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Redefining the EV Battery End of Life: Internal Resistance Related Limitations

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ABSTRACT

Currently Electric Vehicle batteries are considered to reach the End of Life once their State of Health reaches 70-80%. However, notions of circular economy suggest that the battery first-life should be extended as much as possible to reduce their environmental impact.

Previous works have considered the range limitations of the drivers, arguing that the End of Life threshold is too conservative for many cases. However, to validate this statement, the increase of the internal resistance must be addressed.

In this work a battery model is used to simulate the battery performance under different driving cycles synthesized from real data. Results show that the functional End of Life is forced by capacity, power or safety related issues. The dominant cause for reaching the End of Life depends highly on the battery size. The underperformance is in most cases found after 70-80% State of Health, validating that the first life of most batteries could be extended without affecting the performance of the vehicle.

Keywords: Electric Vehicle, End of Life, Degradation, Internal Resistance

NONMENCLATURE

Abbreviations	
BoL	Beginning of Life
DoD	Depth of Discharge
EoL	End of Life
EV	Electric Vehicle
IR	Internal Resistance
Li-ion	Lithium-ion
SoC	State of Charge
SoH	State of Health

1. INTRODUCTION

The Electric Vehicle (EV) market is expected to grow at a fast pace in the upcoming years [1]. As a consequence, the manufacturing of their key component, the Lithium-ion (Li-ion) battery, is under a big pressure. Several voices have raised concerns on the potential shortage of metals for the manufacturing of new automotive batteries [2]. To avoid this situation, an optimized use of resources and a switch towards a circular economy based system is needed to guarantee that the EV adoption does not come at a high environmental cost.

A line of action in this framework, which remains relatively unexplored, is the possible redefinition of the battery End of Life (EoL). Currently EV batteries are considered to reach the EoL for traction purposes when their capacity fades 20-30%, corresponding to a State of Health (SoH) of 70-80% [3].

However, considering that battery sizes are experiencing an increasing growth [4], it has been suggested that this threshold might be too conservative and that, in many cases, the EoL could be postponed to lower SoH values [5,6].

Previous work on the EoL evaluation has mainly focused on the capacity requirements of the drivers. However, the capacity fade caused by battery degradation comes along with an increase of the battery Internal Resistance (IR) [7], which should be studied.

The increase of IR due to ageing is caused by the growth of the Solid Electrolyte Interface layer, which creates an additional resistance and leads to several effects [8].

On one hand it reduces the power that the battery is able to charge or discharge without exceeding the operating limits, since the voltage drop caused by the flow of current in the battery is proportional to the IR [9]. This may affect the acceleration, gradeability, regenerative braking capabilities and charging times. In addition, higher IR values increase the heat generation rate, which may create safety issues [10] and reduce the battery efficiency [11].

This study combines a battery model with realistic driving cycles to evaluate the performance of the battery at different IR increase levels to evaluate whether the power fade is a relevant limitation when postponing the EoL of differently sized EV batteries.

2. METHODOLOGY

Based on real driving data, the authors have developed a model for the creation of synthetic driving cycles, with the duration of the cycle as the model input.

This model is used to generate reference cycles for two driving styles: semi-urban (SU) and semi-highway (SH). The first contains a higher share of urban roads while the second is more prone to highway sections.

Data collected for over 1.5 years from 24 EVs and 3 different European regions are analysed and used to find representative durations for defining the driving profiles. Two of the regions are representative of urban driving and one also contains highway sections.

Therefore, the data from the two urban regions have been grouped to represent SU driving and the other region has been considered for SH. Based on the duration of the trips between charges, the values that cover 50% and 90% of the trips have been extracted, as shown in Table 1.

Table 1. Description of the reference cycles considered

Ref	Type	Trips covered	Duration (min)
SU_{50}	SU	50%	52
SU_{90}	SU	90%	126
SH_{50}	SH	50%	44
SH_{90}	SH	90%	109

Using the driving cycle model and the selected durations, four reference cycles have been obtained, which are used to evaluate the performance of the battery and are represented in Figure 1. Negative currents represent a discharge of the battery and positive ones the regeneration.

These profiles are performed by EVs with differently sized batteries. Considering EVs on the roads and current market trends, the capacities selected for this study are 16 kWh, 24 kWh, 30 kWh, 40 kWh, 70 kWh and 90 kWh. All batteries are defined to have a nominal voltage of 320V, which is the same as the EV used to create the driving cycle model. The selected voltage and capacity determine the configuration of the cells in the battery pack.

Considering that the driving cycle model was developed using data collected from a 12 kWh Plug-in Hybrid EV, the profiles must be scaled for different sized batteries to account for the differences in weight that affect the consumption level of the EV. Analysing the average weights of different models, a ± 24% variation has been applied for low capacity EVs (16 kWh) and for high capacity ones (70 and 90 kWh).

In addition, a temperature correction factor has been considered to account for the performance variation under different environmental conditions. In cold climates, besides the fact that other degradation mechanisms, such as lithium plating, become dominant [12], the specific energy consumption is higher than at warmer temperatures due to the need for the heating and auxiliary services of the vehicle [13].

For the same driving cycles and battery capacities, the functionalities required by the driver can be compromised due to colder temperatures. Therefore, for each of the reference cycles defined, an additional use case is considered, in which the discharge current is

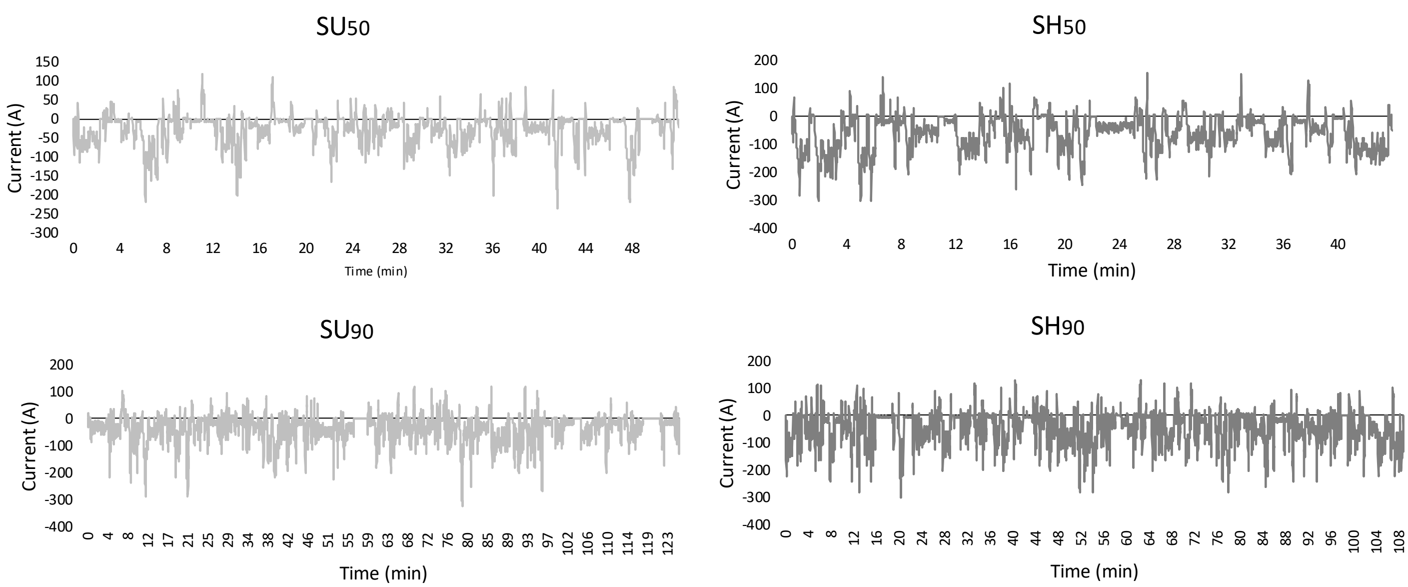

Figure 1. Synthetic current profiles considered for the simulations (SU: semi-urban, SH: semi-highway)

increased by a factor of 29%, obtained from comparing the EV consumption at average annual temperatures of 18ºC and 8ºC [13].

2.1 EV battery model

The reference cycles are introduced to a battery model with different levels of degradation. The model consists of a 1RC equivalent electrical circuit and has been implemented using the battery block from Matlab Simulink as shown in Figure 2.

The model parameters considered are listed in Table 2 and have been obtained from an existing literature model for NMC Li-ion cells [14]. The values correspond to the average for the entire range of the battery State of Charge (SoC) and for 25ºC.

Table 2. Parameters of the battery cell

Parameter	Value
Polarization resistance	0.0366 Ω
Polarization capacitance	1110.076 F
Internal Resistance	0.0618 Ω
Nominal Voltage	3.6 V
Minimum Voltage	2.5 V
Maximum Voltage	4.2 V
Nominal Capacity	2 Ah

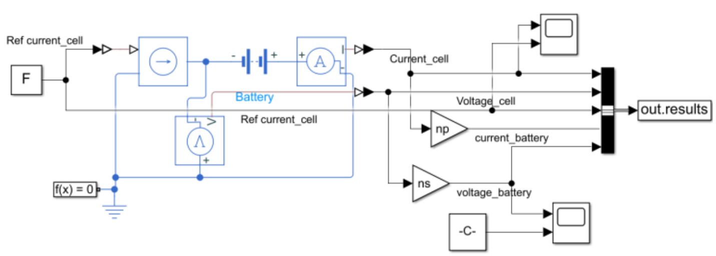

Figure 2. Battery equivalent model in Simulink

It should be highlighted that a constant value of the IR has been used also for the cold climate. In reality, the IR increases with lower temperatures [15]. For this reason, in colder climates the IR would be substantially higher, especially in the beginning of the trip, until the cells have heated up.

However, constraints related to the IR are most relevant towards the end of the trip at lower SoC values. For this reason, it will be assumed that the temperature of the cell has already increased at the critical points of the trip through self-heating, reducing the value of the IR.

To account for the temperature dependency of the IR, a thermal simulation would be necessary, which is out of the scope of this work.

To relate the internal resistance increase (ΔIR) with the capacity fade, eq. 1 is used [16], which shows that the IR increases at a higher pace than the capacity fade. The levels of SoH considered for the simulations, with their corresponding ΔIR, are shown in Table 3. The minimum SoH considered has been 40%, below which it is unlikely that the battery will be able to perform correctly.

$$\Delta IR = \ 5.4754 * SoH^2 - 11.301 * SoH + 5.8 \quad (1)$$

Table 3. Degradation levels considered

SoH	ΔIR
100%	0%
90%	9%
80%	29%
70%	60%
60%	102%
50%	155%
40%	219%

3. RESULTS

When considering only capacity constraints, the value of the minimum SoH that can cover each driving trip at the EoL is shown in Table 4 for both environmental conditions considered. The cases marked with the symbol "-" represent those batteries that cannot cover the trips in the Beginning of Life (BoL) or the ones where the capacity constraints appear at 90% SoH or above. For those cases, the battery size has been considered to be too small to meet the driving demands and a larger one should be selected.

Table 4. Minimum EoL SoH (only capacity constraints)

Capacity	Climate	SU_{50}	SU_{90}	SH_{50}	SH_{90}
16 kWh	Regular	40%	-	72%	-
	Cold	52%	-	-	-
24 kWh	Regular	35%	-	63%	-
	Cold	46%	-	83%	-
30 kWh	Regular	28%	87%	51%	-
	Cold	37%	-	66%	-
40 kWh	Regular	21%	65%	38%	72%
	Cold	27%	86%	50%	-
70 kWh	Regular	15%	46%	27%	51%
	Cold	19%	60%	35%	66%
90 kWh	Regular	11%	36%	21%	39%
	Cold	15%	47%	27%	52%

The following images show the voltage response of each battery under the different cycles and levels of degradation. Only the cases in which the capacity is enough to cover the trip have been plotted, thus those cases where the SoH is higher than the one in Table 4. As described in Section 2, the simulations have been stopped at 40% SoH. For each case, the BoL response and the one corresponding to last SoH level where no capacity constraints are present have been plotted. Continuous lines represent the regular climate and discontinuous ones the cold climate.

Figure 3 shows the results of the simulation of the small batteries (16, 24 and 30kWh). The 16kWh one is only able to cover the SU_{50} and SH_{50} profiles. For the SU_{50}, even if the EV holds enough range to cover the driving cycle, it can be observed that the battery at the end of trip tends to reach the lower operating voltage. This takes place at 60% SoH for the regular climate and at 70% for the cold one. The SH_{50} profile, which can only be covered at the warmer climate, does not show any power limitations until the capacity constraints appear. The battery is able to perform the driving trip successfully at 80% SoH, but it gets close to the operating limits towards the end of the trip.

The 24kWh battery can perform the SU_{50} and SH_{50} profiles at both environmental conditions. Once again, in the SU_{50} profile, power constraints appear before capacity ones, at 50% and 60% SoH for the regular and cold climate respectively. The SH_{50} forces the EoL due to capacity constraints before the power ones. The cycle can be performed without any limitations at 70% and 90% SoH for the regular and cold climate, respectively.

The 30kWh battery is able to cover the SU_{50} profile even after important levels of degradation. It is only at

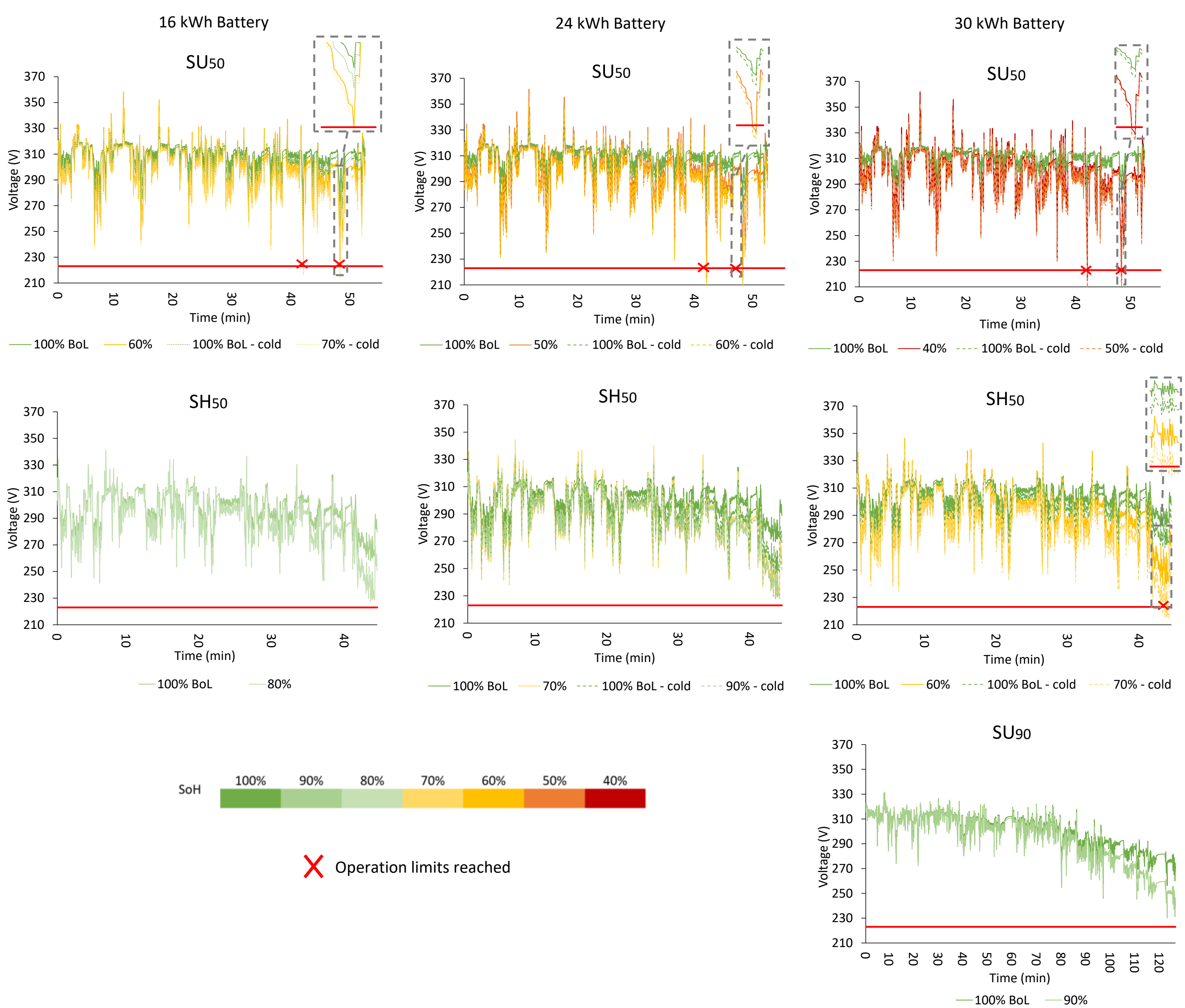

Figure 3. Simulation of the small batteries (16, 24 and 30 kWh)

40% and 50% SoH that power limitations appear for regular and cold climates respectively. In this case, the battery can also perform the SU_{90} cycle, but only for high values of SoH and for the regular climate. The battery can provide the required range at 90% SoH but it is unable to do so at 80% SoH. The SH_{50} profile can be covered until 60% or 70% SoH for regular and cold climates respectively. Only for the regular climate the power limitation appears before the capacity one.

In Figure 4 the voltage response of the high capacity batteries (40, 70 and 90kWh) are represented.

The SU_{50} and SH_{50} profiles can be successfully performed even at 40% SoH for the 70 and 90kWh batteries. For the 40kWh, power constraints appear at

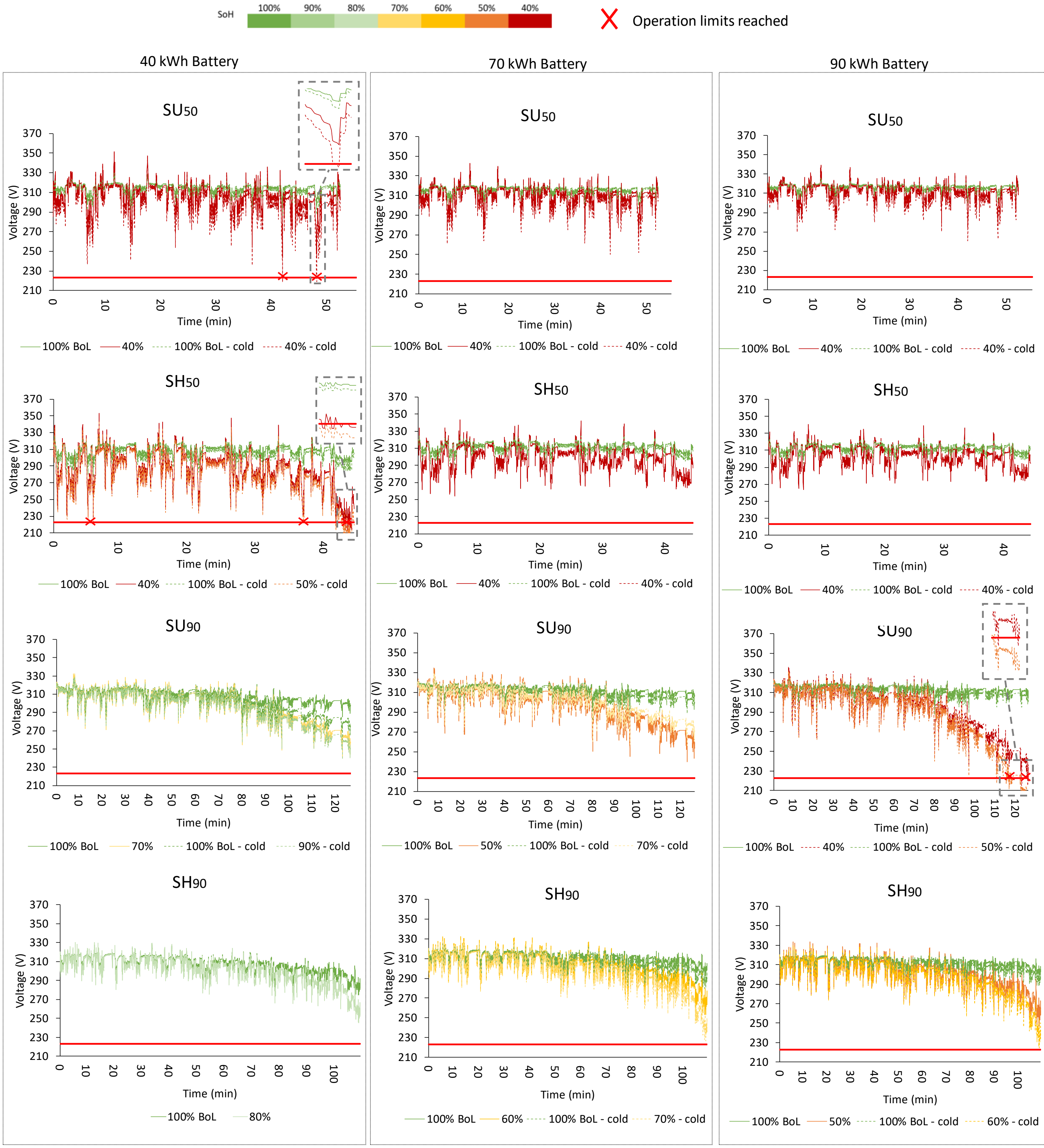

Figure 4. Simulation of the large batteries (40, 70 and 90 kWh)

40% SoH for the SU_{50} cold temperature case and at 40% or 50% SoH for the SH_{50} for the regular or cold temperature.

Regarding the cycles covering 90% of the population, it can be observed that these large batteries are enough to cover the profiles at the BoL. The 40kWh battery does not show any power constraints for the SU_{90} profile at the last SoH value simulated before the battery is unable to provide the required range, which is 70% for the regular climate and 90% for the cold one. The SH_{90} profile can be performed with this battery only at regular climates and no power constraints appear at 90% SoH.

The 70kWh battery can provide the required power for the SU_{90} driver at 50% and 70% SoH for the regular and cold climates. These values are increased to 60% and 70% SoH for the SH_{90} case.

Finally, for the 90kWh battery, the largest one simulated, power limitations arise for the SU_{90} cycle but only after high levels of degradation (40% and 50% SoH for the regular and cold climates, respectively). The SH_{90} profile can be performed without any power constraints at 50% or 60% SoH for the regular and cold climates, respectively.

4. DISCUSSION

The simulation of the driving cycles has allowed to determine the first constraint that causes the underperformance in the EV for each use case. Batteries whose EoL is caused by a limitation of range represent 37% of the cases analysed. Similarly, 37% of the batteries have presented power related constraints that have forced the EoL. The remaining ones (26%) reach 40% SoH while still being functional to cover the driving requirements, both in terms of capacity and range. At this high level of degradation, it may be necessary to retire the batteries for other reasons, mainly safety related considerations, which should be further analysed.

However, when grouping the cases into large (40kWh and above) and small batteries (30kWh and below), the dominant EoL cause changes. Small batteries reach the EoL for capacity constraints in most cases (58%) and the rest are caused by power limitations (42%). Large batteries, on the other hand, tend to reach the EoL due to safety related aspects and not functional ones in 39% of the cases. Then, capacity constraints are more relevant (35%) than power ones (26%).

Figure 5 represents graphically, the EoL reason for each case. In the vertical axis, the capacity margin represents how much capacity is left at the EoL to cover the driving trips (eq. 2). Positive values on the vertical axis, mean that the battery is still able to provide the required range at EoL. Negative ones, on the other hand, mean that the battery has reached the EoL along with capacity constraints and is therefore not able to cover the driving trip. In the horizontal axis, the voltage margin represents how far the minimum voltage of the entire trip is from the operating limits of the battery, as given per eq. 3. Negative values on the horizontal axis are the cases where power limitations are detected at EoL conditions and positive values, the cases where the battery voltage is at all times over the minimum one.

$$Cap.margin = 1 - \frac{Cycle\ \ capacity}{Battery\ \ capacity * \ \ SoH_{EoL}} \qquad (2)$$

$$Voltage\ \ margin = \frac{\min(V_{cycle}) - V_{min,battery}}{V_{min,battery}} \qquad (3)$$

The points placed in the 1st quadrant (positive horizontal and vertical axis values) represent the cases where the EoL battery does not show any range or power limitations. These cases correspond to the ones where the simulations have been stopped at the value of 40% SoH for which safety issues may be the reason to force the EoL event. All EoL batteries which cannot provide the required range are located in the 3rd quadrant (positive vertical and negative horizontal axis values). If the cycle capacity is higher than the available capacity of the EV, it means that the operating limits of the battery will be reached. For this reason, no points are present in the 4th quadrant (positive horizontal and negative vertical axis values). Finally, points in the 2nd quadrant (negative horizontal and vertical axis values) are the cases where

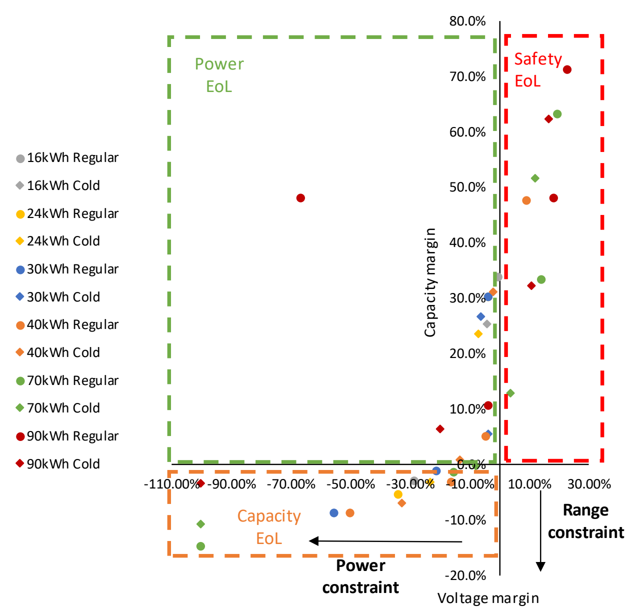

Figure 5. Reasons for the EoL for all battery sizes and climates

the battery still holds range to cover the trips but power limitations have forced the EoL.

Based on the previous results, an important remark can be made. Since the current profile gets distributed into a higher number of parallel strings for the larger batteries, voltage drop in each cell is lower and the power limitation caused by the IR increase is less frequent than for the smaller ones, even for cycling at low values of the SoC.

In addition, the results of this study have shown how far the first life could be extended for each driving style and climate. Figure 6 shows the EoL SoH values classified by the battery size. The commonly assumed threshold of 70-80% SoH correspond to the functional one for 41.7% of the small battery cases (30kWh and below) and 8.7% of the large ones (40kWh and above). For the remaining cases, the EoL could be postponed to lower SoH values. For the small batteries the functional EoL is in half of the cases located between 50% and 69% SoH (25% in the range of 60-69% SoH and 25% in the range of 50-59%) and only a few cases (8.3%) it can go below 49% SoH. For large batteries, the first life can be extended down to 40-49% SoH for 60.9% of the cases considered. However, further analysis must be made to evaluate the heat generation and safety related aspects at such high levels of degradation, where the IR reaches very high values.

With higher levels of the IR, the heat generated by power dissipation is higher, following Joules equation (eq. 4).

$$P = \; I^2 * R \tag{4}$$

The higher heat generation rate adds another load to the system, since the battery needs additional cooling to keep the temperatures in the adequate range. With high values of IR, the heat generation may be high enough to pose safety issues, forcing an earlier EoL. Therefore, besides the capacity and power fade related issues, heat generation and safety aspects should be further analysed. Nevertheless, this may not be as relevant for large batteries where the current is distributed to a larger amount of parallel strings, creating a lower cell current and thus, lower heat generation.

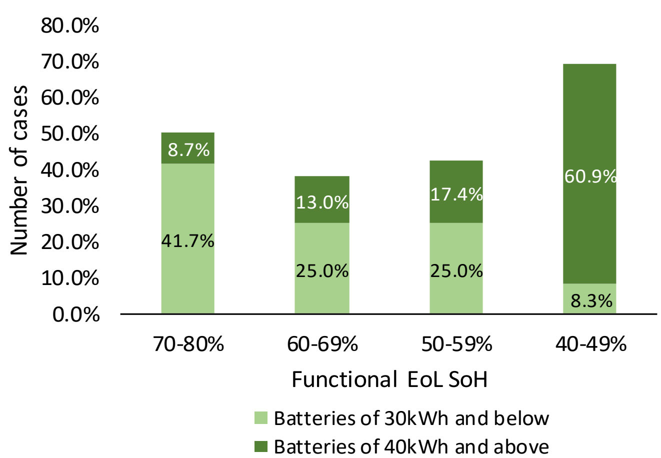

Figure 6. EoL SoH values depending on the battery size

Therefore, the EoL can be, in many cases, redefined to lower values of the SoH. This redefinition should be case specific and should follow a functional criterion that relates the degradation with the expected functionalities. In order to do so, the authors propose the use of an indicator called State of Function (SoF). The SoF provides information on how functional is a battery to the individual driving needs, considering the current level of degradation. The SoF is 100% for the BoL conditions and decreases as the battery degrades until the EoL where the SoF drops to 0%.

It has been discussed that the battery could reach the EoL for three main reasons: capacity constraints, power constraints or safety issues. For that reason, a possible definition of the SoF is given by eq. 5, which shows that the functionality of the battery and its EoL is defined by the most restrictive of the three factors.

$$SoF = \min\left(SoF_{capacity}, SoF_{power}, SoF_{safety}\right) \tag{5}$$

5. CONCLUSIONS

The extension of the EV battery over the commonly assumed threshold of 70-80% SoH has been analysed in terms of the underperformance linked to the increase in the internal resistance. Realistic driving profiles covering 50% and 90% of the population have been simulated for semi-urban and semi-highway cases under two environmental conditions.

The study has shown how, both capacity and power related constraints may force the battery to reach a functional EoL. Small batteries of 30kWh and below, tend to reach the EoL for capacity limitations and power ones in a similar share, with a slight tendency towards presenting capacity limitations first. Larger batteries of 40kWh and above arrive, in many cases, to the EoL for safety reasons rather than underperformance ones linked to a lack of power or capacity. However, the power fade shows a lower relevance compared to the capacity fade due to the reduced cell current demand in these batteries.

These functional EoL constraints appear in most cases, beyond the 70-80% threshold. Therefore, the EV battery EoL can be redefined for a large part of the drivers, especially for those using high capacity batteries, currently found on the market. In fact, in 2021 the top 5 EV models sold in Europe had batteries with capacities over 50 kWh [17], which suggests a large potential for extending the EV battery first-life. This redefinition, nevertheless, should be done individually, by analysing each driving condition and ensuring that the battery can perform safely and providing the required range and power through its entire lifetime. This way, postponing the battery EoL can provide a powerful tool to reduce the environmental impact of the transportation sector.

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