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Influence of V2G Frequency Services and Driving on Electric Vehicles Battery Degradation in the Nordic Countries

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ABSTRACT: Researchers worldwide are investigating whether electric vehicles (EV) Vehicle-to-Grid (V2G) services can be profitable for both customer and involved stakeholders. However, marginal consideration has been given so far to the possible wear of the EV battery while providing energy intense services. This paper intends to clearly distinguish and quantify the impact on the battery life time because of normal driving and frequency based service. A representative 40 kWh EV with battery characteristics modelled as Lithium Nickel Manganese Cobalt Oxide batteries is taken as reference, being subject to realistic driving patterns in the Danish island of Bornholm and providing V2G service with 10 kW fast chargers when grid connected. It is shown that if the service energy requirements are relatively low, short term power flows have limited effect on the battery degradation and despite very long provision periods the degradation is not much higher than from normal driving usage.

KEY WORDS: A-1 Electric Vehicles, C-1 V2H & V2G Power Transmission, E-1 Batteries

1. INTRODUCTION

In the transportation sector the decreasing prices of Lithium-ion (li-ion) batteries are making the electrical vehicles (EV)s an increasingly more viable solution. By allowing the idle EV to perform ancillary services for the Transmission System Operator (TSO) or Distribution System Operator (DSO), it is possible to create value for the owner [1, 2]. At the same time, the TSO can maintain stable operation with an increasing share of renewable energy sources. The risk of rapidly increasing battery degradation is often seen as a main barrier for using EVs for ancillary grid services involving both charging and discharging the EV, also referred to as vehicle-to-grid (V2G). There are however very little quantification of how much additional degradation that occurs on top of what is caused by the normal usage for driving. This study, [3], finds that providing V2G frequency regulation in the PJM area from 9pm to 5am every day would give approximately 8% additional degradation after 5 years compared to only driving. In [3] it is unclear which battery type is used, how much energy is required for this service as well as for driving which the study by itself found to be 17% in 5 years. The present manuscript, presents EV battery degradation from similar service provision times but with a higher focus on the delivered energy, which is found to be the most important factor. Using a 10 kW external charger that can deliver a bidirectional power flow to and from the grid, the EV can deliver primary frequency control (PFC) and generate a revenue exceeding all costs of driving [4]. The bidirectional power flow from PFC is similar to what the battery is experiencing during driving where there are short term high power during acceleration and regenerative braking. A previous study have found that the power from regenerative braking is reducing the battery degradation of electrical vehicles as it is depth of discharge which is the main driver for degradation [5]. It is found that the PFC service in the Nordic power system involves large amounts of energy, which can potentially wear the battery [6]. Battery degradation, resulting in a lower capacity, is the main concern when discussing PFC with EVs [7]. The reduction of the energy capacity is an additional cost that has to be accounted in the revenue of the delivered grid services and can be included in an optimisation if the cost is known. The wear of Li-ion batteries can be separated into two main components, calendar aging and cycle loss. Both depends on a large number of factors, which can be fully grasped only by mean of extensive simulations and experimental validation [8]. The present manuscript quantifies the potential degradation due to the individual wearing factors: namely aging and cyclying. A clear distinction is made in order to assess the cycling due to driving and the one due to grid services, namely

frequency provision. The degradation impact of the PFC service is compared with a base case of average driving and charging in Danish climate conditions. The analysis is based on data from the Danish island of Bornholm. The island, which has been recently selected as national test zone, offers several advantages. While normally synchronized to the rest of the Nordic area via a 60 MVA cable, it is capable of running in islanded mode. The Bornholm power system has a representative distribution grid up to 60 kV and is about 1 % of the size of Denmark, in terms of area and population. It has been used as a test case for several large European research projects as well as well as the Danish EV project Across Continents Electric Vehicle Services (ACES) [9, 10, 11]. The ACES project includes elements of field testing, thanks to the 20 bidirectional 10 kW V2G chargers installed at the municipality premises. The chargers are used to deliver PFC during the night when the 20 EVs are not used for driving. The vehicles are delivering PFC up to 14 hours per day, but on Bornholm as well as in Denmark, the cars on average are parked more than 97 % of the time. On a large scale, a significant number of EVs could provide a significant storing capacity at the disposal of the grid operators [12]. The main objective of the EV is driving so it is important to account the potential degradation due to driving and the additional wear caused by grid service provision. The results of the case study is intended to quantify EV battery degradation from pure calendar aging, driving only vs. driving and high utilisation V2G service, based on a semi-empirical lithium-ion battery capacity fade model is presented. The remainder of the paper is structured as follows:

Methodology: Describes the model and the different input data and parameters.

Results: Describes the accumulating degradation over time in the different scenarios

Conclusion: Contains the conclusion of the study.

2. METHODOLOGY

The methodology adopted in the paper relies on a generic industrial battery model with parameters based on Lithium Nickel Manganese Cobalt Oxide (NMC) 18650 cells. It is complemented with input data, such as ambient temperature, driving and grid frequency from the island of Bornholm. Different kinds of NMC batteries are used in various automotive batteries and 18650 is found to to have similar degradation characteristics as flat cells [13].

The permanent reduction or loss of energy capacity in percent of the initial capacity is called delta loss (Δl). The State of Health (SOH) of the battery is defined as the remaining of the energy capacity normalised to the capacity of a new battery which has a $SOH_{t=1}$=100% [3]. The SOH at a given time is found by subtracting the delta loss from the initial capaticy SOH=100%-Δl. The different dynamics that are taken into account in this study are shown in Fig. 1. The parameters describing the effect of the battery temperature and the state of charge (SOC) on calendar aging and cycle loss are described in this section. In the simulations it is assumed that the temperature and the SOC of the individual cells in the battery is equal and homogeneous.

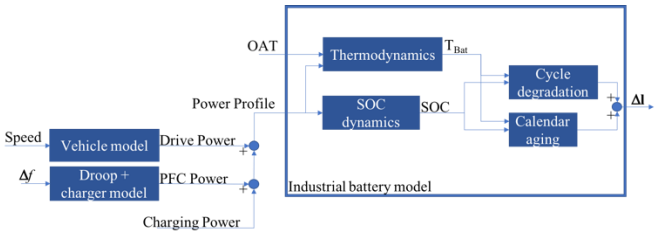

Fig. 1 Input data, parameters and output data of degradation model.

2.1 Calendar aging

The SOH will not remain constant when the EV is idle, as it is affected by calendar aging [14]. The calendar aging is the capacity loss that occurs as a function of time passed since the production, independent of its utilization.

The amount of degradation that occurs per unit of time is highly dependant on the battery temperature (T_{bat}) and the SOC. Such dependacies get stronger with their increase, as seen in Fig. 2.

The model calculates the calendar aging on a second basis, considering SOC and battery temperature at the specific time.

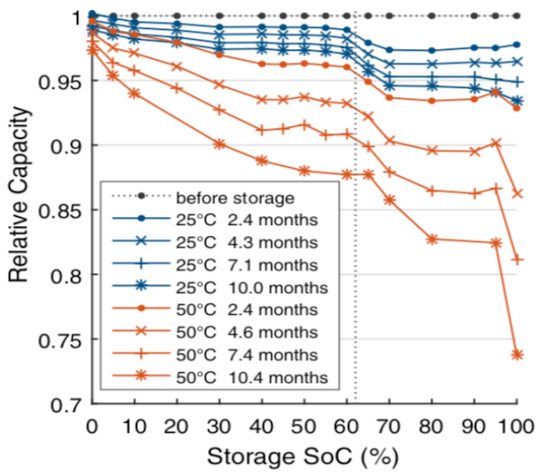

Fig. 2 Calendar aging of NMC cells dependency on SOC and temperature *[15]*

2.2 Thermal modeling

The temperature, T_{bat}, in Fig. 2 represent the internal average temperature of the battery and is calculated in the dynamic simulation with a thermal model, whose input are the outside air temperature (OAT) and the power profile. The dynamics implemented include the thermal balance between generated heat because of Joule losses and the natural cooling of the battery casing. The thermodynamics are a part of the industrial model and is based on a series produced EV. The OAT used in the simulation, shown in Fig. 3, is measured in Denmark every hour during 2017. The climate conditions in Denmark are close to optimal for the calendar aging of automotive batteries as such degradation mechanism is less intense in colder climates [16]. On the other hand the range of the vehicle is shorter when in colder climates as the usable battery capacity is reduced and some energy is used for heating.

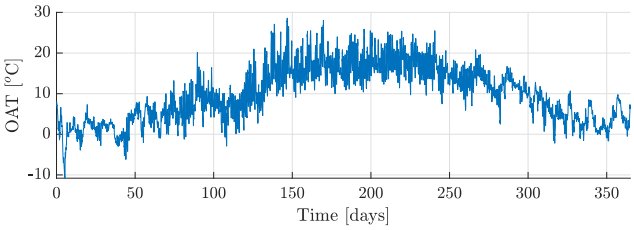

Fig. 3 Outside air temperature in Denmark during 2017.

2.3 SOC dynamic

The SOC of the battery is calculated based on the power flow determined by both driving and grid services and divided by the battery size of 40 kWh. In this simulation the battery size only has an effect on the cycle loss as the same energy results in fewer cycles for a larger battery.

An initial SOC of 80% is chosen to avoid unnecessary high degradation. As the daily driving distance only is 39 km, it is not necessary to fully charge the EV so it is assumed to be charged daily to the reference of 80%, which also is a standard option for some EV models. The specific daily actual behaviour of the SOC is shown in the result section.

2.4 Cycle degradation

The capacity loss caused by the amount of energy cycled through the battery is called the cycle loss. It is a function of the total evolution of the SOC quantified as equivalent full charge/discharge cycles: for example 10 driving trips using 10 % SOC results in one full cycle. This energy usage is either for driving or for frequency regulation depending on the investigated case. The power during driving is based on a measured sample, where both the speed and battery power are measured. The power flow during PFC depends on the specific hardware, the grid code and the specific frequency which also is presented in the following section. The effect of each full cycle equivalent on the SOH is also a function of T_{bat} as shown in Fig. 4.

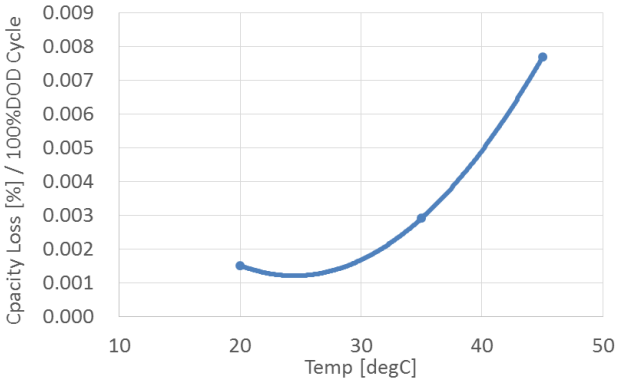

Fig. 4 SOH degradation dependency on battery temperature *[16]*.

The OAT, the driving speed and the PFC power are the inputs to the model, which internally calculates T_{bat} and the SOC during the days and uses the parameters from Fig. 3 and 4 to estimate the evolution of the SOH over five years.

2.5 Primary Frequency Control in the Nordic countries

The TSOs of RG-N have a shared set of grid codes with the purpose of maintaining system stability. PFC is called, Frequency Normal-operation Reserve and is a symmetrical service activated for all system frequency deviations (Δf) up to 100 mHz. It is a fitting reserve for EVs, as the EV both would charge and discharge, depending on the frequency, and thereby be a source of short term power rather than energy. The TSOs in RG-N are jointly responsible for constantly procuring 600 MW of normal operation reserve, proportional to each TSO's share of the production.

FNR is a symmetrical service, which requires the provider to offer the same power capacity for upwards and downwards regulation. Frequency reserves must be provided linearly, with full activation for deviations of 100 mHz.

Battery degradation is a function of both depth of discharge and number of full charge and discharge cycles [17] . However, PFC in the Nordic area requires continuous regulation with limited amount of power due to fluctuations around 50 Hz [6]. This power behaviour would cause a series of small charges and discharges. These micro-cycles are also experienced when driving with regenerative breaking, creating reverse power flow and are therefore not very different from the intended use of the battery.

2.6 PFC based power flow

The power flow from PFC depends on the amount of activation as linear function of Δf. A representative 14 hour sample of the frequency measured every second on Bornholm from 12th

September 2017 17:00:00 to 13th September 2017 07:00:00 is shown in Fig. 5.

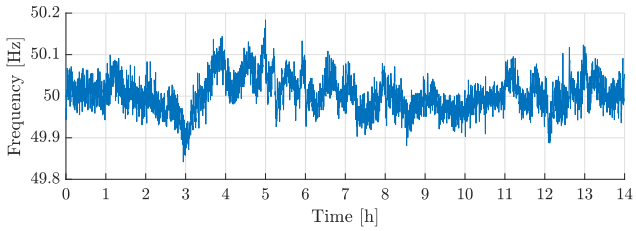

Fig. 5 Frequency measurement during period 17:00-07:00.

The frequency is Gaussian distributed but the average is higher than the nominal value of 50 Hz, as shown in Fig. 6.

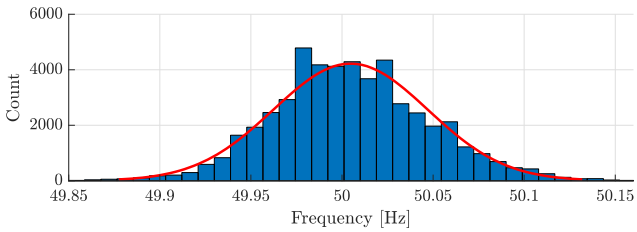

Fig. 6 Frequency distribution with mean and standard deviation μ=50.0047 Hz, σ=0.0424 Hz.

The EV is therefore expected to charge a positive amount of energy during the 14 hour period. The frequency deviation is calculated by subtracting 50 Hz from the frequency measurement as

$$\Delta f = f_t - 50\ Hz$$

The energy company ENEL has developed a V2G charger that has a rated charging power of 10 kW and discharging power of 9 kW, measured at the grid connection on the AC side. Using this charger, series produced EVs with the CHAdeMO plug can be used for V2G services such as PFC. When providing PFC, a symmetrical response is required, so if the average deviation is zero there would be a zero energy balance with the grid. However, the service obligation is from the grid side which means that when taking the efficiency of the charger into account the resulting energy loss must be covered by discharging the battery. The efficiency of the specific charger can be seen in table 1 and is also presented in [6] with a more thorough description of the service.

Table 1: Average efficiency in p.u. for AC power flows in kW in different ranges [6].

Power range	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10
Charging	0.15	0.43	0.64	0.74	0.78	0.81	0.83	0.85	0.85	0.88
Discharging	0.65	0.74	0.79	0.82	0.83	0.85	0.86	0.88	0.89	-

To avoid that the losses discharges the battery, the setpoint can be set with an offset such that the power measured on the battery side over a long period on average is zero. Another and more problematic issue is that the frequency often has an average significantly above or below 50 Hz for several consecutive hours, resulting in the EV being potentially fully charged or depleted. Service provision would therefore be compromised, especially when bidding the full capacity. In Fig. 7 is shown how the energy exchange with the grid would evolve if PFC is provided for 24 hours with 9 kW starting at midnight every day of the week from which the sample was taken. The energy exchange is calculated by integrating the power responses up to time t and divide with the number samples per hour, ΔT. The reserve capacity is P_{cap}=9 kW and the full reserve is implemented for 100 mHz deviations.

$$Exch_t = \frac{1}{\Delta T}\sum_{0}^{t}\frac{\Delta \mathrm{f}}{100\mathrm{mHz}} * \mathrm{P_{cap}}$$

It can be seen that during just one week the EV could have been asked to charge charge up to 20 kWh or discharge up to 25 kWh in the time of one day.

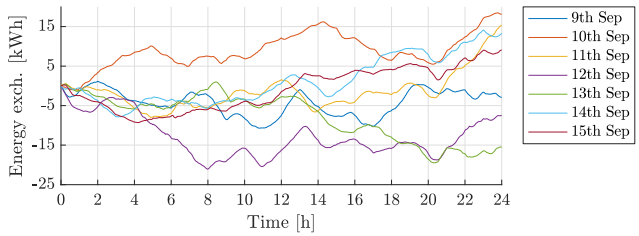

Fig. 7 Energy exchange with the grid when providing PFC with 9 kW during one day.

This issue can be handled by bidding less than the full power capacity such that the remaining power can be used for changing the setpoint during the service provision. These setpoint changes can be implemented in several ways that influence the SOC. For this analysis is instead chosen a period where the frequency over the entire period is close to being balanced, thereby avoiding any control algorithm running simultaneously to maintain an acceptable SOC range. The PFC power is chosen to 9 kW during the whole period of 14 hours. In the sample shown in Fig. 6, since the frequency on average is higher than 50 Hz the EV will charge from the grid. Given the average deviation of 4.7 mHz and P_{cap}=9 kW reserve in 14 hours result in the charged energy

$$\frac{4.7mHz}{100Hz} * P_{cap} * 14\ hours = 5.9\ kWh$$

The 5.9 kWh covers a bit more than half of the efficiency losses when using the charger efficiency from table 1 as a look-up table. It is therefore only necessary to set the offset to 0.35 kW and not 0.77 kW which is the average loss. At the end of the period the

SOC is 0.15 kWh or 0.38% higher than in the beginning as shown in Fig. 8. By integrating the absolute power, the overall energy throughput of the battery is calculated to be 38.9 kWh of absolute energy flow. The power delivery to the grid is calculated with P_{offset}=0.35 kW, after Δf has been truncated to maximum 100 mHz

$$P_{PFC} = \frac{\Delta f}{100\text{mHz}} * Pcap + P_{offset}$$

Fig. 8 shows the DC power on the battery side of the V2G charger including the offset and the efficiency look-up table in table 1.

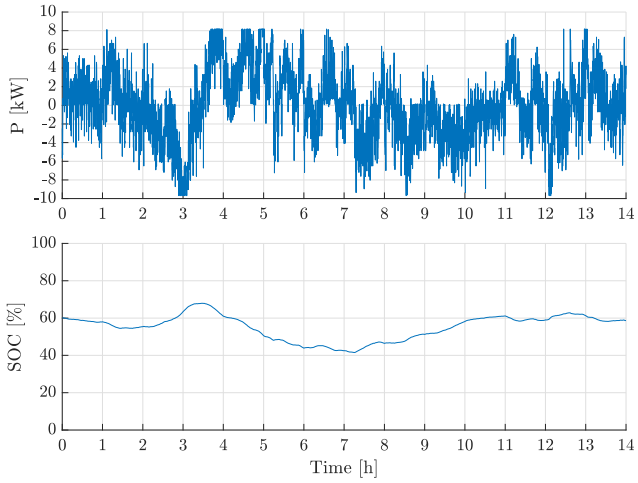

Fig. 8 DC Power and SOC of the battery during PFC provision with 9 kW for 14 hours.

2.7. Driving based power flow

The national Danish transport survey consists of 110,000 interviews conducted in Denmark over the last 10 years, describing the daily travelling [12]. It is found that cars in Denmark on average drives 45 km per day while the cars on Bornholm only drives 34 km per day caused by the limited size of the island.

The overall commuting is thus split in two trips per day each of nearly 20 km: the morning commute is at 8:00-8:30, while the return is at 16:30-17:00. The work time in Denmark is 8 hours per day which is assumed be the period 08:30-16:30. The average distance driven per car on Bornholm is higher on the work days than in the weekend, but the distance for an average day is used so the simulation is not differentiating between workdays and weekend.

The magnitude of the power during acceleration and braking depends on the internal power converter, the driven route and the driving style. The top graph of Fig. 8 shows the measured speed during a 39 km drive, including both city driving and highway. The bottom graph shows as a yellow line the powerflow measured at the battery during the drive by the Battery Management System and read through the Onboard Diagnostics-port. The blue and red line shows the calculated power consumption from the same industrial model based on the speed measurements and characteristics such as the weight and drag of the vehicle and the efficiency of the motor. The blue line is calculated for a summer day while the red line is calculated for a winter day where the cabin heating is considered.

The measurements and calculated result are similar during acceleration but differentiates at higher and constant speed, because the specific temperature, wind speed and changing altitude that has a large effect on the measurements and not are taken into account in the calculations. Additionally the EV is using power for heating as the drive was made during the winter in December 2017. When the electric heater is on during driving, it is supplied by the 12V auxillary battery which is supplied by the main battery via a DC/DC converter [18]. According to the measurements the drive has resulted in a consumption of 8.7 kWh while the calculated power flow only gives a consumption of 4.4 kWh for pure driving and 6.2 kWh when including an average of 2.5 kW for heating. The measured power flow is used as it is more comprehensive, but the trip is split in two trips such that the driving pattern in Fig. 9 is including both trip to work and return.

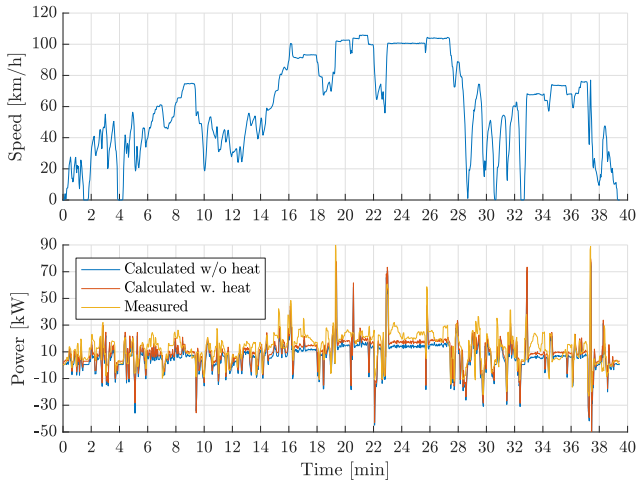

Fig. 9 Power consumption and speed from 39 km drive in December 2017.

In the only driving scenario the charging is conducted when the EV returns home while in the driving and V2G scenario the charging is conducted before leaving for work as seen in Table 2.

Table 2. Applied schedule

Only driving	**Driving and PFC**
Driving 08:00-8:30 (0.5 h)	Charging 07:00-08:00 (1h)
Work 8:30-16:30 (8 h)	Driving 08:00-8:30 (0.5 h)
Driving 16:30-17:00 (0.5 h)	Work 8:30-16:30 (8 h)
Charging 17:00-18:00 (1 h)	Driving 16:30-17:00 (0.5 h)
	Frequency reg 17:00-7:00 (14 h)

3. RESULTS

The degradation is investigated for the following three cases, showing the effect of calendar aging, driving and PFC over a period of 5 years.

3.1 Calendar aging

When investigating the effect of pure calendar aging, the SOC is initially set to 80% and kept constant for 5 years. T_{bat} is only affected by the OAT and is following with a delay as it has a large thermal inertia. The calendar loss is not occurring linearly but more in the beginning with a capacity loss from calendar aging alone of 0.1254% on the first day while the last day only gives an additional loss of 0.0010% of the original capacity. The difference of the OAT between winter and summer means that the calendar aging increases most in the summer and is close to constant in the winter. After 5 years the calendar aging has increased to Δl=6.1%, reducing the SOH to 93.9%.

3.2 Cycle loss from driving

In the base case where the EV only is used to drive the average distance per day, the power and the SOC is shown in the top graph of Fig. 10. The EV is charged with 10 kW once per day when it returns home, as can be seen by the constant negative power flow from 17:00 to18:00. The SOC is after the second drive reduced from SOC=80% to 55%, giving a reduction of 25%.

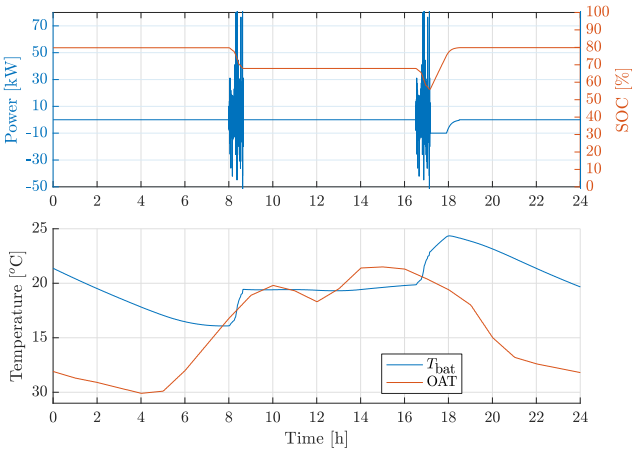

Fig. 10 Power, SOC, OAT and T_{bat} during a daily drive and charge pattern

The battery temperature depends both on the power and the OAT as seen in the bottom graph of Fig. 10. T_{bat} increases both during driving and charging. Since the battery is conceiled in the EV, it takes about half a day before the temperature returns to the OAT, even though the surroundings during the night are up to 10ºC colder. T_{bat} is in the beginning of the shown period higher than the OAT because of the charging of the previous day.

The cycle loss from driving increases linearly with the number of cycles, which increases linearly with time. On the first day there is a reduction of the capacity of 0.0003%. Considering that the daily driving corresponds to 25% of a full cycle, each full cycle causes to 0.0012% degradation.

After 5 years, the degradation caused by pure driving is 0.8% compared to just being parked.

3.3 Cycle loss from PFC provision

Fig. 12 shows how the equivalent full cycles accumulate when the SOC is decreasing. During the PFC provision the battery experiences 20% acumulated cycle resulting in a degradation of 0.0011% per 14 hour period, which also scales linearly per period. Even though the total energy throughput is close to a full cycle it is only the actual movement of the SOC that increases the degradation and since most of the power cancels out the result is only 20% equivalent cycle during the 14 hours.

The added degradation of 14 hours of PFC with 9 kW every day for 5 years is 2%.

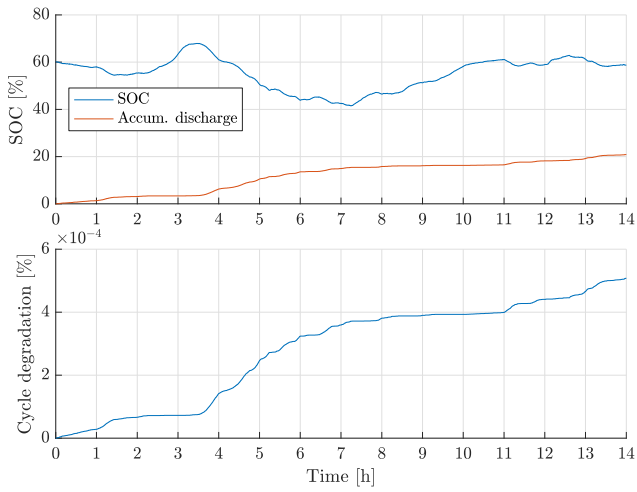

Fig. 11 SOC, accumulated discharge and corresponding cycle degradation

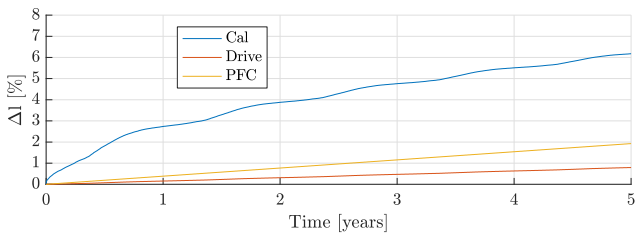

Fig. 12 Battery degradation of each factor.

Fig. 12 reports the combined degradation from both calendar aging and driving and PFC provision. The calendar loss will always occur but the other cycle losses depends on the amount of usage. By only using the EV for driving the SOH will after 5 years

be reduced with 7% to 93%, while if the EV also is used to perform PFC it would be reduced with 9% to 91% SOH.

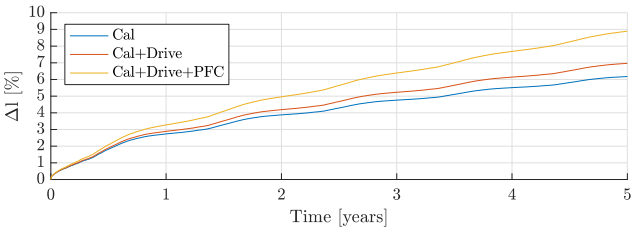

Fig. 13 Battery degradation during the first 5 years.

CONCLUSION

It is found that the dominant degradation comes from calendar aging which over 5 years results Δl=6.1%, reducing the SOH to 93.9% and that the usage has a minor impact compared to this. From using 8.7 kWh equal to 39 km per day or 14,235 km per year for driving with a 40 kWh EV the added cycle loss is equal to 0.8% compared to the situation when the EV just is parked. The cycle loss from PFC is more than twice as high and results in 2% added degradation over 5 years. It has to be remarked though, that the simulated service is rather intense in terms of power and provision time. Based on this initial assessment, the authors claim that PFC service is not causing a significant additional wear on the battery life.

The degradation is calculated based on full cycle equivalents with degradation empirically found by full charge cycles 0-100%, but the degradation from an equivalent cycle that only moves within a small SOC range is found to be significantly lower [16]. On the other hand, choosing another frequency sample could have led to significantly more cycles per period so future works intend to investigate the degradation when the service is provided every day with a new set of frequencies. Additionally such analysis should extend over different services, less energy intense but nevertheless valuable for the grid operators. Moreover, the economic impact of such degradation on the service probitability will be evaluated.

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