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Electric Vehicles' Potential to Contribute with Frequency Regulation

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Executive Summary

The cost of frequency regulation in Sweden has increased significantly. Vehicle-to-grid (V2G) technology offers new ways to resource-efficiently balance the power grid using the rapidly expanding fleet of electric vehicles (EVs). This study quantifies the practical possibilities for EV owners to use their batteries for frequency regulation. By analysing driving patterns from 431 cars, the study estimates the power and energy potential of EVs for grid balancing. It explores various charging behaviours and strategies, assessing their impact on available power and energy and revenue from frequency regulation services. The findings highlight significant economic benefits and small battery degradation from participating in these services. The study underscores the importance of daily plug-in habits and optimal charging strategies to maximize the potential of EVs in frequency regulation, offering valuable insights for future research and policy development.

Keywords: Electric Vehicles, Consumer behaviour, Smart charging, V2H & V2G, Smart grid integration and grid management

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1 Introduction

Frequency regulation is essentially about balancing the active power in an electrical grid. This means that on a second-by-second basis, the power going to loads in the system must be matched by an equal amount of power from producers in the grid. The total cost of frequency regulation in Sweden has increased significantly in recent years and is expected to continue rising in the coming years [1]. This has created increased interest in batteries and their potential to support the grid. However, batteries and associated power electronics are costly, while there is a growing battery capacity in the country's EVs, with some forecasts indicating that Sweden could reach 2.5-3 million rechargeable vehicles by around 2030 [2][3]. Aggregators are in Sweden already using EVs and their charging infrastructure to deliver frequency regulation such as FCR-D [4][5], and FCR-N [6]. So far, this is mainly done by varying the charging power, but with the help of bidirectional charging, known as vehicle-to-grid (V2G), the opportunities to balance the grid in a resource-efficient way increases. The project's overall aim is to study and quantify EV owners' practical possibilities and economic conditions for allowing their batteries to be used for frequency regulation through V2G.

1.1 Frequency regulation services

There are three main frequency regulation services that can be provided in the Nordics, Fast Frequency Regulation (FFR), Frequency Containment Reserves (FCR), and Frequency Restoration Reserves (FRR) [7]. The FCR is further divided into three products- FCR under Normal operation (FCR-N), FCR under Disturbance operation upregulation (FCR-D up), and FCR under Disturbance operation downregulation (FCR-D down). The FRR on the other hand consists of automatic (aFRR) and manual (mFRR) products. Of the three main services, this study's primary focus is on the FCR services during the disturbance operation, i.e. FCR-D upwards and FCR-D downwards.

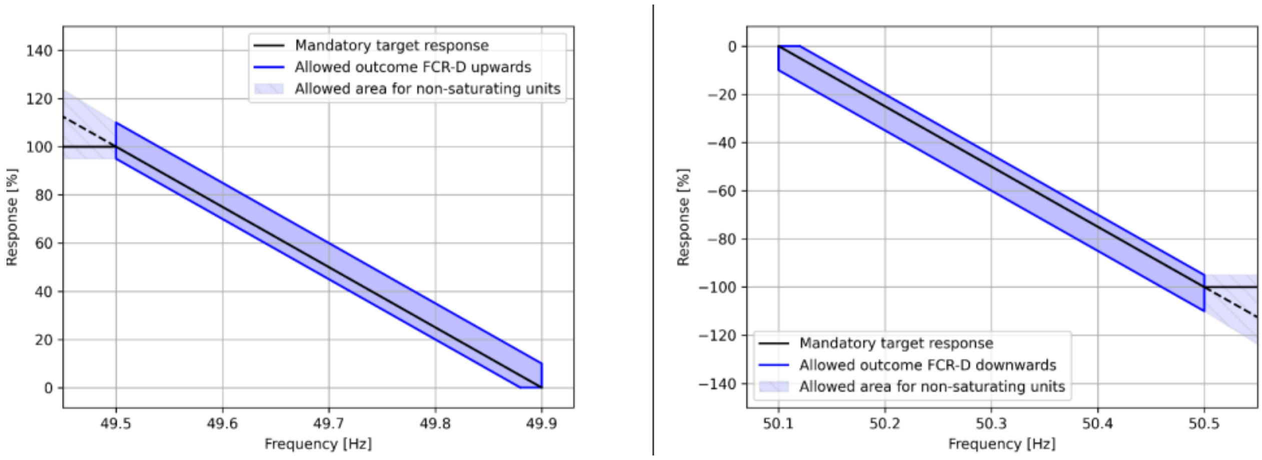

Figure 1: FCR-D linear activation for upward (left) and downward (right) regulation [8].

The FCR-D upward and downward services are activated when the frequency is outside the standard operating range of 49.9 Hz to 50.1 Hz. Both the products are activated linearly as described in the technical requirements [8]. FCR-D is compensated for the prequalified capacity but not for the energy during the provision of the service. However, the FCR-D providing entity should have an endurance of 20 minutes at prequalified capacity to be able to participate in the service.

2 Method

This study utilizes the driving patterns from 431 privately driven conventional passenger cars measured with GPS over 1-3 months in Sweden [9][10]. We estimate the energy use for hypothetical BEVs with the same individual movement patterns as the conventional cars in the database. To single out the effect of these movement patterns we intentionally leave out possible differences due to driving behaviour, road and climate conditions and traffic situation etc., and focus only on trip distances and the length of pauses in between trips. The potential availability of the car battery will depend on the recharging options in the form of access to charging posts at, for example, workplaces, in public parking areas, and in private garages. There is also a need for enough time to recharge the battery before the next trip as well as a willingness to actually recharge when possible. In this study, only home charging is considered, represented by parking periods of 10 hours or more. When EVs are used to deliver frequency regulation today it is through a modulation of the charging power. This limits the availability to the actual charging sessions. The introduction of V2G enables the EV and its battery to be used outside the charging session. In this study, the EVs and chargers are assumed to be compatible with V2G with a reaction time fast enough when delivering or receiving electricity in order to fulfil the requirements for FCR services. The cars are assumed to have a 62.5 kWh of battery capacity of which, 50 kWh is usable. Considering a consumption rate of 0.2 kWh/km while driving, the state of charge of the EVs for the whole duration are calculated. The data is then extrapolated to one year while retaining the daily and weekly trends. Exemplary user cycles for frequency regulation are developed, adapted to the individual driving patterns and two different types of frequency regulation services. Revenues are estimated based on historical compensation levels for participation in frequency regulation. Battery degradation from expected usage from both driving and frequency regulation is modelled. Overall, this provides an opportunity to study the economic conditions for EV owners to participate in frequency regulation. Estimation of available power for frequency regulation from a fleet of EVs with a requirement for economic neutrality for the EV owner is carried out to illustrate the collective potential of EVs to contribute to frequency regulation.

2.1 Charging behaviour

The project studies the practical possibilities of individual EVs to participate in frequency regulation services on an aggregated level. When it comes to EV-charging, some people tend to plug-in and charge at home every day while others only plug in and charge when needed (which can be several times a week, every other week etc.). Some users want their charging to start immediately after the EV is plugged-in, other users delay their charging to night-time to avoid high electricity cots. The SOC-level at the end of a charging session can also vary between users. Some prefer to always charge the EV to 100% SOC level, other charge regularly to 80% SOC since this could be better for battery health. As such, different parameters that influence the potential of participation in the frequency regulation services on an individual EV level are considered and their corresponding impacts are evaluated under different scenarios.

An important aspect to consider is that plugging-in the charger does not necessarily mean that the EV will be charged. The incentive for the EV owner for this behaviour is the revenue that could be earned by being connected to the grid and ready to provide the frequency regulation services when needed. And since the EV can only be charged when it is plugged in, different combinations of plug-in and charge behaviours are possible. It is important to note that these behaviours are not included in the actual drive cycle data. Five different plug-in and charging scenarios are considered. B1 corresponds to the case where the driver plug-in at home every day and charge the EV every day. B3 corresponds to the case where the driver only plug-in and charge when in need to charge to be able to manage the next day's driving. B2 corresponds to the case where the driver charges only when needed but still plug-in the EV every day to, for example, make the battery available for balancing services. Scenarios B4 and B5 correspond to cases where the driver keeps the car plugged in only during the charging session. Although this might be uncommon for home charging, these scenarios serve to show the minimum availability. They also illustrate situations where EVs are plugged in overnight but, due to technical reasons, can only participate in frequency regulation during active charging sessions. When EVs without V2G are used for frequency regulation by modulation of charging power, the availability bears the closest resemblance to scenarios B4 and B5. Table 1 shows the possible combinations of plug-in and charge behaviours with their respective notations.

Table 1: Charging behaviour of EV owners.

Plug-in	**Charge**	**Notation**
Every day	Every day	B1
Every day	When necessary	B2
Day of charging	When necessary	B3
When charging	Everyday	B4
When charging	When necessary	B5

When the EV is plugged in and set to enter a charging session, various charging strategies can be opted. Three charging strategies, immediate (I), late (L), and combined (C) [11] are considered in the study. In the case of immediate charging, the EV is charged as soon as it is connected to the charger. When it comes to late charging, the charging is delayed for as long as possible, making sure that the SOC level is at the required level just before departure. The combined charging is a blend of immediate and late charging, where the EV is charged to 50% SoC level as soon as it is connected to the charger and the remaining 50% of the energy is charged just before the departure. The late and combined charging strategies assume a perfect foresight on the time of departure. Figure 2 shows the SoC of one single EV when different charging strategies are used. The EV is connected to the charger when the pause is equal to 1.

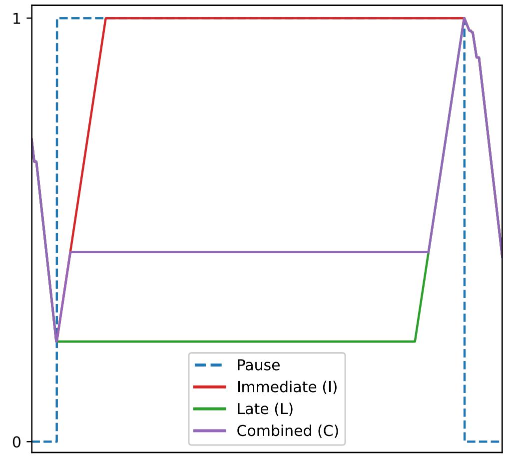

Figure 2: Comparison of the charging strategies. The pause (blue) indicates when the EV is connected to the charger. The battery here is charged to 100% of the usable capacity (50 kWh).

The EVs can be charged to a specific SoC level, SoC_{final}, during the charging process based on different factors such as the driving distance and battery degradation. Three levels of SoC_{final}, 100%, 80% and 50% are included in the study. These percentages correspond to the usable battery capacity of 50 kWh. Charging the EV battery to 100 % corresponds to a case when the driver wants the car to be fully charged; charging the EV battery to 80% corresponds to a case when the driver is more careful about battery degradation; charging the EV battery to 50% is used as a reference case. The drive cycle data is a combination of daily commute and the occasional long-distance trips. As such, the energy demand for the next day is a dynamic variable. The 100% SoC_{final} case is not affected by this, as the EV always has a full battery for the next day. However, this is not the case with the 80% and 50% SoC_{final} levels. At times, the energy demand for the next day could be greater than 50% or even 80% of the EV battery capacity in some cases. Therefore, to make sure that the energy content in the batteries is always sufficient, the energy demand for the next day is tracked. As long as this energy demand is less than the corresponding SoC_{final} level, the EV is charged to that value (80% or 50%), otherwise the EV is charged to 100% instead.

2.2 Scenarios for case studies

The impact of the different parameters, described in Section 2.1 on an aggregated level are presented in this section. The location of charging is fixed to home charging in this paper to emphasize the impact of the rest of the parameters. The charging behaviours, strategies and SoC levels are compared such that only one parameter is varied in each comparison. To avoid overcomplication, all the EVs are assumed to have the same parameters, and they charge at a constant power of 11 kW. The scenarios are coded based on the notations mentioned in Section 2.1. For example, LB1_100 indicates that the late charging strategy has been used (L) with both, the plug-in and charge behaviour, being every day (B1), and the battery is charged to 100% of the usable capacity, i.e. SoC_{final}, by the end of every charging process.

2.3 Degradation modelling

We have analysed the battery degradation for the EV battery with and without frequency regulations. Battery degradation typically consists of cycle aging and calendar aging. In the literature, there are several methods to calculate battery degradation. In this study, we adopted the method from [12][13] that considers more detailed parameters that can affect battery degradation. Degradation consists of various stress factors. For calendar aging, stress factors based on DoD, time, and temperature are considered, which are shown in Eqs. (1) to (3), respectively., Eq. (5) depicts the cycle aging by considering these stress factors.

$$S_\delta(\delta) = (k_{\delta 1}\delta^{k_{\delta 2}} + k_{\delta 3})^{-1}, \tag{1}$$

$$S_\sigma = e^{k_\sigma(\sigma - \sigma_{ref})} \tag{2}$$

$$S_T(T) = e^{k_T(T - T_{\text{ref}})\cdot\frac{T_{\text{ref}}}{T}}, \tag{3}$$

$$S_t(t) = k_t t, \tag{4}$$

$$D_{cyc} = S_\delta(\delta) * S_\sigma * S_T(T), \tag{5}$$

where $k_{\delta 1}$, $k_{\delta 2}$, $k_{\delta 3}$, k_σ, k_t and k_T are the coefficients of the stress models used from [12]. δ presents the cycle depth of discharge, which is obtained from the rain flow counting algorithm. σ and σ_{ref} are the cycle

average SoC and reference SoC level. T and T_{ref} are the operating temperature and reference temperature, respectively.
For calendar aging, the SoC average stress model, time stress model and temperature stress model are considered as represented by Eqs. (2), (3) and (4). For the SoC stress model, average SoC is considered for the whole period. For the stress model, consider the time when the battery is in an idle period. Calendar degradation is presented by Eq. (6). Total degradation is the sum of cycle and calendar aging as in Eq (7).

$$D_{cal} = S_{\sigma} * S_t(t) * S_T(T), \tag{6}$$

$$D_{total} = D_{cyc} + D_{cal} \tag{7}$$

2.4 Estimation of available power

In Section 2.2, the impact of the behaviours and strategies on the available energy of the fleet was described. However, as FCR-D upwards and downwards deal with the capacity market, the total available power of the entire fleet is calculated for a year considering the constraints on SOC levels, availability, and charging of each individual EV. The EVs can participate in one of the two services, provided they have the required SOC level to be eligible. The available power for the two options is formulated as follows:

$$P_i^{FCR-D\ up\ available} = \begin{cases} 2 * P^{max} * A_i * x^{SOC_{min}+M \leq SOC_i}, & C_i = 1 \\ \quad P^{max} * A_i * x^{SOC_{min}+M \leq SOC_i}, & C_i = 0 \end{cases} \tag{8}$$

$$P_i^{FCR-D\ down\ available} = \begin{cases} P^{max} * A_i * x^{SOC_i \leq SOC_{max}+M}, & C_i = 0 \\ 0 \quad , & C_i = 1 \end{cases} \tag{9}$$

Where, $P_i^{FCR-D\ up\ available}$ and $P_i^{FCR-D\ down\ available}$ are the available powers for FCR-D up and FCR-D down respectively for the i^{th} EV, P^{max} is the maximum charging/discharging power, which is considered as 11 kW in this case. A_i is a binary pause indication of each EV, and x being a binary variable that indicates whether SOC_i is within the specified range. The SOC_{min} here is considered as 10% and SOC_{max} as 90%. M, the endurance margin, is the energy that must be available to provide the service at full capacity P^{max} for 20 minutes. C_i indicates whether the EV is charging or not. It is assumed that the EVs charge at full power P^{max} when C_i is 1. When providing FCR-D up during the charging process, the amount of power available is twice the P^{max} as the charging rate can be regulated. For FCR-D down, however, the available power is zero while charging as the charging rate is limited to P^{max}. Considering the constraints for the availability of the fleet power, the impact of the individual EV behaviours on the available power and the consequent revenue is studied.

2.5 Revenue

The frequency regulation services FCR-D upwards and downwards are remunerated for capacity but not for the energy delivered during the service [7]. Therefore, the hourly power bids are calculated from the estimated available power for each scenario to estimate the potential revenue that can be generated annually for providing these services. The hourly prices for FCR-D upwards and downwards in EUR/MW for Sweden are published by the Swedish TSO Svenska Kraftnät (SvK) on the Mimer platform. The annual revenue for each service is calculated by taking the product of the hourly estimated power bids with the hourly pricing.

3 Case studies and results

3.1 Fleet energy

The impacts of the individual EV behaviours described in Section 2.1 are observed in the total energy available in the batteries of all the EVs that are connected to the charger that can potentially be discharged into the grid, along with the empty reserve that can be charged up. Firstly, the charging strategies are compared as shown in Figure 3, with behaviour B1 and a SoC_{final} of 100%. As the EVs are connected at home, the daily trend can be observed in all three scenarios, with the highest availability during the night and the lowest availability during the day. The immediate charging scenario (IB1_100) has the highest available energy as the EVs are charged as soon as they arrive home and remain at a high SoC level throughout the pause duration. The late charging scenario on the other hand keeps the SoC of the EVs at the lowest level during the entire pause duration and thus has the lowest available energy. As expected, the combined charging lies in between the two. The empty reserve, however, is the exact opposite of the available energy.

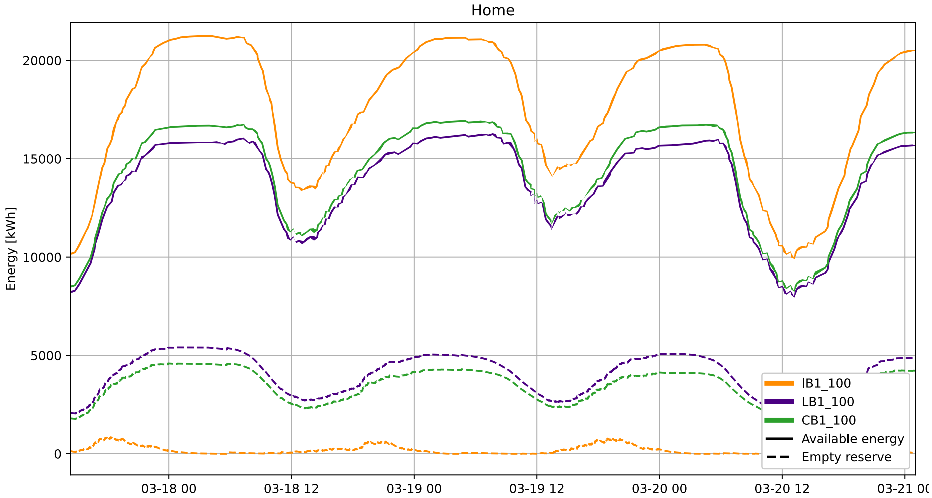

Figure 3: Total available energy and empty reserve of the entire fleet that is connected to the charger at home when the different charging strategies are considered. The charging behaviour and SoC level are fixed in all three cases.

The charging behaviours have a significant impact on the available energy and the empty reserve. As with the previous comparison, the charging strategy and the SoC level are maintained constant while only changing the charging behaviour. In this case, the late charging strategy with 100% SoC level are chosen. The energy of the fleet for this scenario is presented in Figure 4.

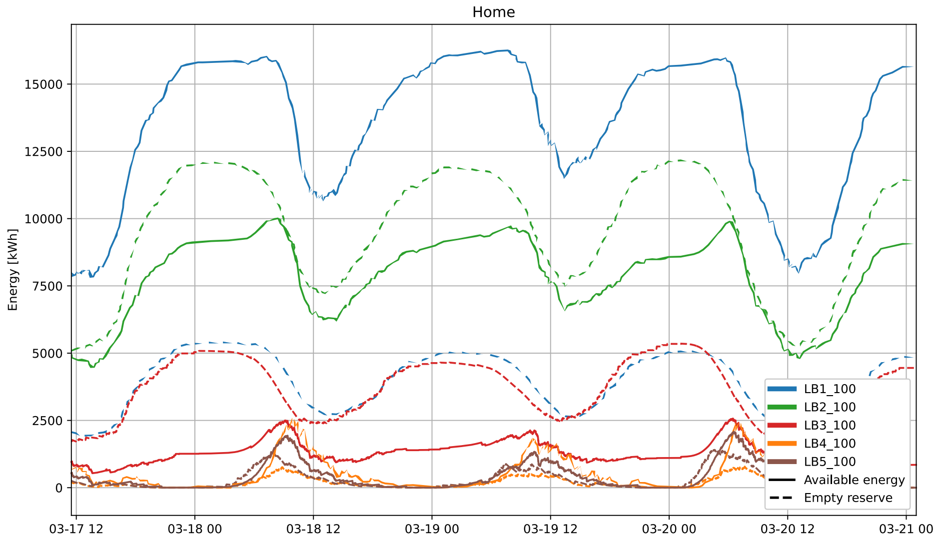

Figure 4: Total available energy and empty reserve of the entire fleet that is connected to the charger at home when different charging behaviours are considered. The charging strategies and SoC level are fixed in all cases.

Behaviour B1 (LB1_100) is when the EV owner plugs-in and charges every day. Charging every day keeps the average SoC at a high level, which is reflected in the total available energy and consequently the empty reserve for this behaviour is lower than the available energy. An interesting aspect of behaviour B2 (LB2_100) is that the empty reserve is higher than the available energy. As most daily commutes are short distances, the number of charging events are reduced. And since the owners with behaviour B2 charge only when necessary, the SoC level is maintained much lower than B1. Behaviours B3, B4, and B5 primarily differ from B1 and B2 based on when the EV is plugged in to the charger. B3 is a variation of B2, with the change being that the EV is plugged in for the entire pause duration only on the day when the EV needs charging. This behaviour has a drastic impact on the availability of the EVs. Behaviours B4 and B5, however, have the lowest available energy as they are only plugged in during the charging process. The time of charging depends on the charging strategy chosen. In this case, the late charging strategy is used, which results in energy peaks just before the departure time of the EVs.

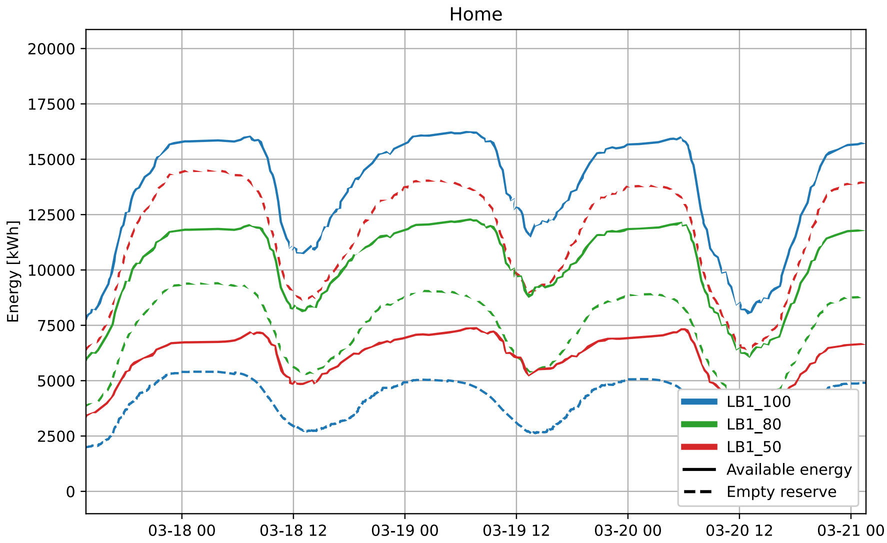

Figure 5: Total available energy and empty reserve of the entire fleet that is connected to the chargers at home when different SoC are considered. Here, the charging strategy and the behaviour is maintained constant.

As all the EVs in the fleet charge to the same SoC_{final} corresponding to the case, the significance of the SoC_{final} is reflected in the available energy of the fleet as shown in Figure 5. As expected, charging the EVs to a higher SoC level will result in a higher available energy. The available energy and the empty reserves are the closest in the case of 80% SoC_{final}.

3.2 Battery degradation

Battery degradation comparisons for various scenarios are considered, including different charging strategies, SoC levels and the provision of frequency regulation services. The average total, cycling, and calendar aging values are analysed for a 1-year operational period for 431 EVs. Table 2 summarizes the results across different scenarios.

The comparison between LB1 and LB2 scenarios highlights the impact of charging strategies on battery degradation. LB1 exhibits a higher average total degradation than LB2. A breakdown of the degradation components reveals that calendar aging is the dominant factor in LB1. On the other hand, cycling degradation is reported more in LB2 compared to LB1. This is because, in the LB1 scenario, vehicles are charged to high SOC when there is a chance, and thus the average SOC of EV battery is much higher compared to LB2. A higher SOC leads to more calendar degradation.

A further comparison is made among the scenarios LB1_100, LB1_80, and LB1_50, where the battery is charged to 100%, 80%, and 50% SoC, respectively. The data show that total average degradation increases with an increase in charging SoC level. Figure 1 shows the comparison of the SoC level effect on degradation. Again, this is mainly due to the average SoC of EV batteries. A high average SoC level leads to much larger calendar degradation, which will lead to more overall degradation.

Regarding frequency regulation services, the scenarios LB1_100_FCR-D up and LB1_100_FCR-D down are compared. The degradation levels in both scenarios are almost identical to LB1_100, which indicates that the provision of frequency regulation services does not significantly affect overall battery aging in this context. This is because the duration of frequency support is typically very low, leading to small fluctuations in SoC levels. The small fluctuations do not affect the total degradation a lot. This suggests that the regulation service, as implemented here, does not add substantial stress to the battery as compared to the baseline charging strategy.

Table 2. Battery degradation comparison considering charging strategy

Scenario	Avg. Total Degradation (%)	Avg. Cycling Degradation (%)	Avg. Calendar Degradation (%)
LB1_100	2.208	0.303	1.905
LB2_100	1.686	0.333	1.352
LB1_80	1.830	0.262	1.567
LB1_50	1.466	0.250	1.216
LB1_100 _FCR-D up	2.201	0.305	1.895
LB1_100_FCR-D down	2.207	0.303	1.904

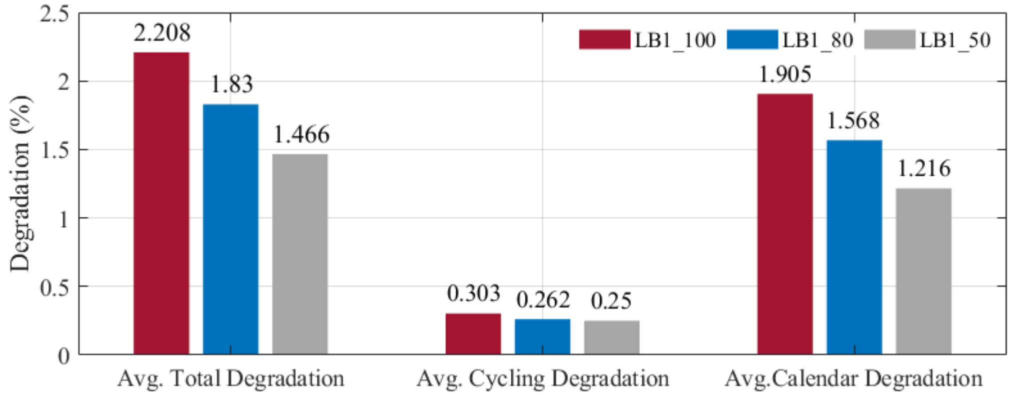

Figure 6. Comparison of Degradation by SoC levels

To conclude, battery degradation is influenced by charging strategies and target SoC levels. Frequent charging and discharging lead to more cycling aging. If it stays idle or has no charging and discharging activity, it leads to more calendar aging. Overall, for this study and with this modelling calendar, aging is dominant for all scenarios. Furthermore, providing frequency regulation services does not add noticeable extra stress on the batteries. Please note that this study considers the LMO battery type. The degradation results may vary for various types of battery chemistries.

3.3 Available power and revenue

The total available power from the EV fleet for the provision of FCR-D up and down, calculated using Eqs. (8) and (9), while considering the impact of the charging behaviours, charging strategies, and SOC levels are shown in Figure 7. In the case of FCR-D up considering different behaviours, B1 only has slightly higher power available as compared to B2 even though the charging takes place every day. Behaviours B4 and B5 have a low power availability as the EVs are only connected during the charging process and also that the charging time of the EVs are spread out. The potential in the case of B3 is reduced in comparison to B2 due to the EVs being plugged in only on the day when charging is needed. The spikes in all the behaviours are a result of the charging process. B2 fairs better than B1 when it comes to FCR-D down as a result of lower charging instances, which keeps the EVs at a low SOC level for majority of the time. As B4 and B5 are only available during the charging process, there is no buffer to provide the service and hence they are zero. B3 has some available power as the charging only takes place close to the departure.

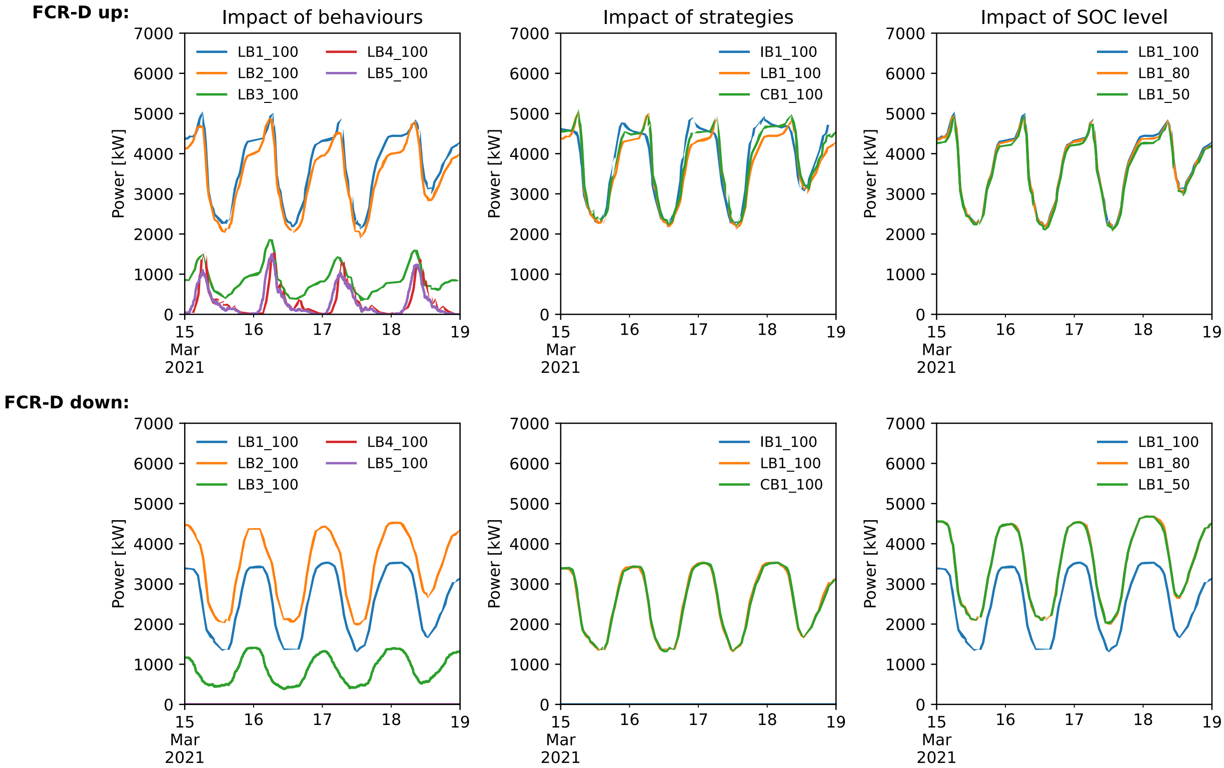

Figure 7: Total available fleet power for the provision of FCR-D up (top row) and FCR-D down (bottom row) considering the impact of the different behaviours, strategies, and SOC levels.

The charging strategies do not have a significant impact on the available power for FCR-D up. The charging times can be noticed here, where the immediate charging has a spike at the beginning of every peak, while the combined and late strategies have it towards the end. As for FCR-D down, the immediate charging cannot provide the service as the EVs start charging as soon as they are plugged in. And since they are charged to 100% by the end of the charging session, they do not have the endurance margin (see Section 2.4) to provide the FCR-D down service. The late and combined strategies have almost identical power available. Changing the final SOC level has very low impact on the available power for FCR-D up, as all three SOC levels are well above the endurance margin requirement of 7.33%. When charged to 100% SOC level, the energy content in the EVs is much higher than the other two cases for the same driving pattern. When these EVs are connected to the charger after a short commute, they will not have the required endurance margin to provide the FCR-D down service. Therefore, the EVs that charge to a 100% SOC level have a lower potential than the ones that charge to 80% and 50%.

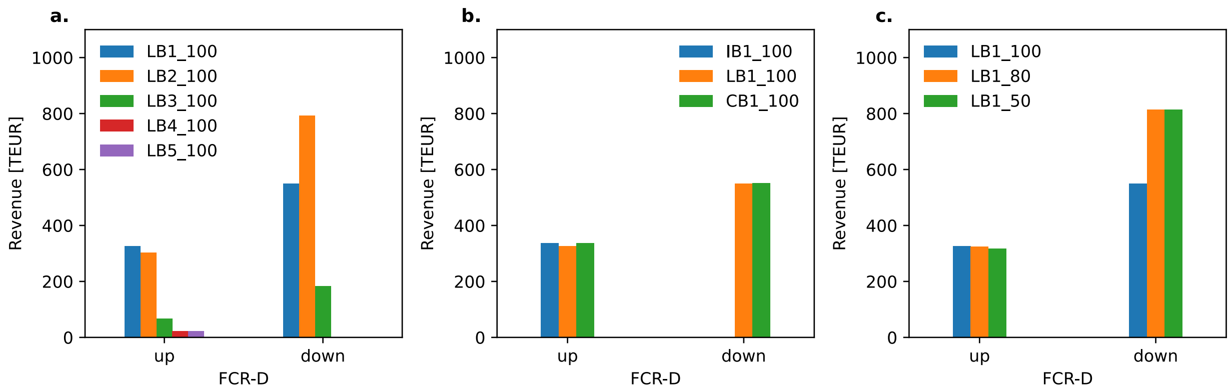

Figure 8: The annual revenue generated for the whole fleet when providing FCR-D up and down services: charging behaviours (a), charging strategies (b), and SoC_{final} (c).

The annual revenue for each service is calculated by taking the sum of the product of the hourly estimated power with the hourly pricing for the whole year. Figure 8 shows the revenue for the three cases with the impact of charging behaviours (a), charging strategies (b) and SoC_{final} (c). The revenues for FCR-D down are much higher in comparison to FCR-D up for all three cases due to higher pricing of FCR-D down service during 2024. The behaviour B1 generates the highest revenue for FCR-D up, followed closely by B2 which is only 6.98% lower, even with far less charging events. The potential revenue is reduced by 78% when the behaviour changes from B2 to B3. If the EVs are only connected during the charging process like B4 and B5, the revenue diminishes to approximately 7% of B1's revenue. In the case of FCR-D down, behaviour B2 generates close to 43% more revenue than B1, while B3's revenue is scaled down by approximately same amount as in the case of FCR-D up. As the available power for FCR-D down is zero for both B4 and B5, they cannot participate in the FCR-D down service.

As the available power for all three charging strategies are similar for FCR-D up, it is also reflected in the revenues. While the immediate charging scenario cannot provide FCR-D down, there is barely any difference in the annual revenue for late and combined charging scenarios. Charging the EVs to 100%, 80% or 50% does not have significant impact on the revenue for FCR-D up. The low available power for the 100% SOC level results in a lower revenue than the 50% and 80% for FCR-D down. Reducing the SOC level from 80% to 50% does not increase the potential revenue.

4 Discussion

There is a significant impact of the charging behaviours, charging strategies, and SoC_{final} of each individual EV on the overall potential to participate in different frequency regulation services. The trivial decision of whether or not to plug-in the charger is of considerable importance, which is highlighted when considering the behaviours B3, B4 and B5 where the EVs are plugged in less frequently based on how the EV owners would act in a typical situation. Today's use of cars for frequency regulation is limited to the B4 and B5 case and with V2G the potential increases substantially. This however requires V2G technology in both cars and chargers. We have here assumed this technology in all cars and chargers. As the behaviours are homogeneous throughout the fleet for each scenario in this study, the effects are amplified when analysing the potential on a fleet level. The amount of available energy for the whole fleet in Figure 4 and the corresponding available power in Figure 7 show that there is a huge untapped potential to provide frequency regulation services which is accessible by just plugging in every time the EV is standstill next to the charger. By inducing the habit of plugging the charger in during this time, which corresponds to behaviours B1 and B2, this untapped potential can be utilized. The revenue for these behaviours shows that B1 generates about 15 times more revenue than B4. Even when behaviour B3 is considered, B2 generates about 4.5 times more revenue than B3. Depending on the level of compensation, this could be a great motivation for the EV owners to alter their behaviour. The need for charging the EV again comes down to the behaviour of the EV owners. Some EV owners tend to charge the EV every day, as depicted in B1, to ensure that they always have a set amount of energy available. While there are others that use the EVs just like a regular gasoline car, where they don't necessarily charge the EV every day unless they need to (B2). Although the high energy availability of B1 might suggest more potential, the available power indicates otherwise. In fact, not charging every day keeps the SoC at a lower level, which increases the potential to participate in the FCR-D down market. As the FCR-D down pricing was higher during the year of 2024, opting behaviour B2 was more beneficial. The combined revenue for both FCR-D up and down for B2 was 25% higher than B1's revenue.

Charging the EVs immediately when they are connected to the charger affects their potential to participate in the FCR-D down service as the empty reserve available for charging is very low. The revenue from only the FCR-D up service cannot compensate for the total revenue that can be generated by the late and combined charging strategies. The introduction of the grid tariffs should also make it less favourable to immediately charge the EV with full power when arriving at home. These drawbacks suggest that delaying the charging process is more beneficial not only from the revenue perspective, but also from a battery degradation perspective. The available power and the revenue show that it does not seem to make a large difference between the late and combined charging scenarios. This is due to a high SoC_{final} chosen for comparison, which results in a high average SoC level and consequently diminishes the difference between the two strategies. A different SoC_{final} could show a larger difference but it is not included in this study.

The comparative analysis of battery degradation across various operational scenarios offers valuable insights into the effects of charging behaviour strategies, SoC targets, and the provision of frequency regulation services. In terms of charging behaviour strategies, in scenarios where vehicles are charged to a high SoC whenever possible, the average battery SoC becomes high. This leads to high calendar aging, which results in contributing significantly to total battery wear. A closer look at SoC targets in various charging behaviour strategies reveals that higher charging thresholds lead to greater total degradation. Interestingly, the inclusion of frequency regulation services has minimal effect on total degradation, suggesting that the short-duration, low-amplitude SoC fluctuations due to such services do not impose significant additional stress on the battery, hence do not pose a significant impact on revenue. The same goes in the case of other behaviours such as B2, B3, B4 and B5. Therefore, it could encourage EV users to participate in these frequency services. Overall, calendar aging dominates the degradation profile across all scenarios, particularly in high-SoC and idle conditions. However, it is important to note that degradation behaviour may vary across different battery chemistries.

5 Conclusion

The study demonstrates that EVs have significant potential to contribute to frequency regulation in Sweden. By analyzing driving patterns and theoretical charging behaviors, it is evident that EVs can provide substantial support to the grid, especially through vehicle-to-grid (V2G) technology. The impact of each individual EV on the overall potential of the fleet to provide frequency regulation is explored in the study by considering the charging behaviours, charging strategies and the choice of SoC_{final}. The major findings are summarized below:

- Behaviours B1 and B2 generate significantly higher revenue than the rest of the behaviours, which signifies the importance of plugging-in every day. B1 has the most potential to provide FCR-D up while it is B2 that can provide FCR-D down the most.
- Due to higher FCR-D down pricing for the considered year (2024) than FCR-D up, the annual revenue is the highest for B2 with the combined revenue of FCR-D up and down being 25% more than that of B1.
- There is no significant difference between the combined and late charging strategies when behaviour B1 and a SoC_{final} of 100% are considered, but the immediate charging strategy cannot provide FCR-D down service.
- Battery degradation analysis shows that charging behaviours and different SoC levels have a significant impact on battery aging. The average degradation can reach up to 2.208% over one year of battery use. Changing the SoC target from 50% to 100% can increase degradation from 1.466% to 2.208%. On the other hand, frequency regulation has minimal impact on degradation, which encourages EV users to participate in such services.

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Presenter Biography

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