducing the cost and weight of the EV and, consequently, improve its consumption, b) use a functional EoL instead of the fixed threshold of 70-80% to extend the battery lifetime when possible and c) Vehicle to Grid (V2G) as the tool for value extraction based on sharing instead of the second-life applications.

In particular, the study aims at obtaining a general EoL range requirement that batteries should meet to cover the common driving trips and to evaluate whether the current batteries found on the market are able to arrive to 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 finally, the different circular economy based approaches are compared in terms of economic revenue.

2 Methodology

This study starts by estimating the requirements that EoL batteries should meet to cover the range requirements of most drivers. According to [10], the daily mileage can be represented using a Weibull distribution in which 90% of the daily trips consist of less than 60km. 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 [11], it is estimated that the EoL battery should be able to provide **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. The model combines the degradation caused by driving the EV (D1) and the one caused by a specific application like the V2G profile or the second-life application (D2).

2.1.1 Degradation model D1

To model the degradation caused by driving, the mileage done through their entire first life is assessed, as it is a direct indicator of their degradation level. The lack of retired EVs forces to adopt several assumptions to evaluate this EoL mileage.

First, it is 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 [12], 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 standard deviation of 91,505 km. Considering 90% of all vehicles retired, the EoL mileage obtained through this distribution is **344,532 km**.

The second assumption is to consider that the degradation patterns found in UK fleet vehicles can be representative of the rest of the vehicles. It should be noticed that each EV can output a different degradation level even for the same mileage, depending on the driving conditions. However, building a degradation model based on the analysis of the ageing tendencies of different EVs allows to cover several driving conditions simultaneously. Geotab offers an EV Battery Degradation Comparison Tool that collects data from different EV models of company fleets and provides their average SoH over time [13]. In this study, the most sold EV models in the UK are considered, which are Tesla models, Nissan Leaf, Volkswagen e-Golf and BMW i3.

The ageing tendency found using Geotab is relatively linear and can be represented by equation (1), where α is the parameter that relates the ageing of the battery through time. This ageing tendency is 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 relates the ageing of the battery depending on the mileage. Both α and β depend on the EV battery capacity, as shown in Table 1.

$$SoH_{D1} = 100 - \alpha \cdot \text{age} \qquad (1)$$

$$SoH_{D1} = 100 - \beta \cdot \text{km} \qquad (2)$$

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

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. In this case, the battery performs discharging at constant currents unlike during driving conditions. The model developed by Olmost et al. for NMC cells has been employed for this purpose [14]. Following the assumption from the model D1, a linear relationship has been considered between Full Equivalent Cycles (FEC) and SoH. In addition, all the cycling has been considered to take place at 25ºC, 1 C-rate for charge and discharge and starting at 100% State of Charge (SoC). The average SoC (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.

$$SoH_{D2} = 100 - \ a * e^{(bcDoD+c)} * (1 + \mathrm{d}\mathrm{SoC_m}(1 + \frac{\mathrm{SoC_m}}{\mathrm{e}})\ ) * \mathrm{FEC} \quad (3)$$

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 case definition

The baseline for this study considers the scenario where all batteries are given the same EoL threshold of 80% SoH regardless of their capacity. Then, in light of the additional value that can be exploited from them, different options are analysed:

- **Case 1:** considering the fixed threshold, the battery serves a second-life application prior to recycling, which is an approach commonly found in the literature.
- **Case 2:** considering a reduced battery capacity combined with a functional EoL.
- **Case 3:** including different V2G profiles combined with a functional EoL.

V2G technology enables EVs to provide a bi-directional flow of energy when they are connected to a power 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. There are several services that EV batteries can provide. In this study the residential use, peak shaving and the participation in Demand Response (DR) actions have been considered. In this section the assumptions made regarding the V2G profiles are presented. It should be noticed that the approach in this study is to consider V2G as an important source of value extraction, exploiting the battery first life as much as possible. Other works, however, may view V2G as an opportunistic behaviour and therefore reduce the frequency of the service to lower values.

- Residential: EV batteries can be used to provide energy to the 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 [15]. This means that the battery provides 5 kWh daily.
- Peak shaving: this service aims at reducing the power consumed by a building by providing energy from the 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 a value of the DoD that should not be exceeded to avoid range limitations to the driver is considered. This value has been set to 25% and the frequency of the service has been 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 a congestions or frequency deviations caused by an unbalance between supply and demand. Batteries are considered to be ideal to provide primary and secondary frequency control services due to their fast response time [16]. These services are only activated during a short period of time. For this

study, 30 minutes of discharge at 1C have been considered for each activation, the frequency of the service has been assumed to be 3 times per week and the battery availability has been set to 5 hours/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 have been 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 minutes at 1C	156	45 minutes at 1C	365

2.2.1 Economic analysis

The different use cases are compared in terms of cost during the lifespan of the EV battery, before it is sent to recycling, as represented in Figure 2. For the Case 1 batteries, the first life ends at 80% SoH and the second life at 60% SoH. An additional restriction is set for the second-life lifespan, considering that batteries cannot be employed forever and that they eventually become obsolete. For this reason, the second-life will not exceed 15 years since the battery retirement from the EV. Case 2 and 3 batteries reach the EoL considering the functional criteria of 20 years. This section contains the description different cost and revenues which are summarized in Table 4.

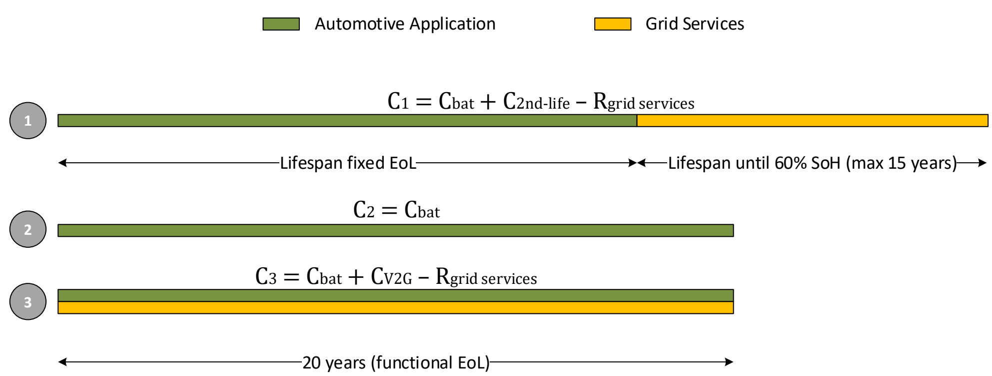

Figure 2. Cost calculation for each use case

The battery cost (C_{bat}) for this study has been set to 120€/kWh for the year 2021 [17].

The cost associated to V2G (C_{V2G}) comes from the purchase of a bidirectional charger instead of the usual Level 2 one. Considering the market costs of different chargers, it has been estimated that a bidirectional charger implies an additional cost of 5200 €.

The cost related to the second-life application ($C_{2nd\text{-}life}$) contains the repurposing of the battery which is assumed to be 87 €/kWh for a direct reuse approach [18]. Additionally, the use of the second-life battery requires the purchase of an inverter with an estimated cost of 80 €/kW [19]. The power considered in the inverter has been set to 40kW for the peak shaving and DR services and 5 kW for the residential one.

The revenue obtained from the grid services ($R_{grid\ services}$) depends 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, difference in cost between peak and off-peak periods has been estimated in 0.13 €/kWh.

In a similar way, peak shaving reduces the energy consumed during peak periods with the goal of reducing the power consumed at these times. In this case, it will be 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 of 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 reduces the annual cost on 369 €/kW. 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 DR services comes from the availability and utilization concepts. The first is related to the time period during which the power is available for providing frequency regulation and the second considers the actual energy provided. The values considered are 4 €/MW/hour for availability [16] and 0.023 €/kWh for utilization obtained from the Spanish capacity market prices in 2021 [20].

Table 4. Summary of the assumed costs

Reference	Concept	Value
C_b	Battery purchase	120 €/kWh
C_{V2G}	V2G equipment	5200 €
$C_{2nd\text{-}life}$	Second-life refurbishment	87 €/kWh
	Second-life inverter	80 €/kW
$R_{grid\ services}$	Residential revenue	0.13 €/kWh
	Peak shaving revenue	0.035 €/kWh 1.4 €/kW excess 369 €/(kW contracted *year)
	DR revenue	0.023 €/kWh 4 €/MW/hour

3 Results

Figure 3 a) shows the EoL battery capacity and SoH for different sizes considering the fixed threshold (Case 1). All batteries, except the 16 kWh ones, reach EoL at a healthy state with additional value to be extracted. However, the mileage performed by the EVs in this case, shown in Table 5, is lower than the usual mileage of the EoL vehicles, especially for the small capacity batteries. Figure 3 b) shows a more realistic scenario where the functional EoL is considered, meaning that the battery and EV reach the EoL at the same time, with the previously derived mileage of 344,532 km after 20 years.

Table 5. EoL mileage for the fixed threshold and early retirement (Case 1)

Battery capacity (kWh)	EoL mileage (km)	Early retirement (years)
16	88,106	-
24	124,224	-
30	155,039	-
40	206,186	4.9
70	240,964	3.7
90	312,500	1.1

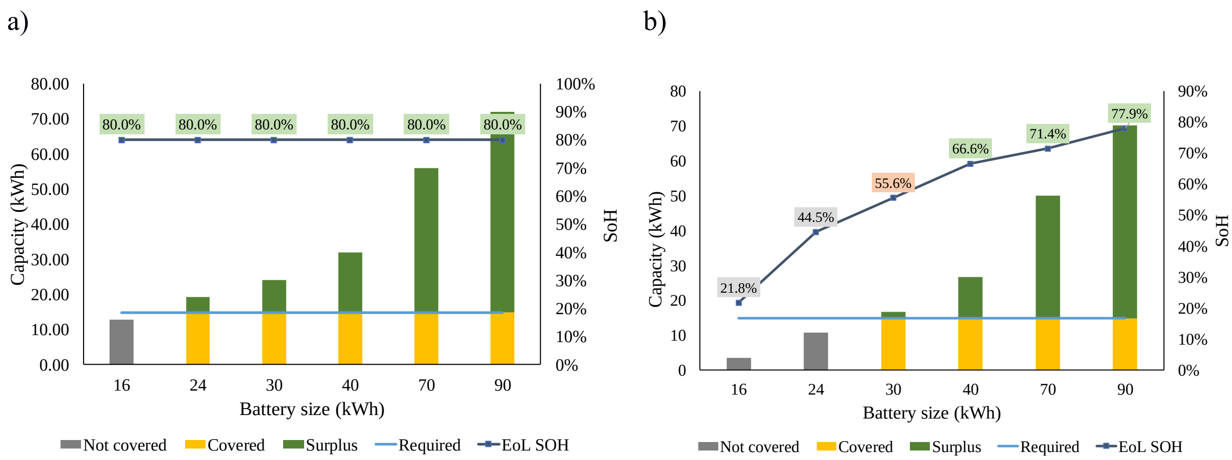

Figure 3. EoL capacity for different sized batteries considering: a) a fixed threshold and b) a functional threshold

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. 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 over 40 kWh 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 (Case 2). Larger batteries are able to reach the EoL with a large residual capacity and with SoH values over 70%. Therefore, these batteries can either serve a second-life application or extend their use during their first life by providing V2G services, which has been studied through the Case 3 path. Comparing the fixed and functional EoL mileage, it is estimated that the batteries are retired between 1.1 and 4.9 years earlier, depending on the capacity, as shown in Table 5.

If V2G is used during the first-life of these larger batteries, the degradation increases, ending with more aged batteries at EoL, as shown in Figure 4 for the different V2G profiles. In all cases, except for the DR service with the 40 kWh battery, we see how the EV is able to provide V2G services while reaching 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 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 application is the DR one, followed by peak shaving and the residential one.

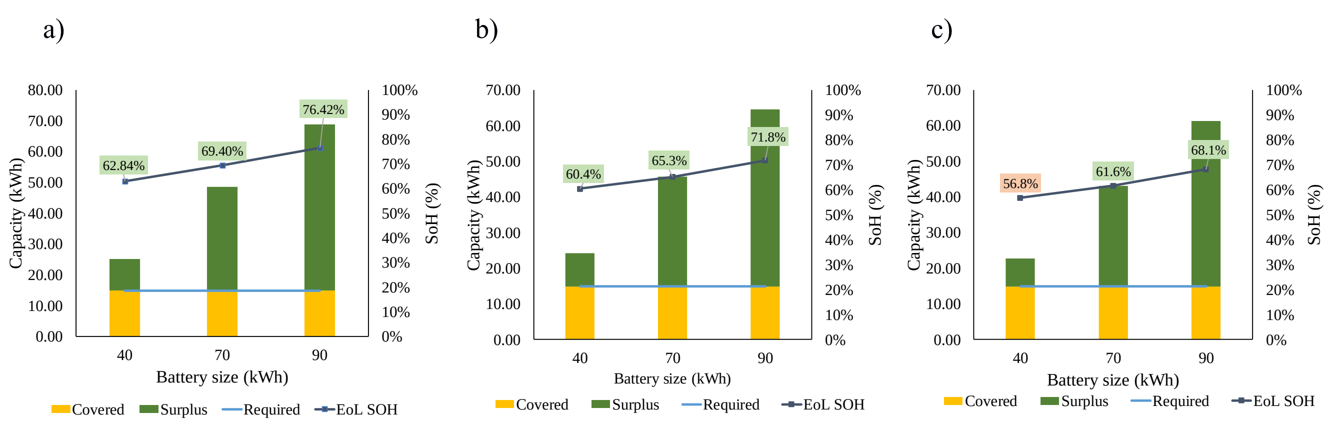

Figure 4. EoL capacity for different sized batteries considering V2G services: a) Residential, b) Peak Shaving and c) Demand Response

Instead of the V2G service during the first-life, the batteries retired at 80% SoH can provide a second-life application, as analysed in Case 1. Table 6 shows the lifespan of the batteries during their second-life, calculated as the point where their SoH drops to 60% or they become obsolete, which happens for the residential use case.

Table 6. Second-life lifespan for the Case 1 batteries

Residential 2nd life	**Peak shaving 2nd life**	**DR 2nd life**
15 years	7.3 years	8.4 years

Based on this results, several conclusions have been made, which define the cases to be considered for the economic analysis, summarized in Table 7.

- 16 kWh batteries are not able to provide the EoL range, considering the 80% SoH threshold. The rest still hold potential value for a second-life application which will be analysed in the Case 1 economic analysis.
- With the functional threshold, neither the 16 nor the 24 kWh battery can provide the required range. The 30 kWh battery holds enough range, but its SoH drops below 60% bringing potential safety and power concerns. Therefore, the minimum sized battery has been considered to be 40 kWh for Case 2.
- Batteries of 40 kWh and above are able to perform the three V2G profiles considered without compromising the driving and safety requirements, except for the 40 kWh one providing the DR service (Case 3).
- The 90 kWh battery arrives to the functional EoL with a SoH value over 70% for the residential and peak shaving profile, which means that a second-life could be possible in this case. However, this possibility has not been considered for this work.

Table 7. Cases considered for the economic analysis

Case	Battery capacity (kWh)	V2G services	EoL 1st life	Second-life application
1	24	-	Fixed 80% SoH	Yes
	30			
	40			
	70			
	90			
2	40	-	Functional (20 years)	-
3	40	Yes*	Functional (20 years)	-
	70		Functional (20 years)	
	90		Functional (20 years)	

**Except for the 40kWh providing DR*

3.1 Cost analysis

The results of the cost analysis performed to the use cases are shown in Figure 5. The lowest cost is obtained with the 24 kWh battery with a residential second-life (1R-24kWh) and with the 40 kWh with peak shaving V2G (3PS-40kWh). The 40 kWh battery is able to cover the driving requirements of most drivers during the lifespan of the EV and can still provide important services to the grid through its entire lifetime reducing the cost in comparison to the case where no services are provided (2-40kWh).

In general, we see how the DR and peak shaving V2G cases (3DR and 3PS) are the most profitable. Even for large batteries of 70 and 90 kWh, the cost over the 20 years is less than the one for a 40 kWh with a residential V2G or without providing any service.

The residential V2G, which only obtains profit through the energy arbitrage strategies in a household, does not reduce the cost over the 20-year lifespan. Even if the service is provided every day, the revenue is not high enough to cover the additional equipment purchase. This can be seen for the 40 kWh battery, as the residential V2G use case (3R-40kWh) has a higher cost than the case where no V2G is provided (2-40kWh).

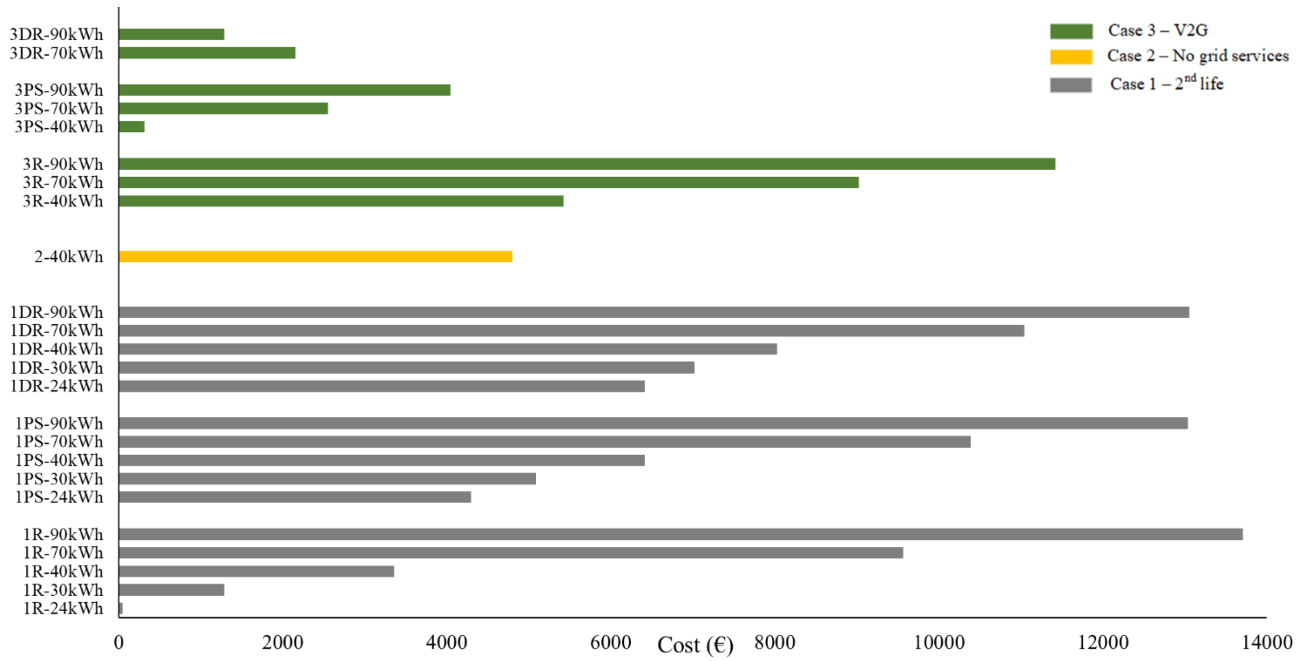

Figure 5. Cost over 20 years for the different use cases (R: Residential, PS: Peak Shaving, DR: Demand Response)

In general, Case 3 batteries, providing V2G, are less costly than similar sized Case 1 batteries, which provide the grid services but only during the second-life. This is better seen in Figure 6 which show the same results but grouped by battery size, allowing to compare the economic cost of same sized batteries providing similar grid services.

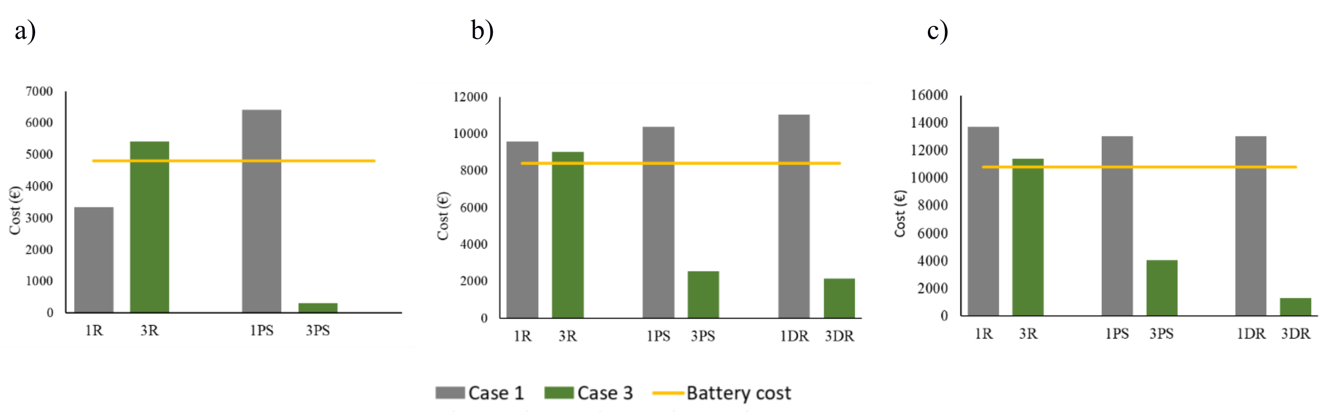

Figure 6. Cost over 20 years grouped by battery size a) 40 kWh b) 70 kWh and c) 90 kWh

The residential V2G does not manage to reduce the cost below the purchase cost. In addition, for the 40 kWh battery, the cost of the V2G is higher than the one of the second-life. This last case for the second life (1R-40kWh) is the only one where the cost is lower than the battery purchase cost. Therefore, it can be suggested that large batteries have the potential to generate revenue through peak shaving and DR services and that this option is more profitable than counting on a second-life.

4 Conclusions

This work has presented a comparison of different circular economy based paths for EV batteries, evaluating the EoL criteria used, the battery sizes and the potential grid services that batteries can provide either during a first or a second life.

The commonly assumed threshold for EoL of 80% SoH has proved to be too restrictive for all batteries of 24 kWh capacity and above, even considering a conservative case where 90% of the driver daily mileages are covered in cold climates where the consumption is higher due to the low temperatures. It is likely that a large amount of drivers will have a lower demand for range and therefore, the EoL threshold should be defined for each particular case, extending the EV battery first life as much as possible while guaranteeing that the driving and safety requirements are met.

Regarding grid services, both V2G and second-life applications can provide value to the electricity grid while generating revenue. For large batteries (40 kWh and above), in general, the V2G profiles considered do not compromise meeting the range requirement. In addition, the profiles defined for the V2G can be considered extreme, as in many cases the services would be provided with less frequency and lower discharge DoDs. Nevertheless, large batteries are able to provide even these extreme services, highlighting the fact that, otherwise, they would remain underused.

Due to the additional costs of repurposing batteries, it is suggested that V2G holds higher value than second-life. However, a second-life may be considered for users with a high requirement for range. In this case, especially for mid and high capacity batteries, the EoL would be reached with a healthy state and therefore a second-life application would allow to reduce the environmental impact and increase the profit.

Finally, the option of reverting the trend of increasing the nominal battery capacity has been analysed. Batteries with 40kWh of capacity can provide the required range to the majority of drivers. Therefore, larger batteries could imply an unnecessary use of materials in many cases, unless important V2G services are provided. Nevertheless, even for the 40 kWh V2G it is still encouraged to provide some type of services to the grid and generate revenue for the owners.

This study has provided a general guideline for 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 to accurately define the EoL and for decision making on whether V2G can be provided without compromising their needs.

Acknowledgments

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