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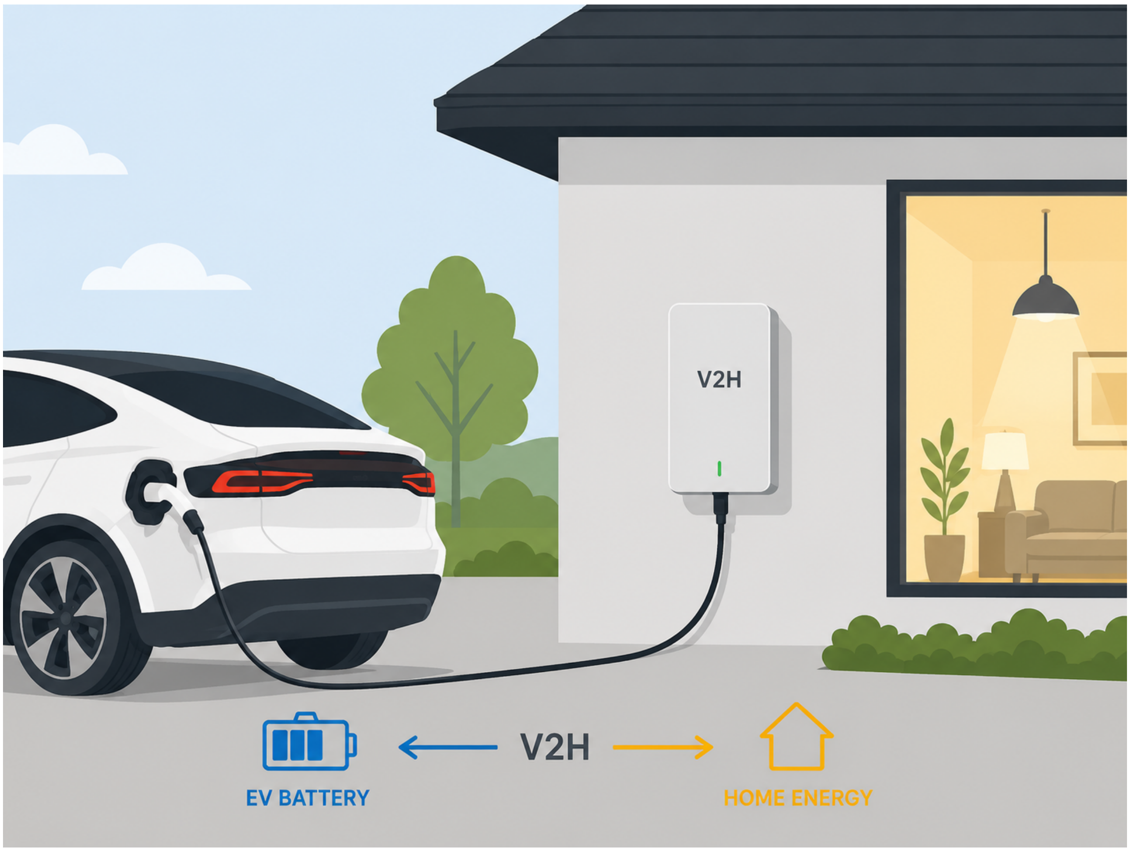

Techno-economic evaluation of EV battery degradation with and without V2H

Master of Science thesis

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Abstract

This thesis presents a techno-economic evaluation of a Lithium-Ion electric vehicle battery with LFP chemistry under different Vehicle-to-Home (V2H) scenarios and introduces Vehicle-To-Grid (V2G) for a cost-effective implementation. The study introduces realistic state-of-charge (SOC) profiles based on daily driving behavior, considering commuting to work between 8:00 and 17:00 with a 30-minute travel time and with an 80 kWh battery electric vehicle (BEV).

For V2H operation, the electric vehicle is used to provide residential peak shaving in a raw house in Gothenburg, and the economic savings are evaluated based on the tariff structure of Göteborg Energi.
For V2G operation, the vehicle provides Frequency Containment Reserve for Disturbances for up regulation (FCR-D up) during office hours and at night, based on market prices from Svenska kraftnät. Moreover, the ageing evaluation is based on the newly developed semi-empirical model proposed by Ahouad M. [1], where parameters are extracted from experimental analysis.

Results show that the ageing model is very sensitive to calendar ageing across all investigated scenarios, while cycling ageing is consistently smaller by two orders of magnitude. Simulations performed over 1 year and 10 years period indicate that 25-30% of the total degradation happens during the first year while the overall capacity loss remains at around 15% at the end of the simulation. The average SOC has the highest impact on ageing, so this study confirms that maintaining the battery between 15% and 50% as [2] mentioned and charging the car twice a week reduces the total degradation to 9% after 10 years.

From an economical perspective, V2H with peak shaving alone provides limited profitability, with savings around 3000 SEK in 10 years in the specific scenario considered. In contrast, combining V2H with V2G for FCR-Dup offers substantially greater economic potential without significant changes in battery degradation.

Keywords: electric vehicles, peak shaving, V2H, V2G, FCR, battery ageing, economics, lithium-ion batteries.

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Michela Porcu, Gothenburg, June 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BESS	Battery Energy Storage System
BEV	Battery Electric Vehicle
BSP	Balancing Service Provider
DSO	Distribution System Opertaor
Ei	Swedish Energy Markets Inspectorate
EOL	End-Of-Life
EV	Electric Vehicle
FCR	Frequency Containment Reserve
FCR-D	Frequency Containment Reserve for Disturbances
ICE	Internal Combustion Engine
LFP	Lithium iron phosphate
SOC	State-of-Charge
SOH	State-of-Health
Svk	Svenska kraftnät
TSO	Transmission System Operator
V2G	Vehicle-To-Grid
V2H	Vehicle-To-Home
WLTP	Worldwide harmonized Light vehicle Test Procedure

Nomenclature

Below is the nomenclature of indices, parameters, and variables that have been used throughout this thesis.

Indices

i	Index for time step

Parameters

A_{cal}	Pre-exponential factor for calendar ageing
A_{cyc}	Pre-exponential factor for cycling ageing
$C - rate$	Rate of charge and discharge
$E_{a,cal}$	Activation energy for calendar ageing
$E_{a,cyc}$	Activation energy for cycling ageing
E_{batt}	Battery capacity
EFC	Equivalent Full Cycle
P_{bid}	Bid power
R	Universal gas constant
SOC_{max}	Maximum SOC
SOC_{mean}	Average SOC
SOC_{min}	Minimum SOC
t	Storage time
T	Temperature
α,z	Fitted parameters for calendar ageing
a, b, m, z	Fitted parameters for cycling ageing
ΔSOC	SOC window
Δt	Time interval

Variables

$\Delta Q_{loss,cal(i)}$	Capacity loss from calendar ageing
$\Delta Q_{loss,cyc(i)}$	Capacity loss from cycling ageing
$P_{batt(i)}$	Current SOC
$SOC_{(i)}$	Current SOC
$SOC_{(i-1)}$	Previous SOC

Contents

1

Introduction

1.1 Problem background

In the last decades, electrification has been one of the solutions for a sustainable transition from fossil fuel sources to green ways to produce electricity. For instance, Battery Electric Vehicles (BEVs) are replacing Internal Combustion Engines (ICEs) and are reshaping the relationship between transportation and energy systems, enabling vehicles to serve as mobile energy storage units within smart grids. Then, the demand increases due to the increase in population and through electrification itself.

This scenario shifts the energy system from a centralized to a bidirectional flow that needs to be managed because it might suffer from grid over-utilization. Moreover, uncontrolled peaks in the grid imply high losses for the DSO (Distribution System Operator) and, consequently, to the TSO (Transmission System Operator) that manages grid energy flows. Nowadays, the problem of high peaks in the grid is a real issue and Sweden is looking for solutions. The TSO Svenska kraftnät (SVK) is discussing with the Swedish Energy Markets Inspectorate (Ei) about mandatory power fees for all DSOs' customers [3]. The aim of the new regulation is to reduce peak loads to properly distribute energy usage throughout the day.

From the customer's perspective, consumption can be monitored through smart meters, while power peaks can be reduced through energy storage. The latter approach, known as peak shaving, allows customers to lower their electricity bills by reducing the charges associated with the power tariff. If peak shaving is provided by an EV to a household, the service is called Vehicle-to-Home (V2H). However, to assess the impact of V2H on the battery, an ageing analysis must be conducted to determine the economic viability of this implementation. For this reason, this thesis conducts a comparative analysis on a lithium-ion LFP battery with and without V2H, from both degradation and economical perspectives.

Battery degradation is affected by two different factors:

- Calendar ageing, which develops continuously depending on the state of charge and environmental conditions, such as temperature;
- Cycling ageing, which depends on the operating conditions during battery charge and discharge cycles.

To test the ageing model, three scenarios form the basis of the thesis work, so that the impact of different state-of-charge (SOC) profiles on battery ageing can be evaluated and solutions to increase the revenue can be proposed.

1.2 Previous work

Several studies have investigated battery ageing models, V2H through peak shaving by electric vehicles and economic assessment on ancillary services. The study by Brennenstuhl et al. [4] is based on similar premises with respect to the household and battery capacity, but the analysis of degradation is partially developed and does not consider the impact of calendar aging when the vehicle is stored. The analysis conducted in [5] display the impact of SOC and SOC window in the battery degradation but the scenarios for V2H are missing, together with the techno-economic evaluation.

Kelm et al. [6] analyzes V2H with peak shaving but the tariff is Time-Of-Use based, therefore dependent only on energy consumptions, and it doesn't consider extra fees for power peaks. However, Nájera et al. in [7] gives a reference for degradation investigation. In fact, its work is based on a semi-empirical ageing model, and it considers the same chemistry, but no EV application scenario is mentioned. On this topic, Tchagang et al. paper [8] considers V2B/V2G peak shaving with EV battery degradation but omits calendar ageing, targets commercial buildings rather than residential demand-tariff structures.

1.3 Purpose

This thesis addresses these gaps by combining a semi-empirical ageing model — accounting for both calendar and cycle degradation — with residential V2H peak shaving scenarios under a Swedish power tariff structure that includes explicit fees for power peaks. Furthermore, an economic assessment is carried out to evaluate the financial convenience of the implementation from the EV owner's perspective. The study offers a novel contribution through:

- Evaluation of calendar and cycling ageing through a semi-empirical ageing model based on experimental data on a LFP cell
- Development of three realistic SOC profiles with different charging routines
- For each SOC profile, analysis on capacity loss and degradation costs with V2H and without V2H
- Calculation of net profits between degradation costs and savings from a bill with additional Power-fee
- Proposal on solutions to increase profits through SOC window variations and frequency regulation.

1.4 Thesis structure

The thesis contains five chapters:

- Chapter 1 introduces the research background, objectives and contributions.
- Chapter 2 presents the theoretical foundations of battery electric vehicles and LFP chemistry, battery ageing, ancillary services considered for the analysis and economic assessment.
- Chapter 3 describes the battery ageing model, the assumptions for the economic analysis and the battery model.
- Chapter 4 shows the results of the simulations with and without V2H and two more profitable solutions.
- Chapter 5 concludes the thesis and mentions future work.

2

Theory

This chapter presents the theoretical background necessary to understand the work carried out in this thesis. It covers the fundamentals of BEV technology and LFP battery chemistry, the mechanisms behind battery ageing, the ancillary services enabled by V2X technology, and the economic framework used to assess the financial impact of the implementation.

2.1 BEV and LFP chemistry

This section introduces the key concepts of battery electric vehicles and the electrochemical principles of LFP cells, which form the basis of the ageing model adopted in this thesis.

2.1.1 BEV, Battery Electric Vehicle

The Battery Electric Vehicle is a fully electric vehicle powered by rechargeable batteries. It stores electric energy which is converted into mechanical energy through the electric drivetrain. BEVs utilize electric engines and engine controllers, so they differentiate from ICEs (Internal Combustion Engines) because fuel is not needed [9].
Vehicles usually carry a substantial weight; thus, a large battery pack must be modelled to provide the required amount of power and guarantee good performance. Battery capacities usually range from 40 kWh to 120 kWh while heavy duty trucks can reach 1 MWh [10].
Energy density, safety and lifespan depend on how the battery is manufactured and material compositions.

2.1.2 Electrochemical cell and LFP chemistry

The performance of the battery is dependent on the choice of materials and chemistry used inside the cell. Lead-acid, nickel metal-hydride, zinc-air are some of the battery technologies available in BEVs market, but this section will focus on lithium and electrochemical cells.

First and foremost, an electrochemical cell converts chemical energy into electrical energy through the movement of electrons. To make this happen, the electrochemical cell needs a positive electrode and a negative electrode, separated by a separator soaked in the electrolyte. The electrodes provide a potential difference to an external load that is connected to the cell through two current collectors. The potential difference is determined by the electrochemical properties of the positive and negative electrodes. In this work, Lithium Iron Phosphate (LFP) is adopted as the battery technology of reference. LFP, which stands for $LiFePO_4$, constitutes the positive electrode, while graphite (C_6) is used as the negative electrode, as shown in Figure 2.1. This combination provides a potential of 3.45 V vs Li/Li+, derived from:

$$E_{cell} = E_+ - E_- \tag{2.1}$$

where E_+ is the potential of the positive electrode, E_- is the potential of the negative electrode and E_{cell} is the potential difference of the cell.

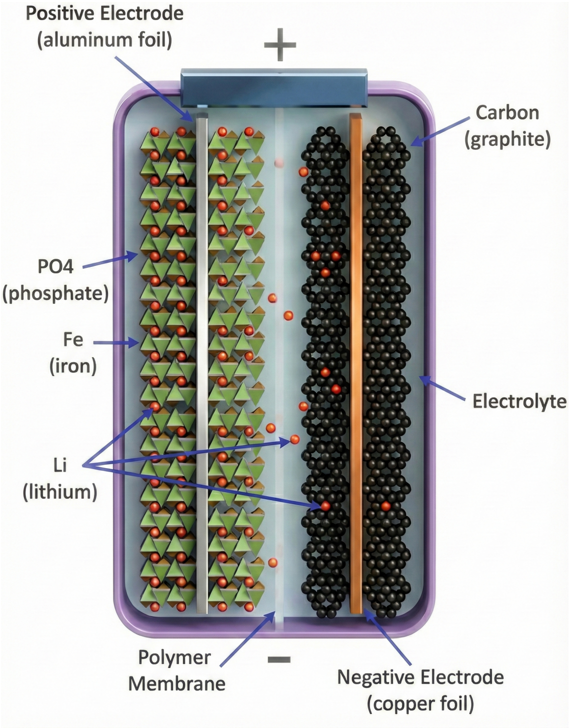

Figure 2.1: Representation of Li-ion LFP battery [11].

During charging, graphene layers host Li-ions from the positive anode, where oxidation took place: Li^+ move through the electrolyte while electrons follow an external path through the current collectors toward the negative electrode. Electrode reactions are defined as:

$$\text{Positive electrode} \quad \mathrm{LiFePO_4} \rightleftharpoons \mathrm{Li_{1-\mathit{x}}FePO_4} + x\mathrm{Li^+} + x\mathrm{e^-}$$

$$\text{Negative electrode:} \quad 6\mathrm{C} + x\mathrm{Li^+} + x\mathrm{e^-} \rightleftharpoons \mathrm{Li}_x\mathrm{C_6}$$

$$\text{Overall cell reaction:}\quad \mathrm{LiFePO_4} + 6\mathrm{C} \rightleftharpoons \mathrm{Li_{1-x}FePO_4} + \mathrm{Li_xC_6}$$

To supply a certain voltage, cells must be stacked in parallel, while they must be placed in series to increase the capacity. Cells in series and in parallel form a battery pack, and packs together form modules. The capacity of an electric vehicle is defined by the BEV module.

2.2 Battery ageing

This section describes the degradation mechanisms that affect lithium-ion batteries over time. Both calendar and cycle ageing are discussed, along with the semi-empirical models used to quantify capacity loss.

2.2.1 SEI formation and SOH

Battery ageing is a phenomenon that affects the battery lifespan from the first utilization. In fact, during the first cycles, the liquid electrolyte starts to decompose, and a thin SEI (Solid Electrolyte Interphase) layer is formed at the negative electrode surface. The SEI layer protects the electrolyte for further decomposition, but over time it gets thicker and the usable battery capacity decreases. Mechanical stress can lead to loss of active material while fast charging can cause Li-ions to deposit as metallic crystals on the negative electrode, known as lithium plating, and can ultimately lead to short circuits.

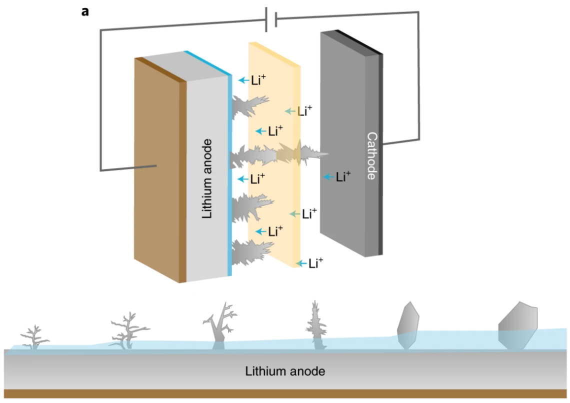

Figure 2.2: Dendrites formation and evolution [12].

Consequently, ageing affects battery SOH (State-of-Health), which compares the current maximum capacity to the factory-new condition. In electric vehicles, battery ageing dictates the car lifespan, where EOL (End of Life) is reached at 80% of capacity original value.

2.2.2 Semi-empirical models: Calendar and cycling ageing

To predict and improve battery lifetime, ageing needs to be quantified. One of the most common solutions are semi-empirical models, which are mathematical expressions that depend on both defined values (such as temperature, SOC, charge and C-rate) but also on experimental fitted parameters.
The model proposed by Ahouad in [1] considers calendar ageing and cycling ageing.

Calendar ageing is loss of capacity due to the storage conditions of the battery. It is expressed by

$$\Delta Q_{loss,cal} = A_{cal} \cdot e^{\left(-\frac{E_a}{RT}\right)} \cdot SOC \cdot t^z$$

where A_{cal} is the pre-exponential factor, E_a is the activation energy, R is the universal gas constant, T is the temperature, α and z are fitted parameters from experiments and t is the storage time.
Cycling ageing is loss of capacity when the battery is actively charging and discharging. It is expressed by

$$\Delta Q_{loss,cycle} = A \cdot (\Delta SOC)^a \cdot (SOC_{mean})^m \cdot (C_{rate})^b \cdot e^{\left(-\frac{E_a}{RT}\right)} \cdot EFC^z$$

where ΔSOC is the SOC window, SOC_{mean} is the average SOC value, C_{rate} is the C-rate of charge and discharge, EFC is the Equivalent Full Cycle, and α, m, b, z are the fitted parameters from cycling tests.

2.3 Ancillary services with V2X

Historically, electric vehicles have been treated as passive loads on the electrical grid, used only for charging. However, the evolution of bidirectional charging redefines them as dynamic mobile energy storage. The term V2X (Vehicle-To-Everything) covers the variety of connections that the EV can establish to provide a service. Two of the most common services are V2H and V2G.

2.3.1 Peak shaving - V2H

On the residential scale, EVs can provide energy support through Vehicle-to-Home. When V2H is enabled, the household sees the vehicle's battery as a BESS (Battery Energy Storage System) that can absorb or supply power when required. Among services that define the term V2H, peak shaving is relevant when speaking about grid overutilization.

During the day, it might happen that households' loads require an intense amount of power from the grid, and on a large scale it can lead to frequency fluctuations and lines overheating. To avoid the issue, peak shaving can locally smooth out power peaks so that extra energy can be managed by the EV battery. For instance, a power level can be manually set so, when consumption exceeds the threshold, the

BEV supplies the required power, as in Figure 2.3.
On one side, the battery goes into a higher number of cycles but, on the other side, the grid doesn't encounter problems with uncontrolled peaks. Moreover, peak shaving is beneficial for decreasing the cost of the bill because TSOs are nowadays introducing power fees, which will be described in the next section.

To activate peak shaving with EVs, the owner must be sure to have a vehicle that supports V2X and to install a bidirectional charging point at home. For energy measurement, the owner must contact the DSO to activate the so called "smart control" on house appliances.

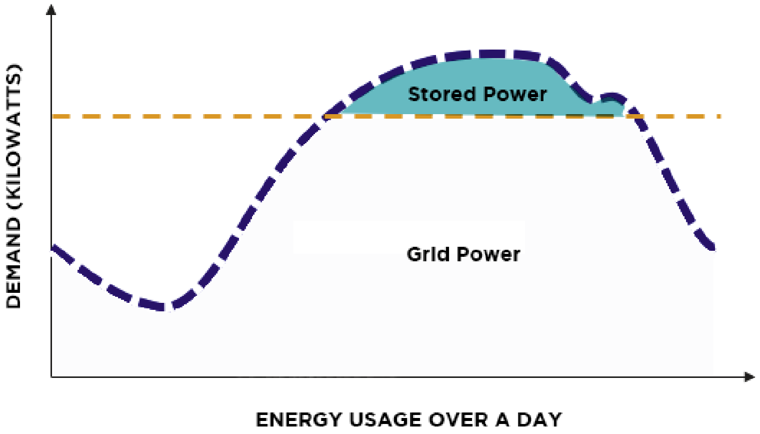

Figure 2.3: Example of peak shaving: a generic consumption curve (dashed blue) is limited by the selected power limit (dashed yellow)[13].

2.3.2 FCR-Dup - V2G

On a larger scale, vehicles can provide ancillary services through Vehicle-To-Grid. FCR (Frequency Containment Reserve) is one of those services, which aims to regulate the grid frequency to its nominal value when it suddenly deviates. In this case, EVs are seen from the grid as BESS that can provide a certain amount of power when required. There are three different solutions based on the type of regulation the driver wants to provide:

- FCR-N (Normal Operation): it handles continuous micro-imbalances of grid frequency, and it is activated from 49.9 Hz to 50.1 Hz;
- FCR-D up (Disturbance Operation "up"): it handles rare and severe under-frequency drops, and it is activated from 49.5 Hz to 49.9 Hz;
- FCR-D down (Disturbance Operation "down"): it handles rare and severe over-frequency spikes, and it is activated from 50.1 Hz to 50.5 Hz.

Each FCR operation is managed by a droop control, which automatically regulates the output power of the battery. In particular, the current frequency is compared to the nominal frequency $f_0 = 50$ Hz, and the difference is divided by the maximum

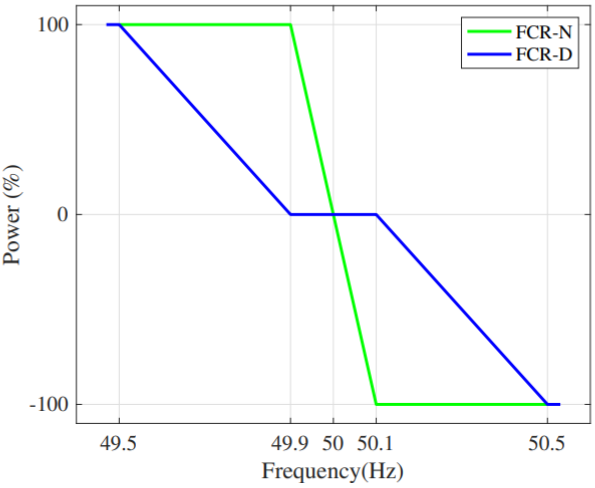

Figure 2.4: FCR activation with respect to frequency deviation [1]

deviation Δf_{max}, which for FCR-N = 0.1 Hz while for FCR-D = 0.4 Hz. The principle is developed through the following expressions, explained in detail in [1]

$$P_{FCR-N} = P_{FCR-N}^{Max} \times \begin{cases} 1, & \text{if } f \leq 49.9 \text{ Hz} \\ \frac{f_{50}-f}{\Delta f_{FCR-N}^{max}}, & \text{if } 49.9 \text{ Hz} \leq f \leq 50.1 \text{ Hz} \\ -1, & \text{if } f \geq 50.1 \text{ Hz} \end{cases} \tag{2.2}$$

$$P_{FCR-Dup} = P_{FCR-Dup}^{Max} \times \begin{cases} \frac{f_{49.9}-f}{\Delta f_{FCR-D}^{Max}}, & 49.5 \text{ Hz} \leq f \leq 49.9 \text{ Hz} \\ 1, & \text{if } f \leq 49.5 \text{ Hz} \\ 0, & \text{otherwise} \end{cases} \tag{2.3}$$

$$P_{FCR-Ddown} = P_{FCR-Ddown}^{Max} \times \begin{cases} \frac{f-f_{50.1}}{\Delta f_{FCR-D}^{Max}}, & 50.1 \text{ Hz} \leq f \leq 50.5 \text{ Hz} \\ 1, & \text{if } f \geq 50.5 \text{ Hz} \\ 0, & \text{otherwise} \end{cases} \tag{2.4}$$

2.4 Economic assessment

2.4.1 SVK new regulations - Power tariff

SVK has an ongoing dialogue about the renewal of the tariff model in the near future [3]. The new model has been published in SVK website as “Översyn av transmissionsnätstariffen” (Renew the transmission Grid Tariff) on February 19, 2026, and it is based on four parts [14]:

1. Kundspecifik avgift (Customer-Specific Fee): monthly fixed fee that covers overhead costs to individual costumers;
2. Energiavgift (Energy fee): fee dependent on the amount of energy used, which covers grid losses during transmission - an allocation factor will be added;
3. Effektavgift (Capacity/Demand Fee): power fee to discourage heavy grid usage during peak times – a voltage regulation fee will also be added;

4. Fast avgift (Fixed Fee): annual subscription to cover residual grid costs.

At present, many DSOs have already implemented a Power Tariff in their customers' bill and that is the reason why the focus of this thesis will be directed only towards "Effektavgift". One of the DSOs mentioned is Goteborg Energi, which introduced the power tariff for residential villa owners in 2021 and a voluntary time-differentiated tariff in 2025 [15].

One of the power tariff options is based on the three highest hourly power peaks from November 1^{st} to March 31^{st} accumulated per month. During weekdays and high price hours (from 07:00 to 20:00), peaks are averaged and multiplied by a fixed fee based on the household power level, while during low price hours, weekends and remaining months, the power fee is 0 SEK/kW. This tariff model allows the customer to shift high-demanding power consumptions to low price hours and avoid grid over-utilization.

2.4.2 Economic evaluation on Peak shaving

As mentioned before, the power fee is dependent on power peaks measurements from the household smart meter. The higher the peaks, the higher the cost. This means that bad management of power spikes can make the power fee relevant on the overall bill. To avoid high prices in the bill, peak shaving is one of the solutions.

Peak shaving can be provided by an energy storage system, such as BESS or BEV, apart from manual control of loads. The operation consists in setting a power limit and supplying the extra power through storage; consequently, the DSO will measure the highest peak as the power limit imposed for peak shaving, decreasing the monthly fee. Since peak shaving is available locally, revenue is based on savings compared to the bill without peak shaving.

2.4.3 Implementation of FCR-D

In contrast to peak shaving, FCR services follow the energy market prices. An individual provider, such as an EV driver, is paid for two types of pricing: energy remuneration, based on the activated energy, and capacity remuneration, based on the sold capacity [16]. The most relevant is the capacity remuneration, which only relies on the availability of the power source. This concept is particularly consistent for FCR-D services, which are activated only if the frequency goes below or above 5% of the nominal frequency and occurrences are not high. EVs must guarantee their maximum bid power for 20 minutes.

The minimum power bid is 0.1 MW, which means that the individual driver must be part of an aggregation of vehicles, known as EV fleet. Moreover, the provider is required to be accepted after a prequalification from a Balancing Service Provider (BSP). A test is performed in accordance with the "Test Program Template" and

Svenska kraftnät rejects or approves the application.

3

Methods

The thesis objectives are achieved through various simulations in MATLAB environment, where both battery model and battery ageing model are developed.

3.1 Battery ageing model

The battery ageing model is based on the semi-empirical model proposed by Ahouad M. [1], where details about experiments and fitted parameters are displayed. The expressions for calendar and cycling ageing are expressed in Section 2.2.2 while in Table 3.1 fitted parameters are listed.

Table 3.1: Calendar and cycling ageing model parameters

Calendar	**Value**	**Cycling**	**Value**
A_{cal}	0.46	A_{cyc}	0.8914
$E_{a,\mathrm{cal}}$	14221.59	a	0.1731
α	0.8628	m	0.2886
n	0.4932	b	0.3979
		z	0.5758
		$E_{a,\mathrm{cyc}}$	10000

This model implements BEV degradation analysis during cycles and storage. To be tested, it requires SOC profiles from the vehicle battery during normal usage. Therefore, in this thesis, battery models are introduced to create various scenarios that could provide different SOC profiles to feed to the ageing model.

3.2 Economic Assessment

Apart from analyzing parameters that affect ageing, this thesis aims to understand the convenience of V2X in terms of costs and profits and compare them with degradation costs. The research focuses on peak shaving service, so Vehicle-to-Home, but the model has been implemented to contribute also to Frequency Containment Reserve for up regulation FCR-Dup.

Peak shaving is locally provided to a household by a BEV. This means that, to have a proper comparison in terms of savings, it has been assumed that the driver is also the owner of the house. For clearance, when the EV is performing peak shaving at home, the BEV is affected by additional cycles but the Power tax from the bill of the driver is decreasing.

The economic evaluation will be developed answering the following questions:

3.2.1 How much savings does the driver gain after performing peak shaving?
3.2.2 How much does ageing cost in the three scenarios?
3.2.3 How much extra profit can the driver gain if FCR-Dup is performed?

3.2.1 Savings after peak shaving

First of all, the case analyzes the bill from Göteborg Energi where the price list can be found in its website [17]. The customer bill has

$$\begin{aligned}\mathrm{Cost}_{\mathrm{month}} = \mathrm{Energy}_{\mathrm{month}} \cdot \mathrm{fee}_{\mathrm{öre/kWh}} + \mathrm{days}_{\mathrm{month}} \cdot \frac{\mathrm{fee}_{\mathrm{kr/år}}}{365} \\ + \mathrm{Power}_{\mathrm{avg\ 3peaks}} \cdot \mathrm{fee}_{\mathrm{kr/kW}} + \mathrm{Energy}_{\mathrm{month}} \cdot \mathrm{fee}'_{\mathrm{öre/kWh}}\end{aligned}$$

where Energy$_{month}$ is the amount of energy consumption, fee$_{öre/kWh}$ is the energy price per month, fee$_{kr/år}$ is the yearly fee based on the power level of the house, Power$_{avg3peaks}$ is the average of the three highest peaks in a month, fee$_{kr/kWh}$ is the power fee and fee'$_{öre/kWh}$ is the fixed tax per energy consumed each month. The variables in the bill are the energy consumption and the power peaks, which will vary by the scenario considered.

In this specific case, the customer chose the time-differentiated power fee: the three highest peaks are registered monthly between 1st November and 31st March and only during the weekdays in the high price interval from 07:00 to 20:00. Profitability is calculated by comparing costs before and after peak shaving

$$\mathrm{Savings}_{\mathrm{month}} = \mathrm{Cost}_{\mathrm{month,\ before}} - \mathrm{Cost}_{\mathrm{month,\ after}}$$

3.2.2 Ageing costs

The degradation costs are performed to understand how ageing and costs of the battery are related. For this analysis, the battery ageing model has been run to know the degradation of the battery for a certain period. The economic evaluation on ageing is conducted as [1] suggests

$$\mathrm{Cost}^{\mathrm{cal/cyc}} = C^{\mathrm{bat}} \frac{\Delta Q_{\mathrm{loss,\ cal/cyc}}}{100\% - \mathrm{EOL}(\%)}$$

where C^{bat} is simplified as the investment cost of the battery, $\Delta Q_{\mathrm{loss,\ cal/cyc}}$ is the capacity loss for cycling and calendar ageing and *EOL* is the End-Of-Life of the battery which is set at 20%. For every scenario, the degradation cost is implemented before and after peak shaving to understand how peak shaving impacts ageing-related expenses.

3.2.3 Extra profit from FCR

An optimization analysis will be conducted to determine how much extra profit the driver gains if the battery is used for V2G. The ancillary service chosen for V2G is FCR-D because it gives a high remuneration, according to [18] , compared to the activation time required. Specifically, between FCR-D up and down, the first option has been chosen because it naturally discharges the battery when needed and brings the SOC to lower values, which is supposed to slightly improve calendar ageing.
To implement FCR-D up, the parameters set are

- SOC_{max}, as the maximum SOC that the battery can reach
- SOC_{min}, as the minimum level of SOC
- P_{bid}, as the maximum power provided by the BEV.

The requirements from SVK are applied to the model in order to guarantee droop control on the power supplied.

3.3 Battery model

The battery model provides SOC profiles based on the amount of power that the battery provides or absorbs, as shown below from [19]:

$$\mathrm{SOC}_{(i)} = \mathrm{SOC}_{(i-1)} - \frac{P_{\mathrm{batt}(i)} \cdot \Delta t}{E_{\mathrm{batt}}}$$

$\mathrm{SOC}_{(i)}$ is the previous value of SOC, $P_{\mathrm{batt}}(i)$ is the power through the battery, Δt is the time interval and E_{batt} is the capacity of the EV battery. When $P_{\mathrm{batt}}(i)$ is positive, the battery is discharging and provides energy, while when $P_{\mathrm{batt}}(i)$ is negative, the battery is charging and absorbs energy.

From what has been said, the SOC profile is strongly dependent on the power that the EV battery supplies or absorbs, so the SOC profile changes based on how intensely and at which moment the battery is charged and discharged. Moreover, this thesis wants to base its results on realistic scenarios, in order to provide simulations for real life applications.
Therefore, three different scenarios are created to show the impact of parameters on battery degradation while providing realistic SOC curves of an electric vehicle with and without V2H.

The assumptions on all scenarios share the same pattern:

- Weekdays
    - Charge car: 06:00 to 07:00
    - Driving: 07:30 to 08:00 / 17:00 to 17:30
    - Peak shaving: 07:00 to 07:30 / 17:30 to 20:00
- Weekends

  - Saturday: Driving: 18:00 to 18:30 / 23:00 to 23:30
  - Sunday: no vehicle usage

From these assumptions, three scenarios differ from each other:

- **CASE 1 - Charge 6/7:** The vehicle is charged every day before commuting to work. The objective is to understand the impact of wanting the car to be at its maximum SOC before leaving to work, which leads to low SOC window and high average SOC.
- **CASE 2 - Charge 2/7:** The vehicle is charged twice a week. The objective is to understand the impact of changing the charging habit, choosing to drain the battery for a longer time. This approach shows the effect on increasing the SOC window and decreasing the average SOC.
- **CASE 3 - Charge 2/7 + remote work:** The vehicle is charged twice a week, but it also provides peak shaving for two entire days in the limited time. This scenario aims to increase the probability of cutting high power peaks, to extend peak shaving to longer periods of time and to add more savings to the bill.

An optimized scenario is implemented based on the research developed by Wikner et al. [2], where they suggest a ΔSOC of 35% at a low SOC to decrease the ageing process. Even if the data used are different from the data used in this thesis, the concept has been found relevant and Case 2 has been implemented. This optimization shows the importance of keeping the battery at a low SOC to prolong its lifetime.

4

Analysis

The data used in each simulation relates to the household consumption, driving cycles, and grid frequency.

First, power consumption of the household is referred to a residential house in Gothenburg with district heating, which consumptions have been multiplied by 3 to work with higher peaks and loads. The residents are two semi-elderly persons. The power data accounts for 2024 consumption with 15-minutes time interval. The house has 16A fuse protection and 14kW is maximum allowable power, while 4kW is the practice maximum power.
Second, driving cycles are taken from the Worldwide harmonized Light vehicle Test Procedure (WLTP) which shows the power profile of the battery of the EV in 30-minutes ride at different driving styles. The BEV considered has a usable capacity of 80 kWh, voltage of 800 V and bidirectional charger of 22kW, with 3-phase 16A current. According to [20], the investment cost of a lithium-ion battery with LFP chemistry is $99/kWh so 920 SEK/kWh will be taken for degradation cost analysis.
Finally, the grid frequency is related to 2022 data of the Nordic synchronous area.
For a long term analysis with the available sources, the data will be repeated for 10 years.

4.1 Analysis with and without V2H

The impact of V2X is first analyzed by peak shaving with V2H and the results for each scenario will be shown.

4.1.1 Case 1 - Charge 6/7

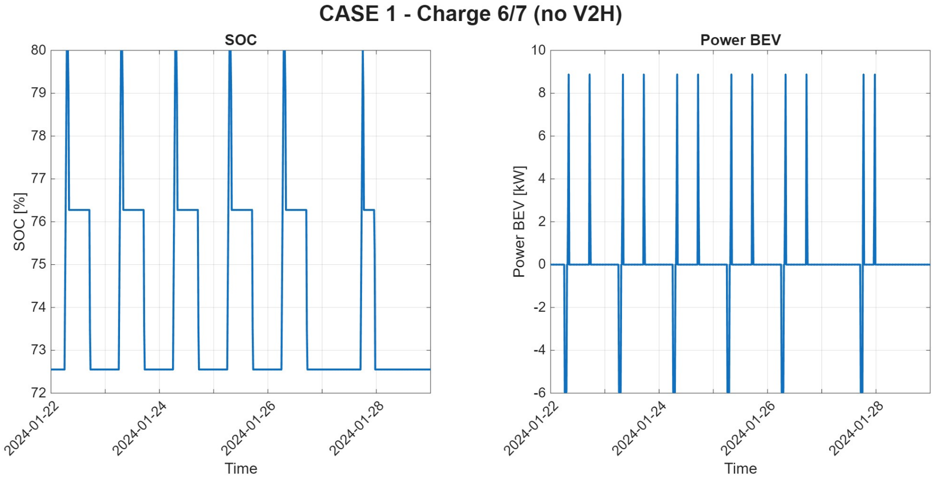

Figure 4.1: Case 1 without V2H: SOC profile (on the left) and BEV power profile (on the right)

For Case 1, the SOC profile in Figure 4.1 shows how the electric vehicle battery cycles during a week in January, precisely from Monday 22 January to Sunday 28. The month of January has been chosen because of the highest peaks throughout the year, and the considered time period will also be applied in the next analysis.

The charging is always performed at 06:00 before the driver commutes to work, so the battery can be stored at the lowest SOC for longer periods of time at night. The discharge is only related to the driving, since no peak shaving is performed yet.

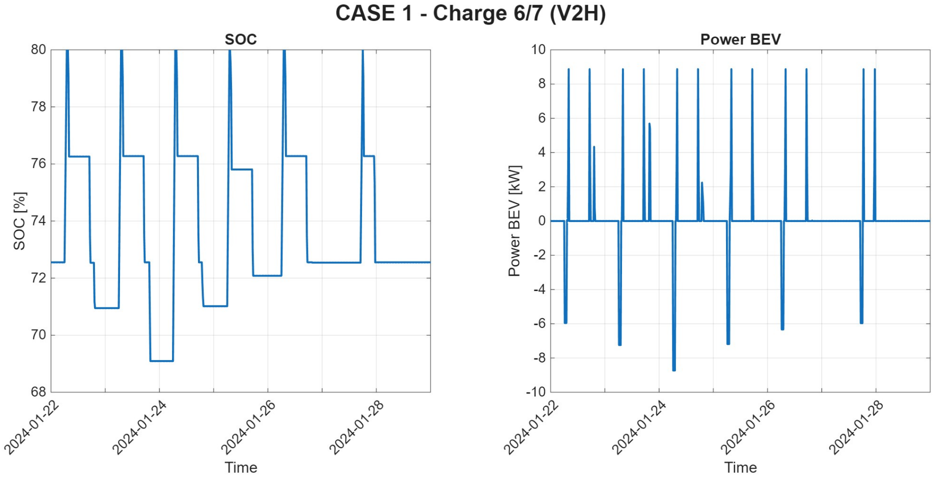

Figure 4.2: Case 1 with V2H: SOC profile (on the left) and BEV power profile (on the right)

Figure 4.2 represents the same assumptions as in Figure 4.1, but peak shaving has

been enabled. This allows to compare the same case with and without V2H and to perform an analysis on both sets of parameters.
An illustrative comparison is shown in Figure 4.3.

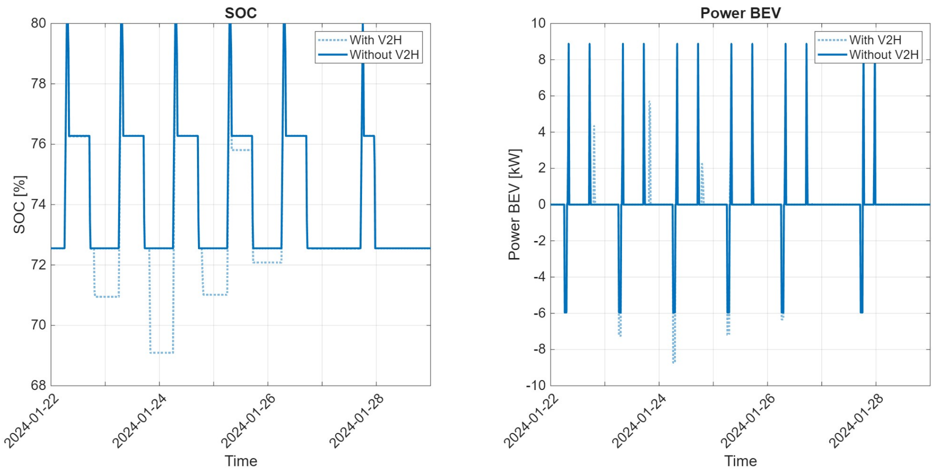

Figure 4.3: Case 1: Comparison with and without V2H

In Case 1, the total capacity loss is 16.11% after peak shaving and 16.61% before peak shaving, while it is around 5.3% in both scenarios during the first year. Figure 4.4 shows the evolution of calendar and cycling ageing over 10 years, with and without V2H. Calendar ageing is the main responsible for battery degradation because a high SOC is consistent for the whole simulation. Cycling ageing is smaller by two orders of magnitude compared to calendar ageing. It depends on the SOC window (ΔSOC), the mean value of SOC (SOC_{mean}) and Equivalent Full Cycles (EFC).

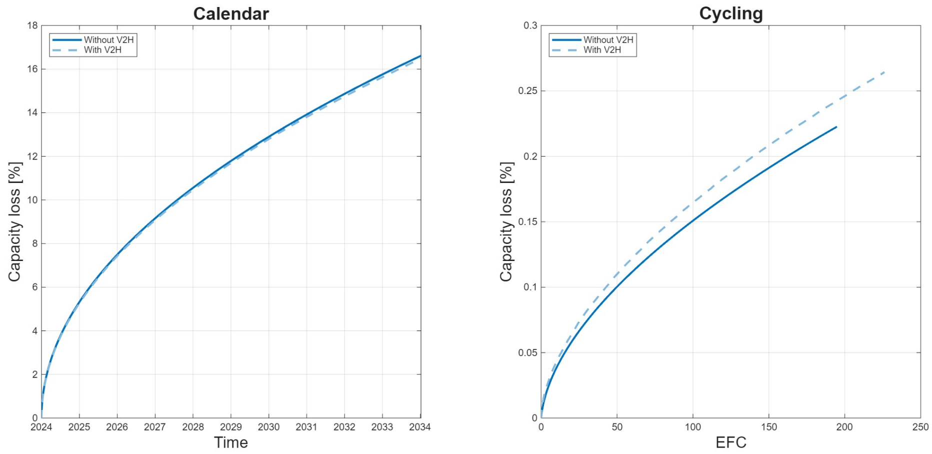

Figure 4.4: Case 1: Comparison in ageing with and without V2H

- ΔSOC is narrow and stable without V2H and slightly higher with V2H, since it depends on the number of peaks shaved;

- SOC$_{mean}$ is very close to the maximum SOC = 80%, which increases significantly the total ageing.;

- EFC increases with peak shaving due to the additional number of cycles needed to supply the service, but the absolute number is relatively low because it never reaches the minimum SOC and it increases proportionally over 10 years.

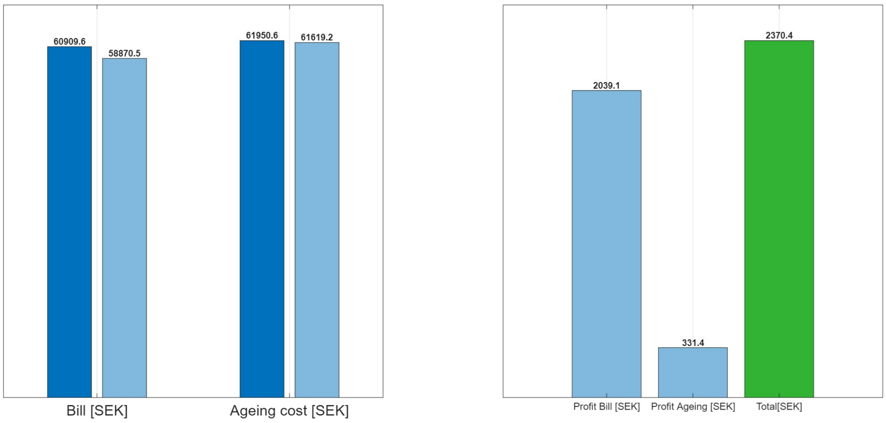

Figure 4.5: Case 1: On the left, bill and ageing costs are compared (dark blue without V2H, ligh blue with V2H). On the righ, the profit from bill and ageing after V2H are added together to get the total profit (green).

On the economic side, peak shaving enables profit both in ageing and in the bill. Over 10 years, the driver earns a total of 2370 SEK when the EV is charged for six times a week. Comparing scenarios with and without V2H, the economic revenue comes primarily from the bill savings after peak shaving. Moreover, even if the profit from ageing is not high, applying V2H does not have a negative impact on degradation costs. In Figure 4.5 the histograms show the difference in absolute profits.

4.1.2 Case 2 - Charge 2/7

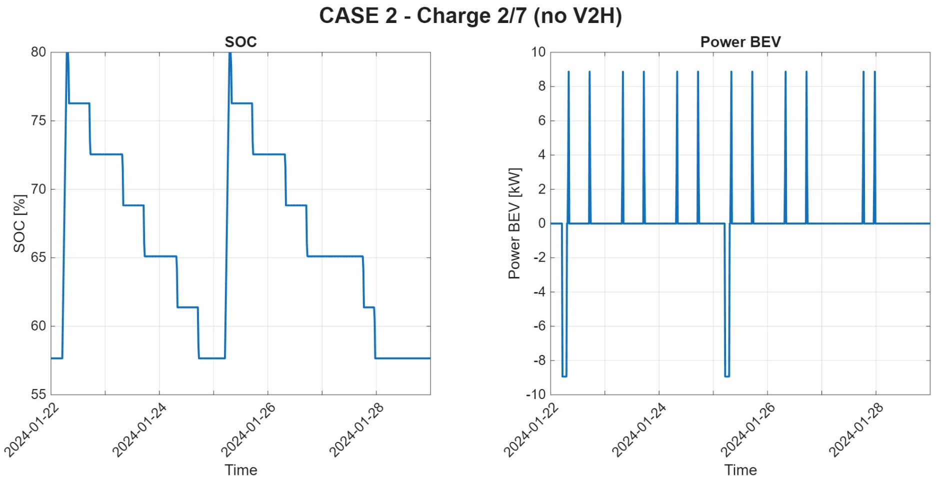

Figure 4.6: Case 2 without V2H: SOC profile (on the left) and BEV power profile (on the right)

For Case 2, Figure 4.6 shows how the battery SOC changes if it charges only twice a day, precisely on Mondays and on Thursdays, and how much more power is needed to recharge the car. This scenario still has not introduced peak shaving and the behavior is predictable.

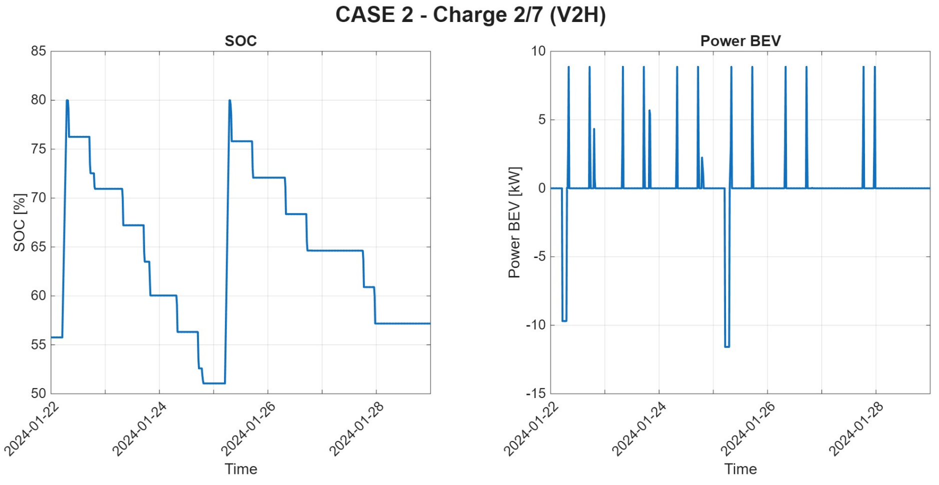

Figure 4.7: Case 2 with V2H: SOC profile (on the left) and BEV power profile (on the right)

In Figure 4.2, the same scenario in Figure 4.6 is implemented but it has also been performed V2H. This results in different patterns throughout the day, and additional power supply during the day. In Figure **??**

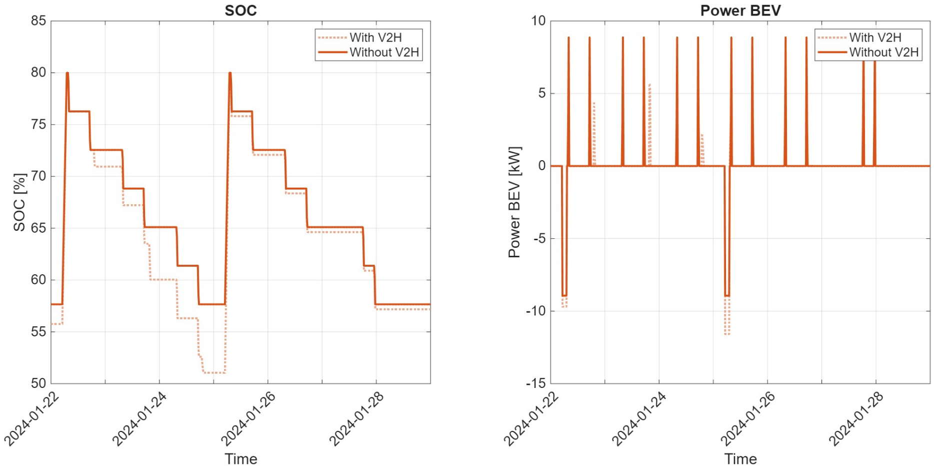

Figure 4.8: Case 2: Comparison with and without V2H

In Case 2, the EV charges twice a week, precisely on Monday and Thursday, so that the battery drains for longer and gets closer to the minimum SOC level.

Without V2H, proportions in calendar and cycling ageing are constant. Calendar ageing decreased by more than 1% after 10 years because of the SOC around 68%. Cycling ageing is higher because ΔSOC and EFC are also higher compared to Case 1, while SOC decreased but with a lower impact than EFC.

With V2H, results are shown for two approaches during peak shaving: "Light", where peaks are cut to 6kW, and "Hard", where the peaks are cut to 2kW. In Figure 4.9 the household consumption is affected by light peak shaving, while in Figure 4.10 hard peak shaving is applied. It can be noticed that not every peak is cut when the power limit is imposed: the reason why relies on tariff time restrictions and the EV availability at home. However, in the current conditions, light peak shaving reduces the cycling ageing by 12% while hard peak shaving reduces calendar ageing by 2.6%, even if in absolute values both decreased -0.1%. Between the two, the "hard" approach will be used for comparisons, since it shows a lower degradation overall. In fact, compared to Case 1, removing 4 charges a week reduces calendar ageing from 16.11% to 14.94%. In Figure 4.11 the difference between the calendar and cycling ageing is displayed, comparing with and without V2H scenarios.

Economically, hard peak shaving increases profits by up to 3854 SEK after 10 years. Compared to the profile without V2H, both the bill and the ageing decrease, by 3.3% in the hard approach and 1% with the light one. In Case 2, ageing costs decreased after peak shaving, so that total profit is comparable to the savings on the bill after 10 years.

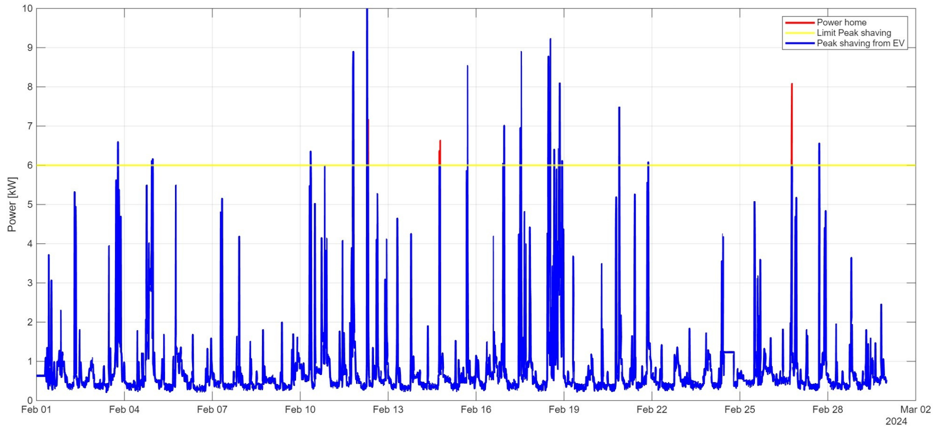

Figure 4.9: Case 2 with V2H: Power consumption with light peak shaving at 6kW.

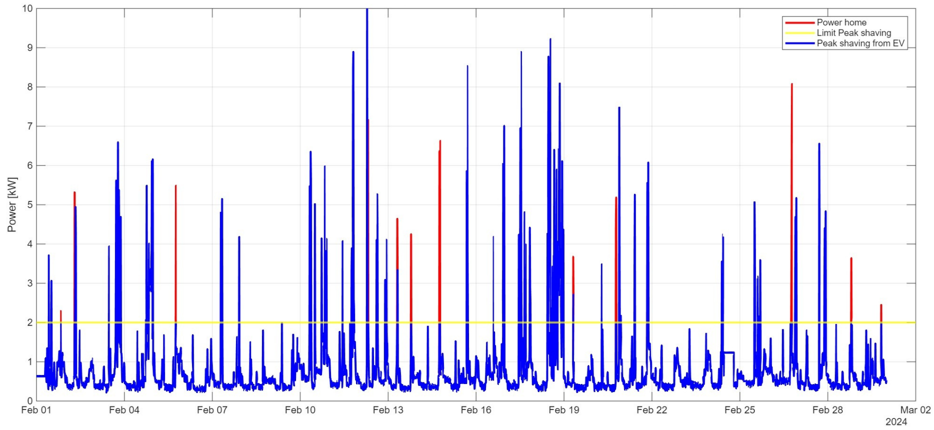

Figure 4.10: Case 2 with V2H: Power consumption with hard peak shaving at 2kW.

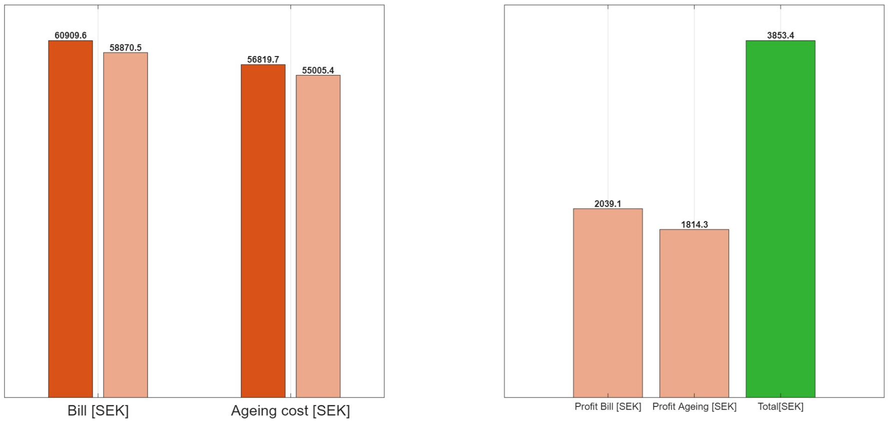

Figure 4.12: Case 2: On the left, bill and ageing costs are compared (dark red without V2H, light red with V2H). On the right, the profit from bill and ageing after V2H are added together to get the total profit (green).

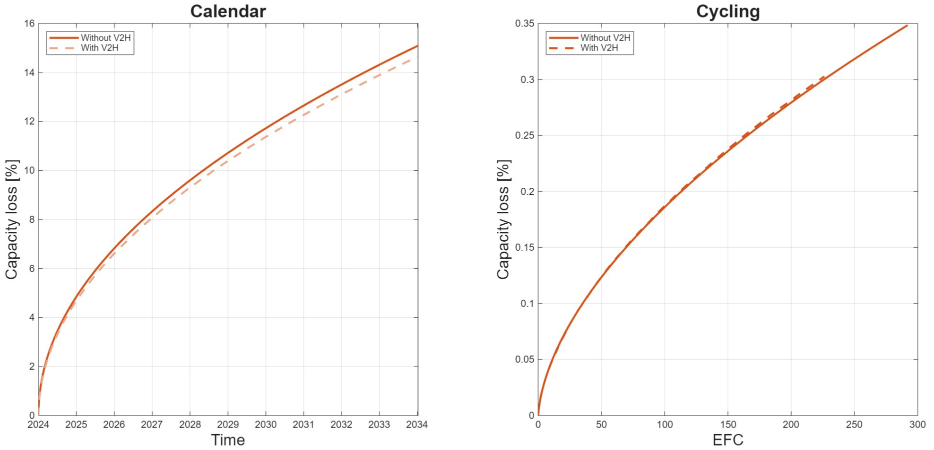

Figure 4.11: Case 2: Comparison in ageing with and without V2H

As it can be noticed, the majority of power peaks are not shaved because of the restrictions set by the model. To truly understand the impact that peak shaving has on the power fee, a comparison will be developed. In fact, three different contributions of the power fee have been extracted from the bill of Case 2: the first power fee is extracted from the bill before peak shaving, the second from the bill after peak shaving and the third considers the best case scenario.

The third case implemented assumes no constrictions applied. This means that the battery provides all the power over the power limit set for peak shaving and, consequently, the grid supply the demanded power until 2 kW. In Figure 4.13 the outcome of continuous peak shaving is showed.

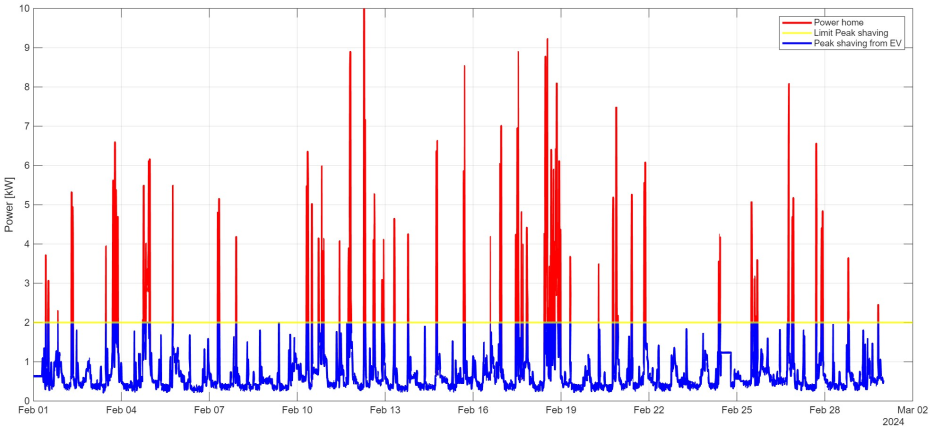

Figure 4.13: Peak shaving with no constraints.

After having considered only power fee contributions on the bill, the results shows that half of the payments due to the power peaks can be cut from the bill if peak shaving is performed all the time. Results are shown in Figure 4.14.

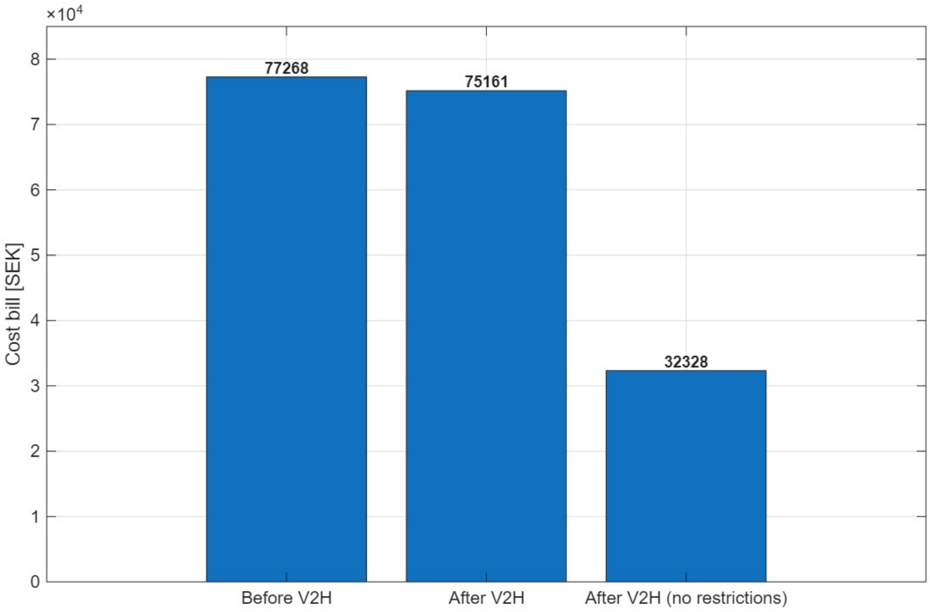

Figure 4.14: Comparison of Power fees in the three cases.

4.1.3 Case 3 - Charge 2/7 + Work From Home

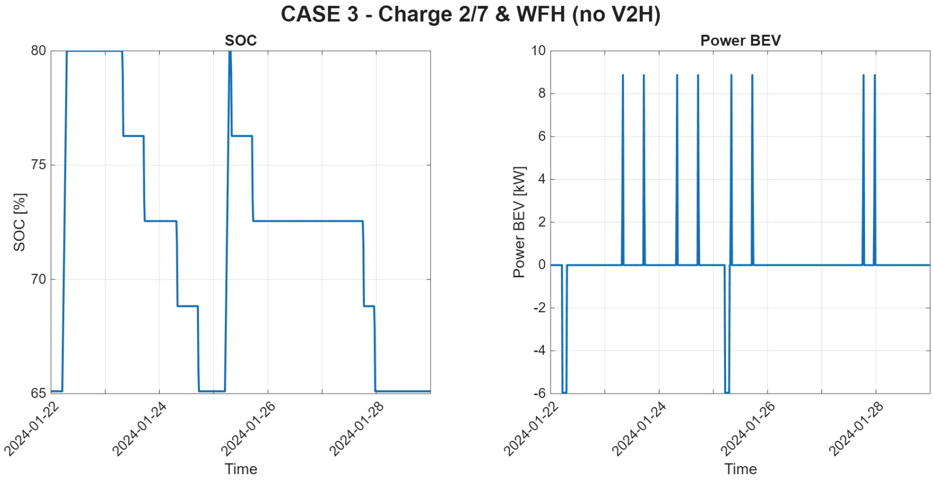

Figure 4.15: Case 3 without V2H: SOC profile (on the left) and BEV power profile (on the right)

For Case 3, in Figure 4.15 no peak shaving is activated but it can be noticed how the SOC and power behave. In fact, two days a week, the driver keeps the vehicle at home and it can be seen from the long flat curves that SOC presents. Power only follows the driving cycles when discharging and the set hour when charging.

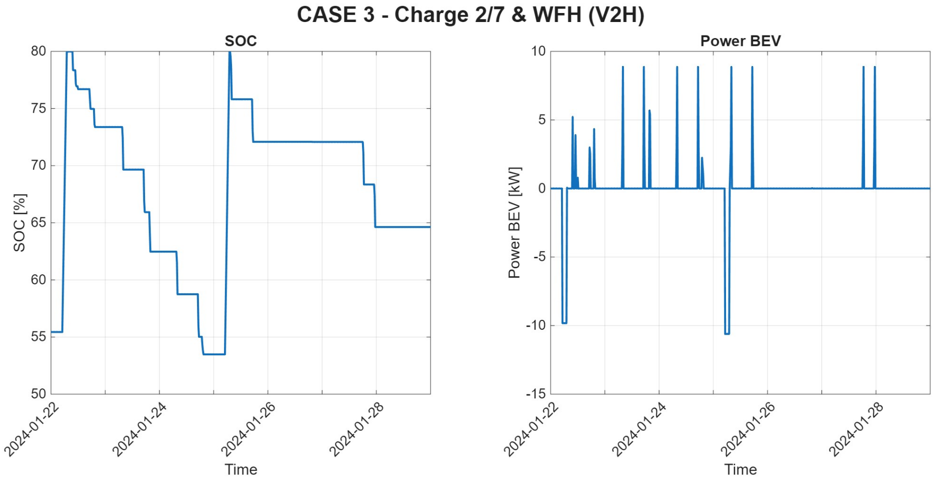

Figure 4.16: Case 3 with V2H: SOC profile (on the left) and BEV power profile (on the right)

In Figure 4.16, peak shaving is activated and it can be noticed from both SOC and power profiles: SOC follows a stochastic pattern based on the height of the peaks it needs to cut off; power profile presents peaks of different heights, which are equal to the difference between the required power from householding loads and the power limit set for peak shaving. A visual comparison is shown in Figure 4.17. The amount of peaks cut increased from Case 2 and it can be seen from the comparison between Figure 4.10 and Figure 4.18.

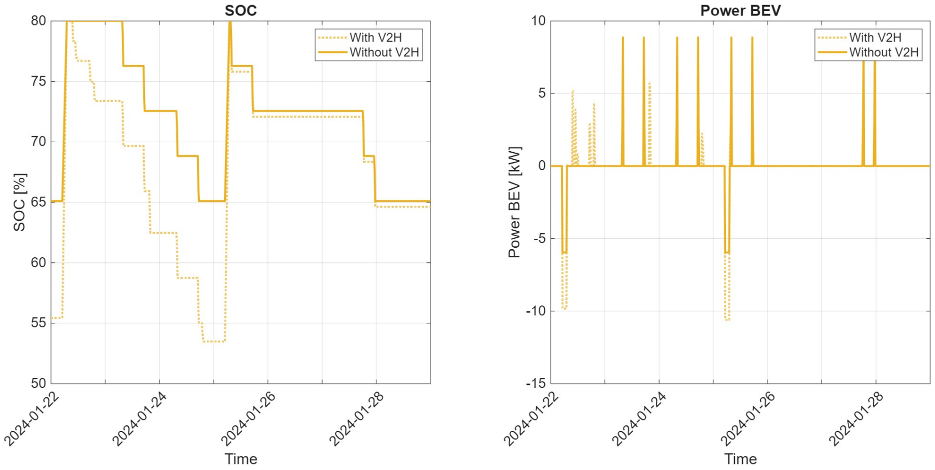

Figure 4.17: Case 3: Comparison with and without V2H

In Case 3, the battery degradation goes from 4.94% to 5.27% if the EV is used only for driving and considering the first year. SOC presents high values when the driver is working from home, therefore the calendar ageing increases. When V2H is

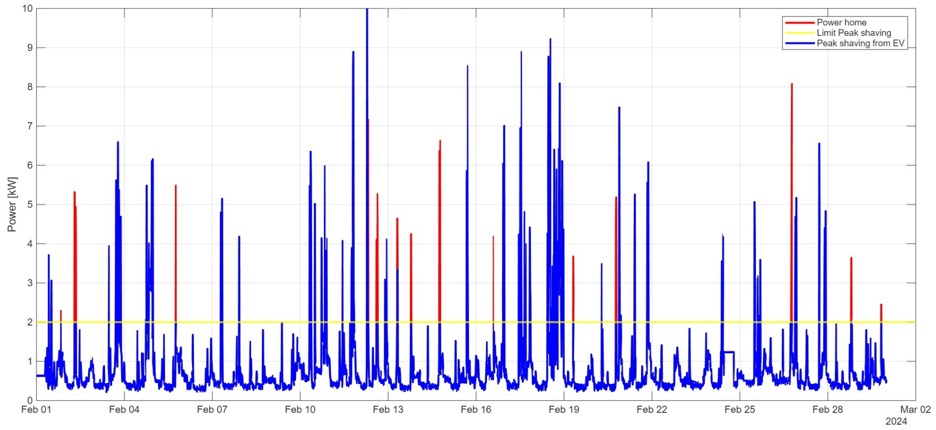

Figure 4.18: Case 2 with V2H and "work from home": Power consumption with hard peak shaving at 2kW.

enabled, ΔSOC increases but SOC is lower and it affects both calendar and cycling ageing. Over 10 years, the total capacity loss will be 15.66%, which is higher than Case 2 and lower than Case 1. In Figure 4.19, the ageing evolution of Case 3 is shown in both calendar and cycling ageing, with and without V2H.

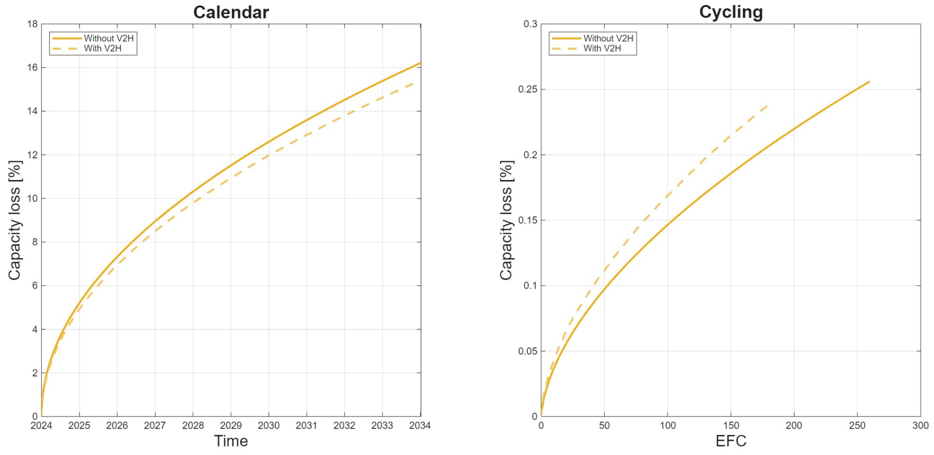

Figure 4.19: Case 3: Comparison in ageing with and without V2H

Case 3 has been implemented to get more chances to cut power peaks at the set value 2kW. In fact, in this scenario it is found that the bill is decreased in cost by -5.3% and ageing by -4.9%. The total profit for Case 3 is 6245 SEK, while the absolute cost of the bill and the cost of the ageing are comparable.

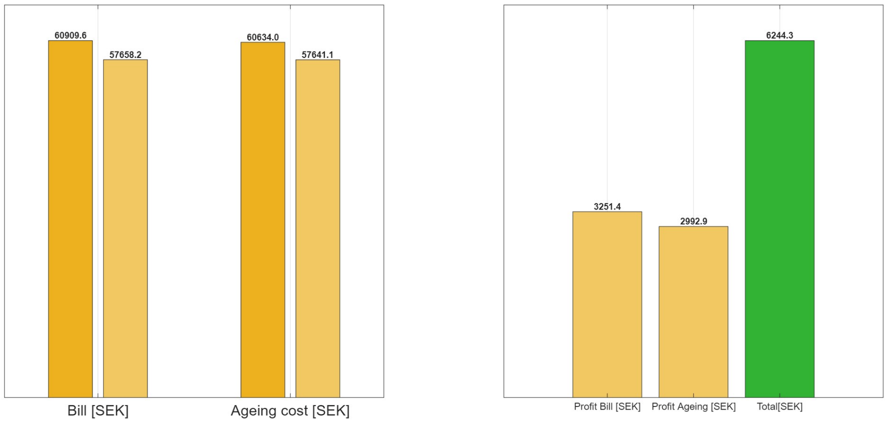

Figure 4.20: Case 3: On the left, bill and ageing costs are compared (dark yellow without V2H, light yellow with V2H). On the right, the profit from bill and ageing after V2H are added together to get the total profit (green).

4.1.4 Comparative analysis

After studying the three cases, the outcome shows that any form of V2H compared with the same scenario without V2H slows down BEV degradation. Losses in the first year are high but the analysis gives reasonable results after 10 years. For this reason, the analysis will follow up with a study directly after 10 years.

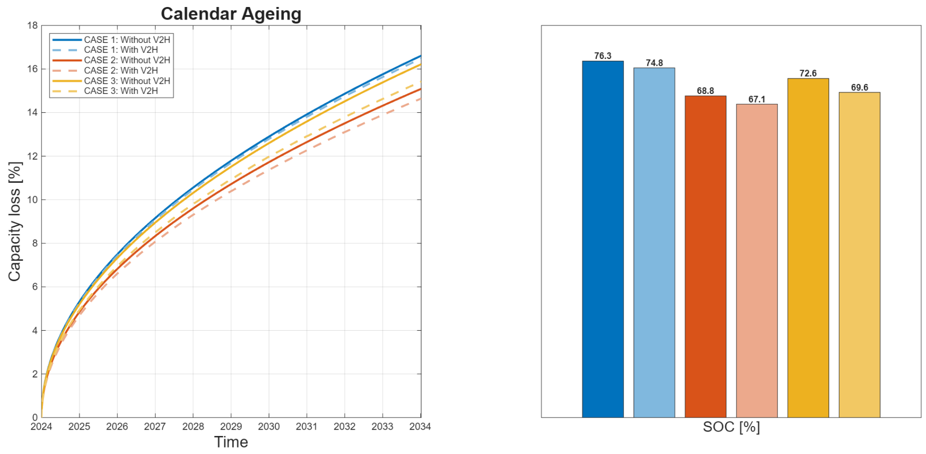

Figure 4.21: Calendar ageing: Comparison of the three cases.

In Figure 4.21, the three cases are joined in the respective graph. As previously mentioned, calendar ageing is strongly related to the SOC level across the simulation. In fact, the capacity loss is proportional to the SOC average value in both with and without V2H scenarios.

- Case 1 reflects the highest capacity loss and, even when V2H is activated, the calendar ageing does not substantially improve. With V2H the capacity loss is 16.11%, without V2H 16.61%;
- Case 2 reflects the lowest capacity loss and, consequently, V2H scenario is the scenario with the lowest capacity loss. With V2H the capacity loss is 14.64%, without V2H 15.09%;
- Case 3 showed losses in between Case 1 and Case 2, but it also provides the highest gap from the original scenario when peak shaving has been activated. With V2H the capacity loss is 15.42%, without V2H 16.22%;

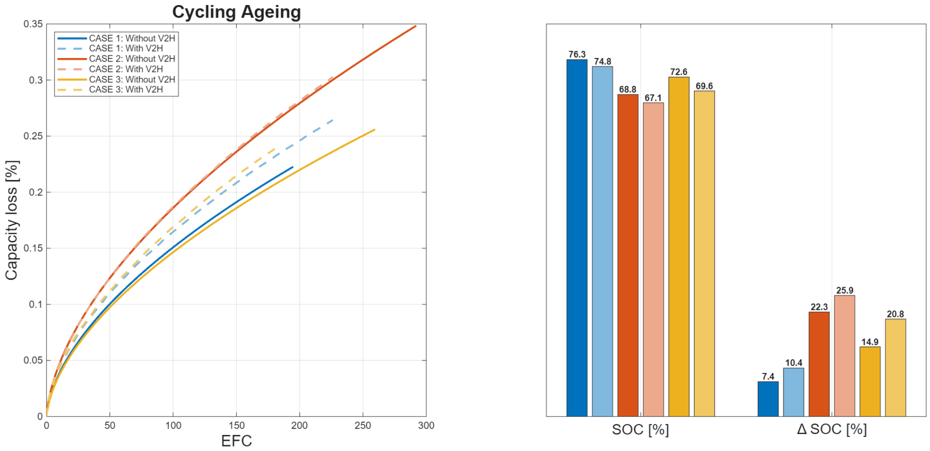

Figure 4.22: Cycling ageing: Comparison of the three cases.

Compared to calendar ageing, cycling ageing does not find a simple and straight pattern, as it can be noticed in Figure 4.22. In fact, cycling ageing is dependent not only on SOC, but also on ΔSOC and EFC. In particular, as ΔSOC increases, SOC level decreases. This is an expected result, since deeper and prolonged discharges of the battery can increase the SOC window from 7.4% to 25.9%. Therefore, always keeping the maximum SOC at 80%, the average SOC decreases as the window gets wider, but not substantially it goes from 76.3% to 67.1%.

To determine which parameter has the highest impact in this case study, a further analysis will follow. The calculation of cycling ageing is mostly dependent on the three parameters SOC, ΔSOC and EFC. However, parameters evolution depends on the fitted parameters from the experimental analysis. In fact:

- ΔSOC depends on a = 0.1731;
- SOC_{mean} depends on m = 0.2886;
- EFC depends on z = 0.5758.

This analysis focuses on the impact that each parameter has in cycling ageing, based on the rate of variation between the scenario with and without V2H. First, the result from V2H will be divided by the result without V2H; secondly, the impact will be weighted with the fitted parameter; finally, each Rate-Of-Change will be analysed and compared with the three cases. The expression used can be simplified by

$$\textbf{Rate-Of-Change} = \left(\frac{\textbf{Parameter with V2H}}{\textbf{Parameter without V2H}}\right)^{\textbf{fitted parameter}}$$

For instance, an extended example is developed for Case 1.

- without V2H: SOC = 76.3%, ΔSOC = 7.4%, EFC = 194
- with V2H: SOC = 74.8%, ΔSOC = 10.4%, EFC = 226

The effect of SOC is expressed as
$SOC_{effect} = (\frac{74.8}{76.3})^{0.1731} = -0.6\%$

This expression has been applied for every case and the effects of each parameter are shown below

Case 1
- ΔSOC = +6%
- SOC = -0.6%
- EFC = +9%

Case 2
- ΔSOC = +2.6%
- SOC = -0.7%
- EFC = -14.6%

Case 3
- ΔSOC = +5.9%
- SOC = -1.2%
- EFC = -19.5%

As it can be noticed, the SOC has the lowest impact on the cycling ageing, while the parameters that impacted most the ageing are ΔSOC and EFC. In particular, EFC is the most influent parameter.

For each specific case, results can be summarized:
- Case 1 shows an increase in cycling ageing with V2H. With V2H the capacity loss is 0.281%, without V2H 0.223%;
- Case 2 reflects the highest capacity loss but V2H decreases the cycling ageing over 10 years. With V2H the capacity loss is 0.303%, without V2H 0.348%;
- Case 3 provides similar results to Case 1. With V2H the capacity loss is 0.241%, without V2H 0.256%;

Taking into account both calendar and cycling ageing, the total capacity loss is always within EOL limit of 20% but the profit is not significant. At this point, it can be questionable whether to provide the service or not.

4.2 Optimization

In the next step, ageing and V2H are both optimized to increase the net profit. On the one hand, the objective is to substantially decrease the degradation costs, and on the other hand, the aim is to increase the profit from V2X more. Based on previous statements, conducting the analysis directly over 10 years is considered reasonable; therefore, results below follow this approach.

4.2.1 Degradation costs optimization

The improvement to decrease capacity losses is directly affecting the degradation cost. It means that decreasing cycling and calendar ageing, the net profit will increase. This optimization refers to [2], where it is suggested to keep the SOC within 15% to 50% to prolong battery lifetime.
The comparison will consider Case 2 with “hard” peak shaving and 2/7 charge. Results display the strong impact of SOC in calendar ageing: it goes from 14.64% to 8.5% after 10 years of utilization. By only charging the car to 50% and ensuring it doesn’t discharge over 15%, the battery lifetime increases by 6%. Cycling ageing is affected by a slight decrease in capacity loss, since the SOC results in half of the value compared to the original simulation.

While the bill is not affected by it, degradation ageing decreases by 41.5%. The decrease can be quantified by the difference between degradation costs before and after the optimization. This results in 22814 SEK profit after 10 years, together with a longer BEV lifetime.

Figure 4.23 summarizes the techno-economic analysis. For the SOC profile, the amount of charging and discharging did not change but the only difference has been a slighted SOC window to the lower limit. This results in a wider gap in the ageing graph between the same case before and after the optimization.

4.2.2 Economic optimization

The economical optimization aims to increase the profit by introducing FCR-D up service combined with V2H. Even in this case, the comparison will consider Case 2 with “hard” peak shaving and 2/7 charge. From the results, the degradation cost is not increasing significantly, but the profit from FCR-Dup is over 146 kSEK after 10 years.

Figure 4.24 illustrate the results of the cost optimization. Both scenarios represents Case 2 with V2H but in one of them also V2G service is provided. The V2G scenario is not visible from the graph on the left because FCR-D up does not provide substantial variation on the SOC profile. In fact, it is a service that is rarely activated and the revenue is mainly dependent by the capacity remuneration. The average

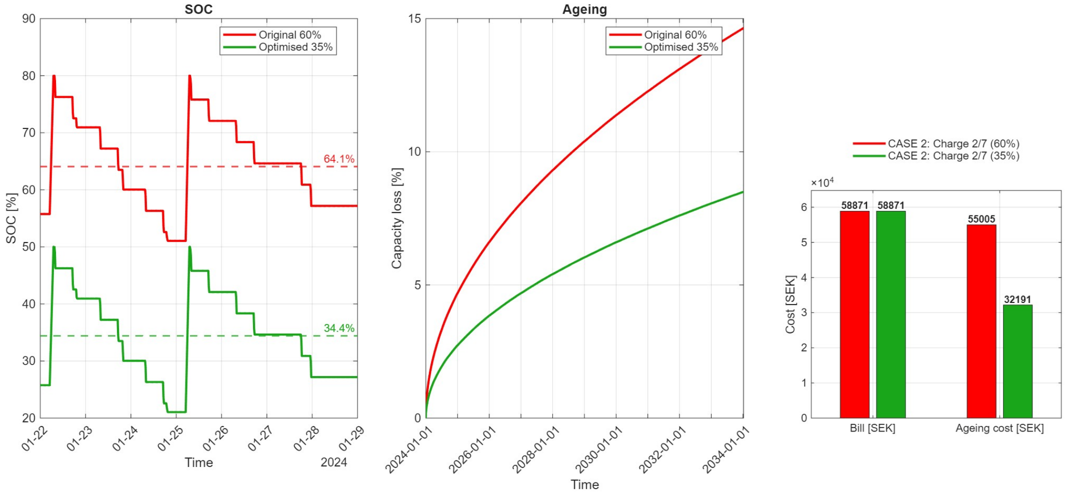

Figure 4.23: Degradation cost optimization: Comparison in SOC, ageing and profit.

SOC is slightly better but it does not influence much on ageing, as visible in the middle graph. On the right, instead, the profit is extremely evident. In this case, both bill and ageing cost are stable but the highest benefits comes from the power bid during the night and office hours.

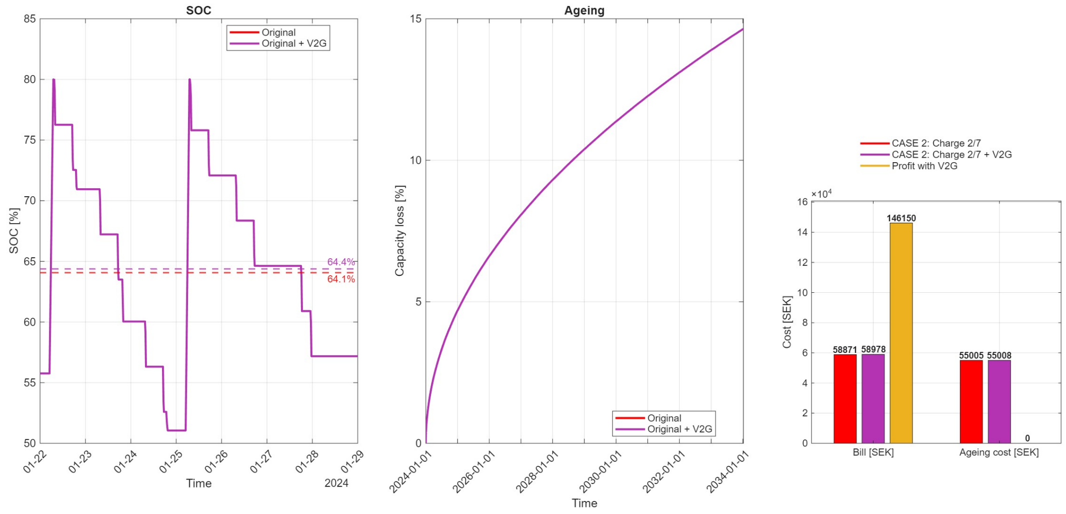

Figure 4.24: Economic optimization: Comparison in SOC, ageing and profit.

4.3 Environmental considerations

Battery Electric Vehicles are considered sustainable because they have no impact on carbon footprint when used in a vehicle. Instead, the environmental impact can be relevant if considering the EOL. A bigger battery pack involves bigger waste in the demanufacturing process.

In this subsection, a battery pack of 50kWh will be taken into account. This choice is beneficial both for the environment, for a lower impact after EOL, and for the case of study, to provide another interesting comparison.

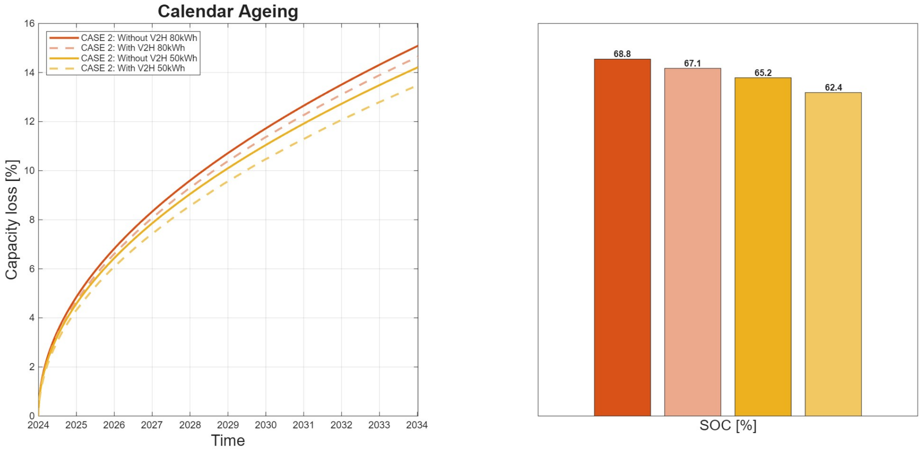

Figure 4.25: Comparison on capacities: calendar ageing

In Figure 4.25, the calendar ageing decreased in both with and without V2H scenarios. Over 10 years, calendar ageing is 14.21% without V2H and 13.49% with V2H. As previously mentioned, the SOC has a direct impact on calendar ageing and also in this comparison, a lower SOC brought to a lower degradation.

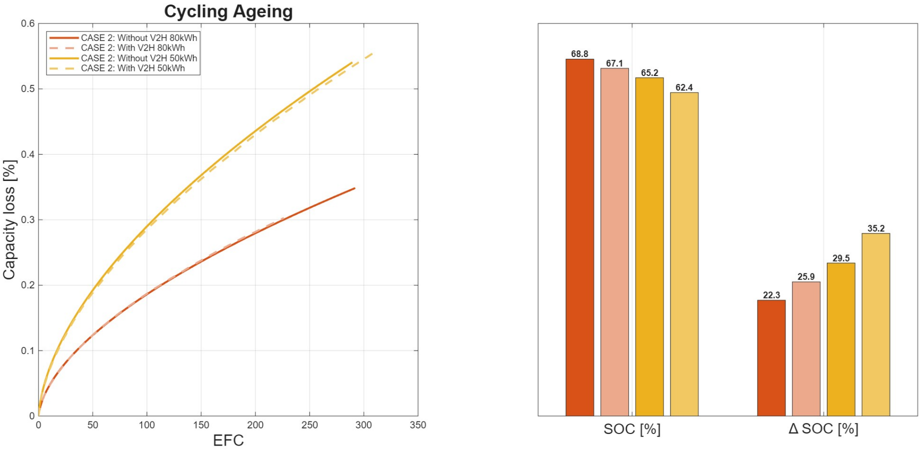

Figure 4.26: Comparison on capacities: cycling ageing

In Figure 4.26, the graph for cycling ageing shows an increase in ageing to 0.554%

with V2H and 0.541% without V2H. The difference between with and without peak shaving are not relevant in both cases but the increase in cycles is expected, since a smaller battery is doing the same work as the original battery of 80kWh of capacity.

From the economic perspective, the degradation costs are low while the bill is comparable with the original case. Without V2H, the bill is 60910 SEK and the degradation cost 33941 SEK. With V2H, the degradation goes down to 32291 SEK and the bill is 58871 SEK. Enven in this comparison, we can see that peak shaving has a positive impact on both bill and ageing, respectively with a profit of 2039 SEK and 1650 SEK, with a total profit of 3689 SEK.

5

Conclusion

5.1 Results from present work

This thesis evaluated the techno-economic analysis on EV batteries with and without providing V2H services and it proposes two solutions to increase profitability.
Comparing the results for 1 year and 10 years, the drop in capacity loss in the first year is around 30% of the total degradation. This is due to the semi-empirical ageing model that follows the power-law evolution, which results in capacity loss within EOL limit on the 10th year.

In every scenario, providing V2H service to the household through the EV is more beneficial than keeping the same profile without V2H. In fact, peak shaving drains more energy from the battery, and the average SOC is lower.
Despite a slightly higher number of cycles, every scenario shows a lower SOC with V2H compared to the same scenario without V2H. Then, the semi-empirical ageing model is found to be extremely sensitive to calendar ageing; therefore, calendar ageing gives the strongest contribution to the decrease in overall capacity loss. The lower the SOC, the lower the calendar ageing.
Combining the two previous statements, every scenario with V2H service presents a lower calendar ageing so lower overall degradation compared to the scenario without V2H. It can be concluded that peak shaving with V2H improves battery lifetime regardless of the case, which leads to lower degradation costs, therefore also a small profit during BEV lifetime.

These results are confirmed by the analysis of the three scenarios listed: in Case 1 the EV is charged daily; in Case 2 it is charged twice a week; in Case 3 twice a week including two days of work from home.
First, results for Case 1 represent a profile with the highest mean SOC, narrowest SOC window and lowest number of cycles but after 10 years the total capacity loss stays within the defined EOL, around 16.83% without V2H and 16.39% with V2H. Peak shaving is not significantly affecting the degradation but it still gives a net profit of 3370 SEK over 10 years.
Secondly, Case 2 represents the profile with the lowest mean SOC, widest SOC window and number of cycles close to Case 1. The total degradation is 15.44% without V2H and 14.94% with V2H. Charging the car less times a week decreases the degradation and allows savings up to 3854 SEK.
Finally, Case 3 is collocated in between the two cases, but it presents the lowest num-

ber of cycles, which sets the lowest cycling ageing. The total degradation is 16.48% without V2H and 15.66% with V2H. Charging the car and working remotely twice a week enables savings up to 6245 SEK.

The three cases revealed good potential for the extension of battery lifetime, but it must be cost-effective to be minted in real life. Hence, two solutions are proposed to increase net profits.
In the first place, a window from 15% to 50% is found to be an efficient solution to reduce degradation costs. Capacity loss was reduced by 41.5% and the net profit increased to almost 23000 SEK. Then, the combination of V2H and V2G increased the profit to over 146000 SEK over 10 years of battery life.
Ultimately, this thesis shows that peak shaving alone slightly decreases both the household bill and the degradation costs related to the EV that provides V2H. Moreover, the net profit can be increased by solutions that reduce the average SOC or that combines V2H to V2G service as FCR-Dup. In Table 5.1, the summary of results discussed in Chapter 4 are shown.

Table 5.1: 10 years comparison across cases

	ΔQ_{cal}	ΔQ_{cyc}	ΔSOC	SOC	EFC	Bill SEK	Ageing
C1	16.11	0.28107	10.3651	74.8175	226.0557	58.871 (-3.3%) +2039	60.320 (-2.6%) +1631
C2 Hard	14.644	0.30269	25.8768	67.0616	226.2067	58.871 (-3.3%) +2039	55.005 (-3.2%) +1815
C3	15.423	0.2405	20.8331	69.5834	182.6370	57.658 (-5.3%) +3252	57.641 (-4.9%) +2993

5.2 Future work

This thesis analyses realistic SOC profiles to validate the semi-empirical ageing model. The profiles are based on a specific Goteborg Energy bill structure, which makes the study very specific. Further research could provide more scenarios with new DSOs tariffs or considering different housing types, in order to study the dependence of household power level on peak shaving cost-effectiveness.
Moreover, the experimental analysis for the semi-empirical ageing model has been carried out on LFP battery of 2.16 kWh, so future studies could test EV batteries for more accurate models in vehicle applications. Other battery typology such as solid-state batteries should be taken into account for future perspective.
In addition, results are averaged in 15 minutes so further works could introduce 1 second data for accurately estimate cycling ageing, when evaluating degradation through V2G. Finally, an environmental assessment should be done to understand the impact of BEV using life-cycle analysis and to consider second-life when reach-

ing EOL.

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