

# Investigation of Bi-Directional Charging Concepts

Design and evaluation in terms of economic profitability and environmental benefits

Bachelor's Thesis in Electrical Engineering

MARCUS ALENVRET  
ABHAY CHOUHAN  
TYRA DERNFALK  
AXEL NILSSON  
ADAM SPREITZ



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MARCUS ALENVRET

ABHAY CHOUHAN

TYRA DERNFALK

AXEL NILSSON

ADAM SPREITZ



**CHALMERS**  
UNIVERSITY OF TECHNOLOGY

Department of Electrical Engineering  
Chalmers University of Technology  
Gothenburg, Sweden 2024

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## **Abstract**

This study aims to explore different concepts of Bi-Directional charging and assess its potential benefits across various scenarios. This research analyzes four distinct cases: Vehicle to Grid, Vessel to Grid, Vehicle to Home, and Bi-Directional chargers on an electric ferry. It examines user patterns, implementation details, economic factors, and environmental impacts associated with this technology. Although the initial investment in Bi-Directional charging is generally substantial, it proves to be profitable across a broad spectrum of applications and in enclosed systems, benefiting both individuals and businesses. Regarding battery degradation, findings suggest that the effects of employing Bi-Directional charging in the cases are mainly minimal. The majority of the scenarios demonstrates a more effective energy utilization through the batteries of electric vehicles.

Keywords: Bi-Directional Charging, Vehicle to grid, Vehicle to home, Vessel to grid, Vessel to marina, electric ferries, electrification of ferries, ancillary services, battery degradation, electric vehicles

## Sammanfattning

Denna studie syftar till att utforska olika koncept av dubbelriktad laddning och bedöma dess potentiella fördelar i olika scenarier. Studien analyserar fyra distinkta fall: "Vehicle to Grid", "Vessel to Grid", "Vehicle to Home" och ett fall där dubbelriktade laddare är implementerade på en elektrisk färja. Den granskar användarmönster, implementeringsdetaljer, ekonomiska faktorer och miljöpåverkan associerad med denna teknik. Trots att den initiala investeringen för dubbelriktad laddning generellt sett är betydande, visar det sig vara lönsamt över ett brett spektrum av tillämpningar och i slutna system, vilket gynnar både individer och företag. När det gäller batteridegradering, tyder resultaten på att effekterna av att använda dubbelriktad laddning i fallen huvudsakligen är minimala. De flesta scenarier visar på en mer effektiv energianvändning genom elbilsbatterier.

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Aim . . . . .	1
1.2	Boundaries and Scope . . . . .	1
<b>2</b>	<b>Important Theoretical Concepts behind Bi-Directional Charging and Other Important Aspects</b>	<b>2</b>
2.1	Theory behind Bi-Directional Charging and Vehicle to Everything . . . . .	2
2.2	Theory behind Battery Degradation . . . . .	3
2.2.1	Empirical Models . . . . .	3
2.2.2	Combining the Models using Eulers Method . . . . .	4
2.3	Theory behind Grid Stability Services . . . . .	5
2.3.1	Electricity System in Sweden . . . . .	5
2.3.2	Energy Balance Markets . . . . .	6
2.3.3	How to Contribute with Ancillary Services . . . . .	7
2.4	Theory behind Load Balancing . . . . .	9
2.4.1	Why Use Dynamic Load Balancing? . . . . .	9
2.5	Theory behind Market Changes and Price Evaluation . . . . .	10
<b>3</b>	<b>General Methodology</b>	<b>13</b>
3.1	Introduction to the Cases . . . . .	14
3.1.1	Case 1: Vehicle to Grid . . . . .	14
3.1.2	Case 2: Vehicle to Home . . . . .	14
3.1.3	Case 3: Vessel to Grid . . . . .	15
3.1.4	Case 4: Electric Ferries . . . . .	16
<b>4</b>	<b>Foundational Outcomes Common to all Cases</b>	<b>17</b>
4.1	Finalized Battery Aging Model . . . . .	17
4.1.1	Battery Aging Models . . . . .	17
4.1.2	Combining the Empirical Models . . . . .	17
4.1.3	Determining the Value of each Degradation Factor . . . . .	17
4.1.4	Calculating Full Equivalent Cycles . . . . .	18
4.1.5	Different Uses throughout the Cases . . . . .	18
4.2	General Result from Ancillary Services . . . . .	19
4.2.1	Introduction to Ancillary Services . . . . .	19
4.2.2	Work Process to Estimate Earnings from Ancillary Services . . . . .	19
4.2.3	Data of Historical Compensation for Ancillary Services . . . . .	20
4.2.4	Standard Deviation of Daily Compensation from Aggregator . . . . .	22
4.2.5	Monthly Correlation Analysis Between Different Sources . . . . .	25
4.2.6	General Compensation for Ancillary Services Related to the Cases . . . . .	26
4.2.7	Analyze of Possible Revenue from Ancillary Services . . . . .	27
4.2.8	Summary of Chapter regarding result from ancillary services . . . . .	29
<b>5</b>	<b>Case Results</b>	<b>30</b>
5.1	Case 1: Vehicle to Grid . . . . .	30
5.1.1	Work Process . . . . .	30
5.1.2	User Pattern for Electric Vehicle User . . . . .	30
5.1.3	Example Users and their compatibility to Vehicle to Grid . . . . .	34
5.1.4	Return for Ancillary Services . . . . .	36
5.1.5	Vehicle to Grid Impact on Vehicle Battery Degradation . . . . .	40
5.1.6	Market for Vehicle to Grid . . . . .	43
5.1.7	Summary of Case 1: Vehicle to Grid . . . . .	44
5.2	Case 2: Vehicle to Home . . . . .	45
5.2.1	Work Process . . . . .	45
5.2.2	Technical Specification for Simulation Model . . . . .	46
5.2.3	Economical Specification for Business Model . . . . .	47

5.2.4	With and Without Bi-Directional Charging during Summer . . . . .	48
5.2.5	With and Without Bi-directional Charging during Winter . . . . .	50
5.2.6	Business Model during January . . . . .	52
5.2.7	Summary of Case 2: Vehicle to Home . . . . .	53
5.3	Case 3: Vessel to Grid . . . . .	54
5.3.1	Work Process . . . . .	54
5.3.2	Electrification of the Swedish Maritime . . . . .	54
5.3.3	Boating User Habits Survey . . . . .	55
5.3.4	Most Common Boat-User and Boat Archetype . . . . .	59
5.3.5	Results of Potential Revenue Streams . . . . .	60
5.3.6	Battery Degradation . . . . .	61
5.3.7	Vessel to Marina Results . . . . .	63
5.4	Case 4: Electric Ferries . . . . .	71
5.4.1	Work Process . . . . .	71
5.4.2	Data from Ferry Operator . . . . .	72
5.4.3	Installation of Bi-Directional Charging system . . . . .	73
5.4.4	Scenario 1: Using Bi-Directional System to Become Diesel Independent During Charger Service Disruptions . . . . .	75
5.4.5	Scenario 2: Incorporating a Buy-And-Sell System between the Cars . . . . .	77
5.4.6	Accelerated Battery Aging of Passenger Cars . . . . .	78
5.4.7	Yearly Business Model of Scenario 1 and 2 . . . . .	80
5.4.8	An Overview of Suitable Ferry Routes for Bi-Directional Electrification in the US . . . . .	82
5.4.9	Summary of Case 4: Electric Ferries . . . . .	82
<b>6</b>	<b>Discussion</b>	<b>83</b>
6.1	General Discussion of the Impacts of Bi-Directional Technologies . . . . .	83
6.1.1	General Return for Ancillary Services . . . . .	83
6.1.2	Accuracy of the Battery Degradation Model . . . . .	83
6.1.3	Market Comparison with USA . . . . .	84
6.1.4	Benefits of the Energy Transformation in Society . . . . .	84
6.1.5	Social Impacts of Bi-Directional Technologies . . . . .	84
6.2	Discussion Case 1: Vehicle to Grid . . . . .	85
6.2.1	User Pattern for Electric Vehicle drivers . . . . .	85
6.2.2	Return for Ancillary Services for Vehicle to grid . . . . .	85
6.2.3	Battery Degradation . . . . .	86
6.2.4	Market and Business Model for Vehicle to Grid . . . . .	86
6.2.5	US and other perspectives on Vehicle to Grid . . . . .	87
6.2.6	Avenues for Further Research . . . . .	87
6.3	Discussion Case 2: Vehicle to Home . . . . .	87
6.3.1	Interpretation of Results during Summer . . . . .	87
6.3.2	Interpretation of Results during Winter . . . . .	88
6.3.3	Limitations with the Investigation . . . . .	88
6.3.4	Possibilities with Vehicle to Home . . . . .	88
6.4	Discussion Case 3: Vessel to Grid . . . . .	89
6.4.1	Survey Results . . . . .	89
6.4.2	Example User . . . . .	89
6.4.3	Battery Degradation . . . . .	89
6.4.4	Results of Potential Revenue Streams . . . . .	89
6.4.5	Vessel to Marina Results . . . . .	90
6.4.6	Evaluation of Possible Business Models . . . . .	90
6.5	Discussion Case 4: Electric Ferries . . . . .	91
<b>7</b>	<b>Conclusion</b>	<b>93</b>
<b>8</b>	<b>Recommendation</b>	<b>94</b>

**References**

**100**

**A Appendix**

A.1 Data on the Most Common EVs in Sweden . . . . .

A.2 Single Line Diagram of M/S Aurora, Öresundslinjen . . . . .

A.3 Vehicle Distribution Statistics, Öresundslinjen . . . . .

# 1 Introduction

The goal for the European Commission is to reduce the carbon dioxide emissions to succeed with the net-zero emissions by 2050 [1]. The use of renewable energy will help reduce emissions [2] and in Sweden the goal is to only use renewable energy resources by 2040 [3]. With the increasing use of solar and wind power, the grid becomes less stable since the weather can be unpredictable. In the change to renewable resources there is a need for energy storage and one possible solution is the use of batteries as an energy storage device [4]. This is where Bi-Directional (BD) charging is relevant, using the already existing batteries in electric vehicles (EVs) and vessels, to be used as energy storage. This is not yet standard but this report aims to explore the topic on a deeper level using different user scenarios to gather information about where the technology can be implemented.

The report employs a multiple case study approach to explore the concept of BD-charging and its potential across various market segments, including recreational boats and personal EVs. Each case defines user scenarios to assess the potential and develop a robust business model based on sound assumptions. Subsequently, the findings are generalized and compared for evaluation.

## 1.1 Aim

The purpose of the project is to explore the potential advantages of BD-charging in general. Both to analyze the economic profitability and environmental benefits of utilizing BD-charging for businesses and local residents. The ambition is to design and analyze different systems that utilize the technology of BD-charging and investigate if the integration will have a positive impact in an energy efficient perspective but also identify if the system is commercially beneficial. Potential desirable effects of the project are:

- To acquire comprehensive data regarding the extent of wear on batteries under prolonged use.
- An assessment of the requirements related to legislation, technical and safety aspects.
- A clear specification of the prerequisites required for operating a household off-grid.
- Validation of profitable business models for companies as well as private home owners.
- New beneficial ways of utilizing energy in a more efficient and sustainable fashion.
- To gain a deeper understanding of the constraints and opportunities associated with BD-charging in a modern society.

The project's outcome aims to provide one or more sustainable and practical business concepts that harness BD-charging which provide a more energy efficient usage of a battery.

## 1.2 Boundaries and Scope

The focus for this work is the possible applications of BD-charging. This report will be using simulations with real data sets to make calculations on the efficiency and the earnings. The report will consist of investigations of different solutions and applications. The possibility of these suggestions will also be discussed with local operators. Each of the suggestions will be complemented with a fundamental business model which will be used to draw conclusions to each applications suitability. When conversion between AC and DC is required, it is assumed to be done using an inverter in the charger.

The project will not be investigating the communication protocol between the charger and vehicle as it is irrelevant in terms of the projects aim, to investigate the suitability of different BD-applications. These chargers will also be assumed to be lossless, as only the net power outtake is considered throughout the report, and the infrastructure of electric cars can vary between 400 [V] and 800 [V] systems, making losses challenging to model. In terms of the business models, potential savings from not having to buy EU Emission Allowances are relevant to include. However, these are not implemented as the price varies and the exact amount of emissions which can be saved is difficult to determine. The interest and inflation is also something that will not be considered.

## 2 Important Theoretical Concepts behind Bi-Directional Charging and Other Important Aspects

The following section provides theory regarding important concepts used throughout the report.

### 2.1 Theory behind Bi-Directional Charging and Vehicle to Everything

BD-charging refers to the technology of being able to send electricity both ways. Traditionally EVs have only been able to retrieve electricity from the grid, but with the technology of BD-charging EVs will be able to send electricity back to homes, appliances and also the grid [5].

The concept of Vehicle to Everything (V2X) is used within the communication field to describe the exchange of information between vehicles (which includes vessels) and the smart transport infrastructure, as well as to describe the ability of the EV to transfer energy from the battery to various systems [6], [7]. The concept has various applications such as Vehicle to Grid (V2G) and Vehicle to Home (V2H), which will be addressed in this report. Smart charging and V2G technology could play a crucial role in stabilizing the energy grid and minimizing the effects of EV fleets on it in the future. In addition to helping balance the power grid, it can help local grid owner with power peaks, provide flexibility to the party responsible for balancing, or assist with frequency regulation and other ancillary services for the electrical system.

A crucial aspect in fostering interoperability among various products, systems, and stakeholders, as well as with the surrounding infrastructure, lies in standards and communication protocols [6]. From EVs to power grids, there exists a multitude of actors as illustrated in Figure 1, standards, and protocols governing both hardware and software. A comprehensive approach is necessary for V2G and V2H to function effectively, encompassing regulatory and technical aspects, as well as realizing the business potential of providing various services to the electrical system. Communication is essential at multiple levels between EVs, chargers, the electricity system, and various stakeholders within the system.

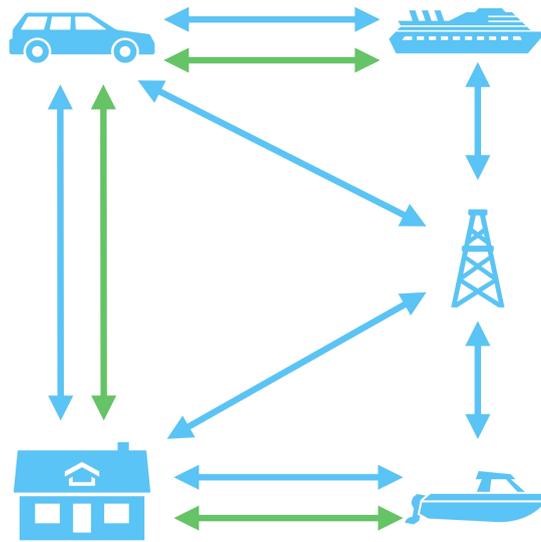


Figure 1: Illustration of stakeholders in the system for BD-charging

## 2.2 Theory behind Battery Degradation

Since the report is an investigation of the possibilities of using a vehicle battery for applications which are not driving, it is important to know if these additional usages will cause any accelerated damage of the battery. This due to the fact that in an EV, the battery contains many rare and toxic materials [8], which makes maximizing the lifetime of the battery relevant.

The degradation consists of many different processes within the battery, such as Solid Electrolyte Interface (SEI), the process of the electrolyte forming a solid layer when it comes into contact with the negative electrode, leading to a loss of electrolyte and therefore capacity [9]. Numerous issues related to degradation are associated with the growth of SEI, including cracking that reveals additional particles in the negative electrode covered by SEI.

Both of these processes are affected by how the battery is used during cycling, and at which state the battery is left with when idle, often referred to as calendar aging. During the calendar aging state, the most significant factors are the battery percentage, hence forward referred to as the State Of Charge (SOC) and the ambient temperature [9]. During cycling, the most important stress factors are the discharge rate, referred to as C-rate, where 1C means that the battery is discharged from 100 to 0 percent state of charge within one hour, the Depth of Discharge (DOD), which indicates how deep the battery is being discharged from its initial state and also the temperature [10]. All of these stress factors contribute to the previously mentioned degradation processes, which has created the recommendation of keeping a battery between 20 and 80% SOC [11].

These facts makes it relevant to model the battery degradation and investigate how different usages can effect the State of Health (SOH) of the battery after a given time. This is a relevant factor when investigating business models, warranties, etc. Since the degradation is non-linear and different from cell to cell, empirical models can be used to model the aging [10]. Also from an ethical and sustainable point of view, it is relevant to investigate to what degree the additional use accelerates the vehicle battery to reach its End-Of-Life (EOL), normally considered at a maximum capacity, or SOH of 70-80 % of the original [12]. In this report we will consider 75% as EOL.

### 2.2.1 Empirical Models

The models can be divided into two equations, one of which describes the so called calendar aging, which occurs when the battery is not cycling, and the cyclic aging, which occurs when the battery is either discharged or charged. One model used for calendar aging, is presented by Roy, et al [10].

This model divides calendar aging into two categories, and claims a square root behavior of the degradation when the ambient temperature is  $-5$  [°C], and another which claims a linear behavior as the temperature approaches  $45$  [°C]. These two models are presented in Equation 1-2 as:

$$C_{cal,cold} = (0.09SOC + 0.01)\sqrt{t} \quad (1)$$

$$C_{cal,hot} = 1 + (0.004SOC)t \quad (2)$$

where  $C_{cal,cold}$  and  $C_{cal,hot}$  describe the capacity loss in terms of percentage, SOC is the SOC the battery is left in as it is being idle in a range of 0-1,  $t$  is time in terms of hours. The model was produced from experiments conducted on a series of NMC cells produced at the University of Michigan [10].

An example of empirical cyclic aging modeling, was presented in [13]. This paper also presents a calendar aging model, which in terms of the previous model [10] exaggerates the calendar aging. However, the cyclic model presented by [13] aligns well with the laboratory results from the cycling study in [10]. The model uses charging current, rather than C-value, and is based on a 12 [Ah] cell, and is defined in equation 3 as

$$C_{loss,cyc} = a_1(t + a_2\sqrt{t} \cdot (V + a_3) \cdot \exp(\frac{a_4}{T}) + I_0 \cdot a_5(DOD + a_6)^2) \quad (3)$$

where  $a_1 - a_6$  are modeling parameters with no physical meaning,  $V$  is the voltage of the cell, which varies non-linearly with SOC,  $T$  is the temperature in Kelvin, DOD is the Depth of Discharge, and  $I_0$  is the charging or discharging current. The ratio between  $I_0$  and capacity in [Ah] of the cell therefore determines the C-rate. The fitting parameters used in equation 3 are presented in Table 1.

Table 1: Fitting parameters from Empirical Model [13].

$a_1$	$4.34 \cdot 10^{-7}$
$a_2$	35
$a_3$	-3.23
$a_4$	-5010
$a_5$	0.64
$a_6$	63.7

In Table 1, parameters  $a_1 - a_6$  are, as previously mentioned, all fitting parameters and have no physical meaning.

It is important to note that the two models were based on two different chemistry's. The model of the calendar aging was based of a NMC cell produced in a University Laboratory [10], whereas the model of the cyclic aging is based on a LFP chemistry, [13]. The degradation characteristics of the two cells are however similar. It is also important to recognize the fact that these models are based on individual cells, and not battery packs in vehicles. The results from both models, propose an EOL at approximately 800 full equivalent cycles. For batteries in electric vehicles, this number is expected to reach at least 1000-2000 full equivalent cycles [14]. The results from the models can therefore be expected to be significantly exaggerated.

### 2.2.2 Combining the Models using Eulers Method

When integrating two equations to form a seamless degradation curve using computational tools like MATLAB or Python, Euler's Method becomes indispensable. By approximating or calculating an initial value, each subsequent value can be calculated as

$$y[n] = y[n - 1] + h \cdot \frac{dy}{dt} \quad (4)$$

which is an interpretation of Eulers Method. In Equation 4,  $h$  is the size of the step. In numerical analysis, when each step is set to 1 unit, the final fraction is only multiplied by one. Consequently, solely the derivative's value at time  $t$  needs to be added to the initial value, which in Equation 4 is  $y[n - 1]$  at  $n = 1$ .

The derivatives of Equation 1-3 would be necessary to calculate if used in Eulers Method. These derivatives can in terms of time be described as

$$\frac{d}{dt}C_{cal,cold} = \frac{0.045 \cdot SOC + 0.005}{\sqrt{t}} \quad (5)$$

$$\frac{d}{dt}C_{cal,warm} = 0.004SOC \quad (6)$$

$$\frac{d}{dt}C_{cyc} = a_1 \cdot \left(\frac{a_2}{2\sqrt{t}} + 1\right) \cdot (a_3 + V) \cdot e^{\frac{a_4}{T}} + a_5 \cdot I_0 \cdot (a_6 + DOD)^2 \quad (7)$$

where all units are the same as in Equation 5-7. These derivatives can then be combined using Eulers Method to study the degradation curve of any customized cycle.

## 2.3 Theory behind Grid Stability Services

The following chapter is providing information about the ancillary services, how they work, what the requirements are and how they are procured, specifically in Sweden.

### 2.3.1 Electricity System in Sweden

The Swedish electricity system is a complex network designed to deliver reliable power from producers to consumers. It is a complex system with multiple actors collaborating to ensure the entire electricity system functions. Svenska Kraftnät (SvK) is the Transmission System Operator (TSO) and oversees the primary transmission lines in Sweden, operating at 220 or 400 [kV], which work alongside regional (130 [kV]) and local (<40 [kV]) lines to distribute electricity efficiently [15], [16]. While regional and local distribution lines are managed by Distribution System Operators (DSOs), Sweden also maintains international AC lines linking to Finland, Norway, and Denmark, as well as High Voltage Direct Current (HVDC) lines connecting to Finland, Denmark, Germany, Poland, and Lithuania.

This transmission and distribution grid physically transports electricity within Sweden and to its neighboring countries. Critical to the system's functionality is the constant balance between electricity production and consumption, crucial for sustaining a stable frequency of 50 [Hz] within the electrical grid [17]. Any disruptions to this equilibrium pose substantial risks, potentially leading to damage or destruction of the grid's technical infrastructure and consequent power shortages. Therefore, SvK plays a pivotal role in maintaining this balance within the electricity system, ensuring it is uninterrupted operation all year-round. To ensure a balance between consumption and production, multiple electricity markets exist where supply and demand can be aligned in advance.

Not all electricity is sold on commercial markets. Some of the important measures of safety and reliability of the power system include voltage control and rotor angle stability, responsibilities of SvK [18]. The same goes for insuring against situations of power shortage. For this, power reserves and disturbance reserves are procured to protect against persistent power imbalances [19]. While the aforementioned measures are crucial for operational reliability, none of them are traded on daily markets.

Except for TSO and DSO there are one more party that plays an important role for the power system, Balance Responsible Party (BRP) [20]. The BRP is responsible for maintaining balance between production and consumption within their designated area of responsibility. In Sweden, there are numerous BRPs collectively responsible for ensuring the supply of electricity matches the demand. When a discrepancy arises between production and consumption within a BRP's jurisdiction, the BRP incurs a penalty fee proportional to the difference, payable to SvK. Additionally, BRPs have exclusive bidding rights on frequency regulation markets. Any entity with a resource capable of

contributing to frequency regulation must go through a BRP to participate in these markets. Such resources, known as Balancing Service Providers (BSPs), supply SvK with frequency regulating resources. SvK is in the process of revising regulations to allow BSPs to participate directly in frequency regulation markets without the intermediary of a BRP. This will come into effect on May 1st, 2024 [20]. What effect this will have on the electricity markets are unknown, but the intention is to make easier for more actors to contribute to these markets.

### 2.3.2 Energy Balance Markets

To adeptly manage disturbances in the power system under any conditions, SvK needs a variety of services and remedial actions [18]. The services and remedial actions vary, for example, in the remuneration and to which extent it is market based. In this report, the grid stabilization markets will only be discussed. The services will be referred to as ancillary services and the different services that SvK provides are presented in table 2.

Table 2: List of ancillary services to the power grid [21], [22].

Ancillary services for balancing		
<b>Frequency Containment Reserves</b>	The goal for FCR is to maintain frequency stability during frequency deviations, which is essential for the overall balance of the electrical system.	
FCR-D Up	Upward Frequency Containment Reserve - disturbance	Stabilizes the frequency upward during operational disruptions. -Minimum bid 0.1 [MW]
FCR-D Down	Downward Frequency Containment Reserve - disturbance	Stabilizes the frequency downwards during operational disruptions. -Minimum bid 0.1 [MW]
FCR-N	Frequency Containment Reserve - Normal	Frequency stabilization for small variations in using or production. -Minimum bid 0.1 [MW]
<b>Frequency restoration reserves</b>		
aFRR	Automatic Frequency Restoration Reserve	An automatically activated ancillary service that restores the frequency to 50 [Hz]. -Minimum bid 1 [MW]
mFRR	Manual Frequency Restoration Reserve	A manual ancillary service designed to complement the automatic ancillary services, restoring the frequency to 50 [Hz]. -Minimum bid 1 [MW] on the capacity market and 5 [MW] on the energy activation market
<b>Remedial actions</b>		
FFR	Fast Frequency Reserve	Addresses the abrupt and significant frequency variations that may arise. -Minimum bid 0.1 [MW]

Figure 2 demonstrates the various roles and activation times of ancillary services [23]. Frequency balancing involves the coordination of these services with the remedial action FFR. In cases of major frequency deviations, such as abrupt changes in production or consumption, FFR initially counteracts the swift and significant frequency shifts. Subsequently, FCR-D is employed within a frequency range of  $50 \pm 0.1 - 0.5$  [Hz] to help stabilize the frequency [21]. To further assist, aFRR and mFRR act as supplements to FCR-D, aiming to return the frequency back to the normal level of 50 [Hz]. During typical disturbances, FCR-N, aFRR, and mFRR are utilized.

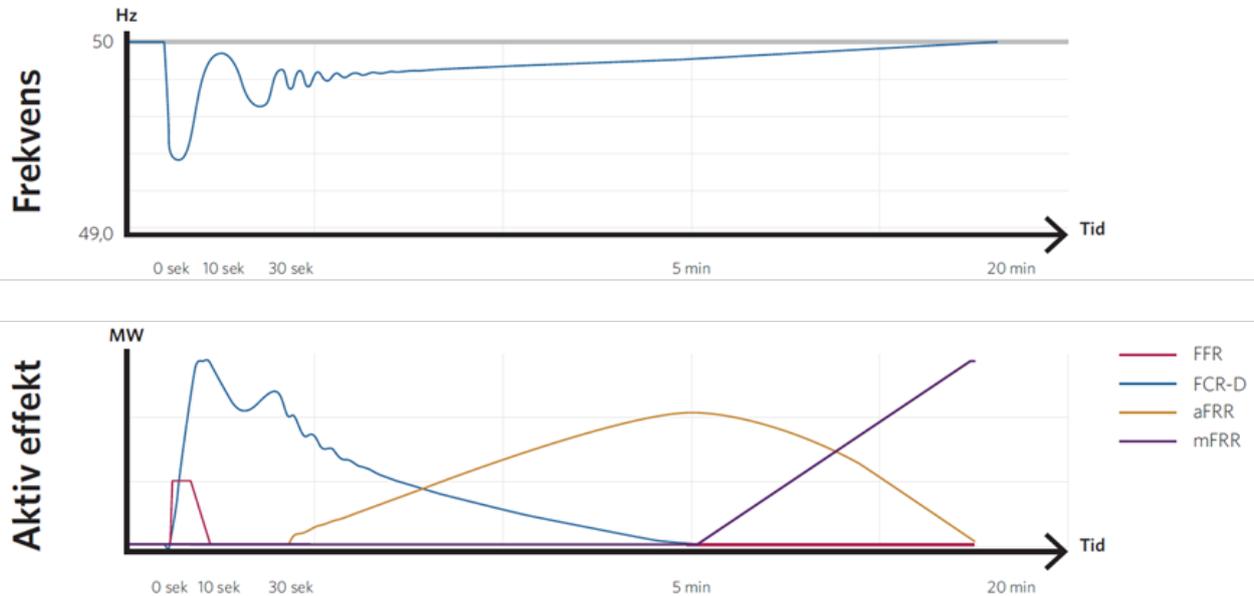


Figure 2: Visualization of the use of the ancillary services. The picture above shows the frequency of the energy system and the picture below shows the active power used from the different ancillary services. [23]. Reproduced with permission.

### 2.3.3 How to Contribute with Ancillary Services

To contribute with ancillary services to the power grid you need to be balance responsible actor [23]. Due to this it is not possible for individuals to assist with ancillary services directly to SvK. In essence, individuals seeking to provide ancillary services must engage through subcontractors to the balance responsible actors or to aggregators. This applies to all the ancillary services except the remedial action FFR which is bought from specific actors.

The process of trading ancillary services unfolds in a manner where the balance responsible actors bid their resources at competitive prices across different ancillary service markets. The trading takes place on either a capacity market, an energy activation market, or both, depending on the specific type of ancillary service. All services are procured on a daily basis except for FFR, which is procured annually.

How much compensation one receives from ancillary services depends on several things, for example the volume available for bidding in the reserve markets and the price chosen for bidding [24]. Where each ancillary service is procured and what is compensated for each is presented in Table 3.

Table 3: Where and how the ancillary services are procured and priced [24].

	Market	Remuneration
FFR	Capacity market	Marginal price, capacity compensation
FCR-D Up	Capacity market	Marginal price, capacity compensation
FCR-D Sown	Capacity market	Marginal price, capacity compensation
FCR-N	Capacity market	Marginal price, capacity compensation+ Energy compensation according to up or down regulations price
aFFR	Capacity market	Marginal price, capacity compensation+ Energy compensation according to up or down regulations price
mFFR	Capacity market and energy activation market	Marginal price, capacity compensation+ Energy compensation according to marginal regulation price up or down

For the different ancillary services procured on the capacity market the compensation from SvK can be calculated as  $Comp_C$  using the equation

$$Comp_C = M_{price} \cdot Sold_C \quad (8)$$

where  $M_{price}$  is the marginal price or the bid and  $Sold_C$  is sold capacity in [MW] [24]. The marginal price is the highest accepted bid. This is valid for FCR-D up and down, FFR, FCR-N and aFFR.

The mFFR is procured on both the capacity market and the energy activation market and the compensation for the activation can be calculated as  $Comp_A$  with Equation

$$Comp_A = Reg_{price} \cdot E_A \quad (9)$$

where  $Reg_{price}$  is the up or down regulation price and the  $E_A$  is the activated energy.

SvK uses two different pricing models for their different services [24]. These are called pay-as-bid and marginal pricing. The process is the same for both models, bids with the lower prices are accepted first. This process continues until SvK meets the hourly quota for each ancillary service. All services related to frequency stability is paid with marginal pricing, that is all ancillary services presented in this section. The marginal price is determined by the final bid that fulfills SvKs capacity quota. All bids included in the quote are valued at this same marginal price. Consequently, all bids are compensated based on the price of the highest bid, resulting in SvK paying the total demand multiplied by the price of the highest bid. It is crucial to note that the prices the suppliers assign to their bids represent the cost for availability. If SvK accepts their bid, the stated price is what SvK will pay for availability, regardless of activation.

## 2.4 Theory behind Load Balancing

As the electricity required to fully charge an EV varies from approximately 50 to 80 [kWh], see Sppendix A.1, the electricity demand will increase enormously. The power of a home charger varies from 11 to 22 [kW] [25] and with the increased electricity demands, it can reach the electrical limit of the main fuse or even overload the electrical grid of the home. The consequences for overloading the electric grid of the home could be power outages, higher electricity costs, damage to electric cables and main fuses [26]. To prevent this, a customer may be inquired about integrating load balancing when installing a charging box for the EV. There are two different systems for load balancing, static - and dynamic load balancing.

### 2.4.1 Why Use Dynamic Load Balancing?

Static Load Balancing (SLB) operates exactly as it sounds, where the home charger is allocated a constant, unchanging power limit. This is illustrated in Figure 3. In Sweden, where the typical main fuse is rated at 16 Ampere [26], the highest achievable power is 11 [kW].

For example if a households power demands fluctuate from 1-5 [kW], SLB could set a steady power limit of about 4 [kW] [27]. Consequently, combining the household consumption and home charger this would give a maximum power usage of 9 [kW] to avoid surpassing the capacity of the main fuse. Even if the households power requirement is as low as 1 [kW] and there is an available capacity of 10 [kW], the home charger would still only draw 4 [kW].

This method is not the most effective for load balancing since it does not utilize electricity efficiently. Moreover, this approach still poses a risk of overloading the electrical grid, especially if the household's power demand spikes from 5 [kW] to potentially 8 [kW], thus surpassing the overall limit of 11 [kW].

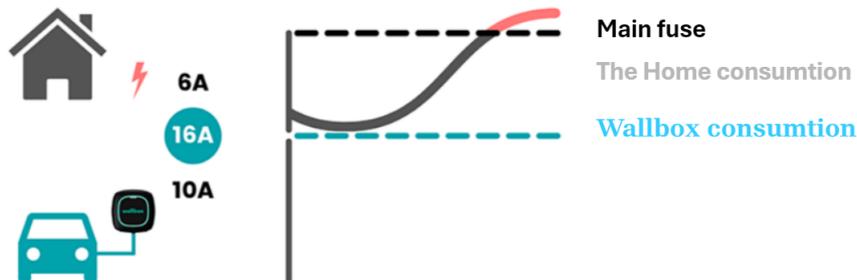


Figure 3: Visualization of SLB, where Wallbox is represented as the home charger. [27]. Reproduced with permission.

Conversely, Dynamic Load Balancing (DLB) takes into account the power needs of the home and the main fuses maximum capacity. DLB makes use of any remaining power after the home appliances are supplied. For example, in the scenario described earlier, if the home demands 1 [kW], then under DLB, the home charger would use 10 [kW]. With the addition of solar power, the DLB system improves the charging capabilities of electric vehicles when the homes power consumption is low and solar production is high. For instance, should the solar panels produce 5 [kW], the home may avoid using grid electricity and instead use 1 [kW] of solar power. Thus allowing 4 [kW] from solar power and 7 [kW] from the grid to be allocated to the home charger. An illustration for the dynamic load balancing without solar power respective with solar power is presented in Figure 4.

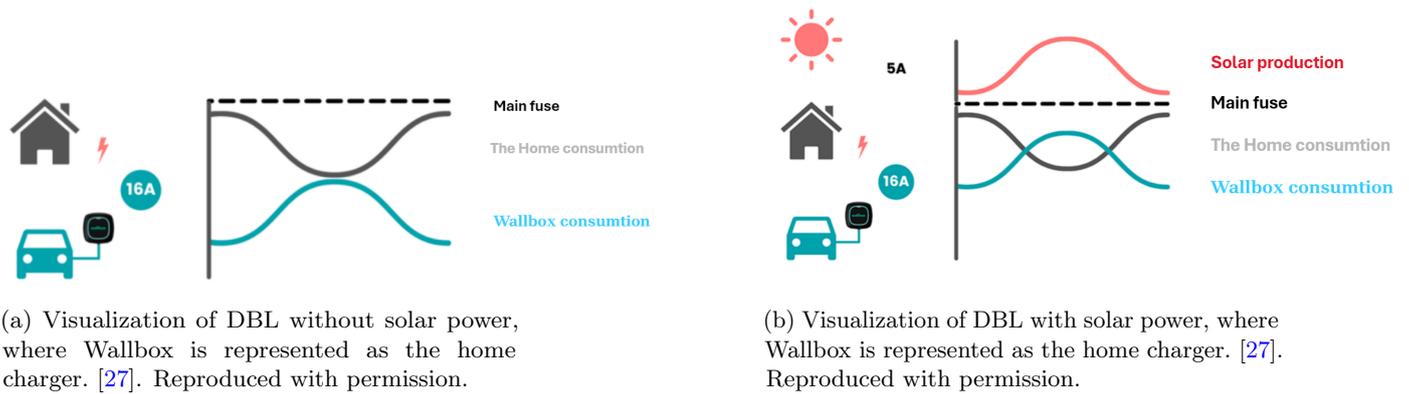


Figure 4: Dynamic Load Balancing

## 2.5 Theory behind Market Changes and Price Evaluation

The theory of supply and demand is a fundamental economic concept that explains how the amount of a product or service provided by producers and the amount sought by consumers interact, and how this interaction influences market prices [28].

In Figure 5 it is shown that when the demand increases, prices typically rise. When the supply increases, prices typically fall. Supply and demand are the basis for adjusting prices upward or downward, and to determine how many are willing to buy or sell the commodity [28]. The resultant price, known as the equilibrium price, signifies a consensus between the producers and consumers of the commodity. At equilibrium, the quantity of the commodity supplied by producers matches the quantity demanded by consumers. All participants must adjust to the markets limitations.

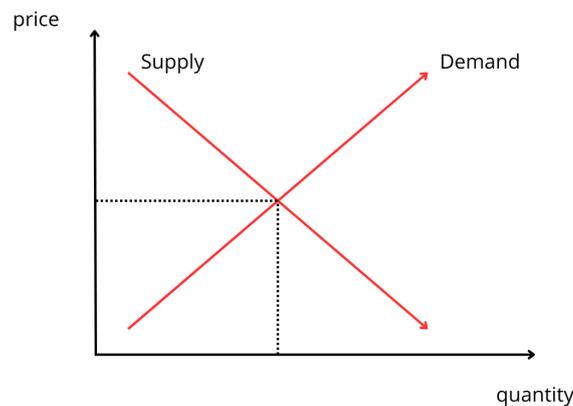


Figure 5: Illustration of supply and demand curves based on the theory from Investopedia. [28].

This economical concept is important to understand with the growth of the ancillary service market and the energy demand in the future. This, combined with the accelerated electrification of the society [29], will constitute a crucial component in understanding the pricing mechanisms of services within the domain.

### Product Life Cycle

The product life cycle theory is a concept used in marketing and product management to describe the stages that a product goes through from its introduction to its decline in the market. This

analyze tool help actors understand the dynamics of their products in markets. Everything from marketing, price points, expansion to new markets, redesigns, etc. These tools help professionals develop appropriate strategies at each stage [30].

This concept is important to consider when examining products and concepts. Understanding where the product is positioned is crucial to determine which strategies need to be employed to create additional value for the product [31]. The stages of product life cycles are defined as introduction, growth, maturity, and decline [30]. These stages are explained below and presented in Figure 6.

- **Introduction:** This stage of the product life cycle, a market strategy is developed, often involving investments in advertising and marketing to raise awareness among consumers about the product and its benefits.
- **Growth:** In this stage, rising consumer interest leads to enhanced production rates and broader distribution of the product.
- **Maturity:** In this phase, the product is firmly established, lowering production and marketing costs. Market saturation sets in as the life cycle matures, emphasizing branding, pricing, and product differentiation to maintain market share. Retailers focus on stocking rather than promotion.
- **Decline:** In this stage, when the competition increases and rivals introduce new features or lower prices, the product enters a decline phase. Market saturation and innovations can hasten this decline. Companies may explore new ventures due to reduced profitability. Production decreases, prices and profits decline, and consumer preferences shift towards alternatives. However, revivals may occur with changing trends reigniting interest in older products.

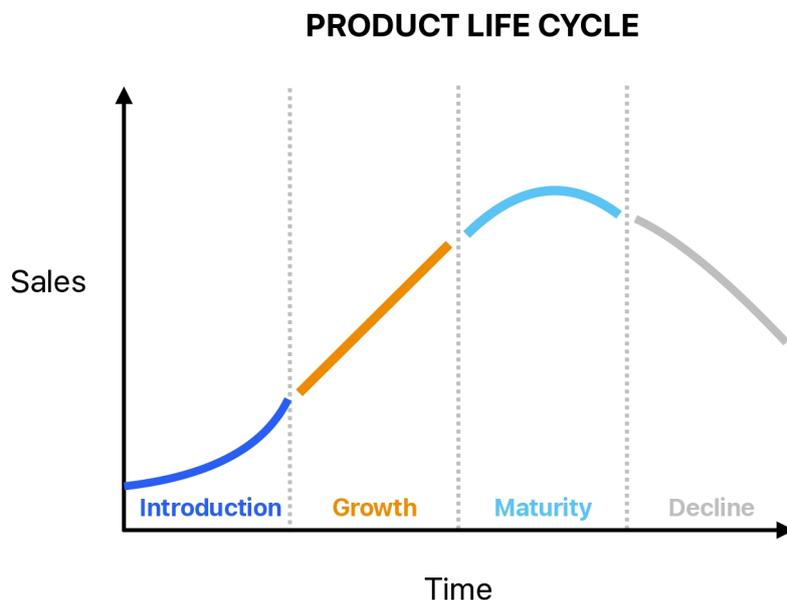


Figure 6: Illustration of the product life cycle and the different stages. The Figure is based on a figure from [30].

This method is important to consider for new concepts and products. In order for actors to make informative decisions about the product development and management process, ultimately contributing to long-term success in the marketplace [31]. Using this method, stakeholders can

identify market dynamics, technology evolution, risk management, etc., for BD-charging. BD-chargers are a relatively new technology and products that combine this technology to use a battery as a power source to the various systems. BD-charging is at the moment in the introduction phase, see section [2.5](#).

### 3 General Methodology

To illustrate the work process a diagram can be found in Figure 7 with arrows showing how the process went.

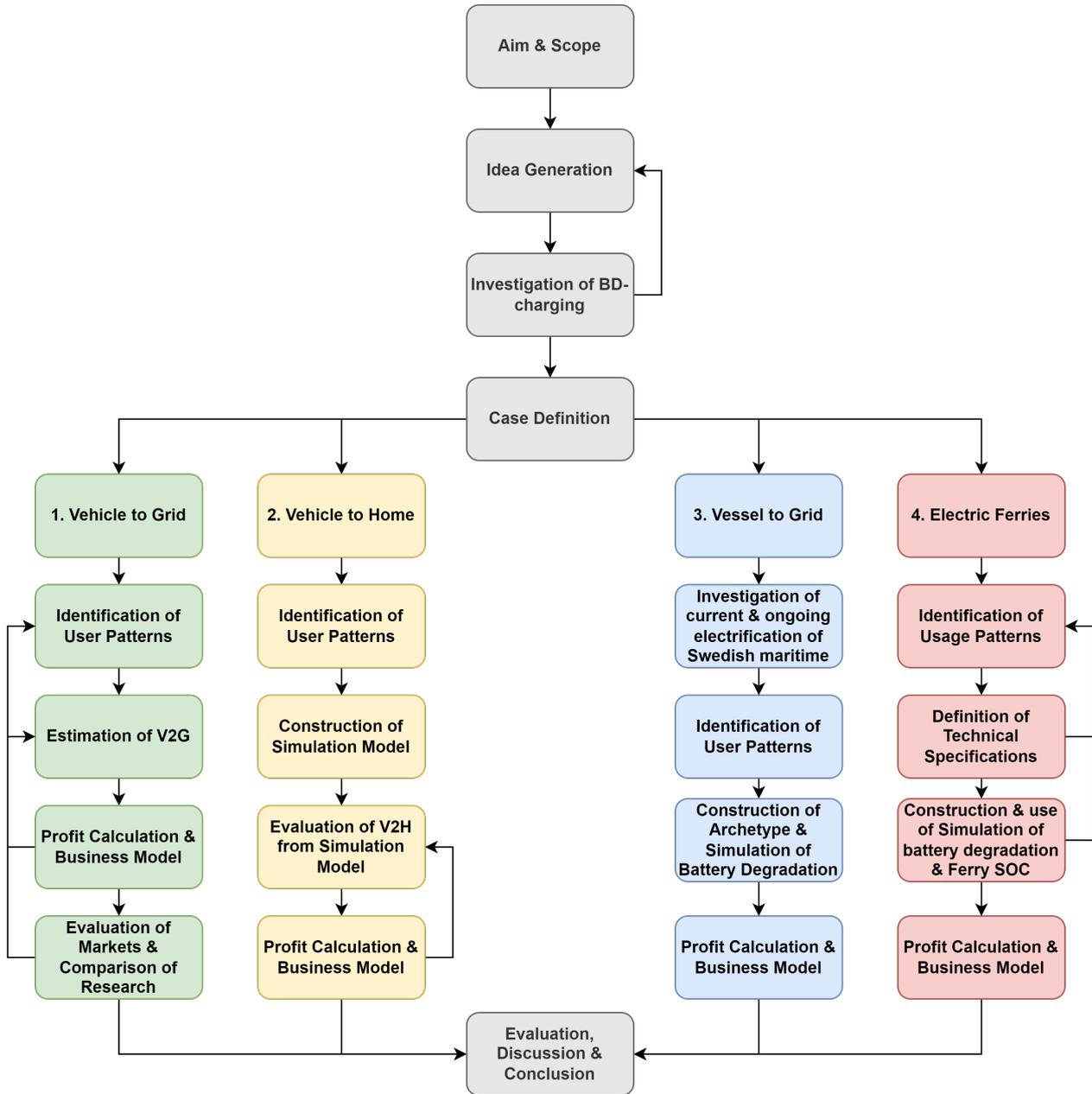


Figure 7: Flowchart illustrating the work process for the multiple case study

Initially the aim and scope were defined based on the given tasks by Volvo Penta [32].

The methodology is based on an investigating multiple case study. The first step, which is to choose which cases to explore, a brainstorming session was held. This was done together with a collaboration group from Pennsylvania State University. After the brainstorming, five cases were elected and defined. The five cases were investigated by using literature studies. From the studies one of the cases were found to be too broad and therefore dismissed after several attempts at redefining the case.

Significantly different methodologies were conducted in the different cases, and the varying parts of the work process are therefore more specifically described separately in each case.

For the identification of user patterns, surveys and interviews were used. The surveys was sent out on the social media platform, Facebook. The interviews were held either on the phone, via Microsoft Teams or in person with the same focus as the survey, to understand the user pattern of an EV owner or boat user.

The profit calculations and business models was done using values collected using a literature study combined with the user patterns and interviews with experts.

To conclude how BD-charging affects the battery health, a degradation model for the battery was created in Python with the data in chapter 2.2. How the battery degradation model is implemented is described separately, as it is relevant to each concept.

The evaluation and conclusion were done by using a comparison of the profit and battery degradation of the cases.

For the final report AI was used to paraphrasing.

### 3.1 Introduction to the Cases

After the idea generation process and initial investigations, four cases were chosen as they had most concrete foundation to create a solid case which to investigate. These are presented below.

#### 3.1.1 Case 1: Vehicle to Grid

Vehicle to Grid (V2G) technology has been widely discussed and is supposedly close to becoming a reality. In order to realize the energy transition that occurs in society, energy storage is an important factor that needs to be investigated to fully move to renewable energy resources. [29]. The number of EVs is rapidly increasing [33], which demands energy solutions to support the increase of energy consumption in the future. The technology of V2G has been discussed as a potential solution to cope with the energy transition. The case of V2G will investigate the user pattern of EV users to analyze the profitability of V2G systems. To draw general conclusions, historical earnings from ancillary service markets were compared with the EV driving pattern. The results of the profitability and usability of V2G systems are discussed and compared with similar research to evaluate the potential benefit of V2G systems. Lastly, a detailed discussion of the case was conducted taking into account possible hindrances and other factors of the case. An illustration of the case V2G can be found in 8.

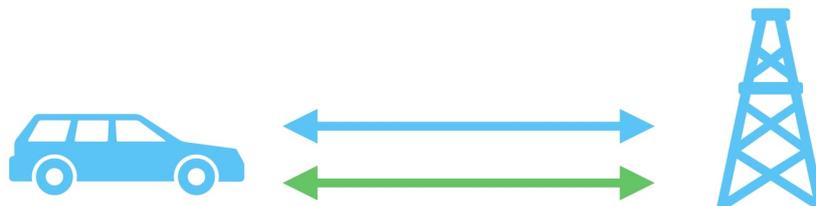


Figure 8: Illustration of V2G

#### 3.1.2 Case 2: Vehicle to Home

With the rising prevalence of solar energy systems and electric vehicles (EVs) in the power grid, the exploration of integrating these technologies becomes increasingly pertinent. Households typically purchase smaller batteries for electricity storage or ancillary services. However, with the growing popularity of EVs [33], the possibility of utilizing the EV's battery for these purposes emerges.

The concept of V2H involves using the EV's battery to store electricity and provide ancillary services. During daytime electricity can be stored in the EV battery and used at night to power the home, potentially allowing the household to disconnect from the grid. The EV battery might also support the energy system through ancillary services. The case is illustrated in the Figure 9.

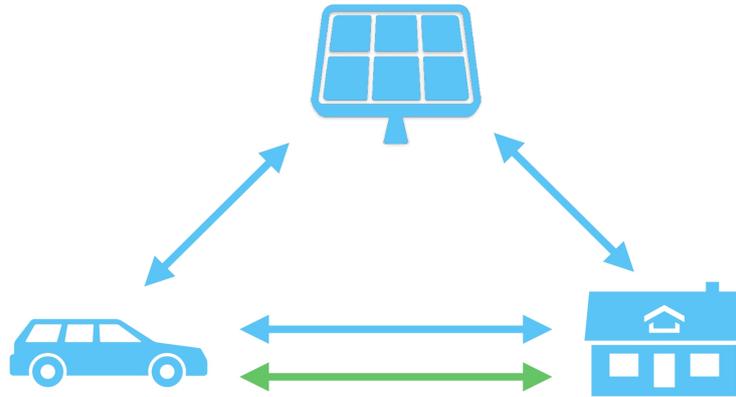


Figure 9: Vehicle to Home

Ultimately, this case study aims to assess how an EV's battery can provide year-round benefits to private homeowners through V2H, in terms of both energy efficiency and economic value.

### 3.1.3 Case 3: Vessel to Grid

The Vessel to Grid case study examines multiple scenarios associated with implementing BD-charging in boats and marinas. Key highlights include the potential revenue from ancillary services and increased wear and tear on the battery. In addition, the case presents the current electrification of the Swedish maritime industry and the expected growth of the electric boat market.

Based on the current battery capacity for electric boats on the market and the expected market growth over the coming years, it is assumed that the total capacity in the future could range from 4.5 to 18 GWh. Additionally, since boats are idle for as much as 90% of the time, they are ideal for ancillary services that could generate passive income, thereby facilitating numerous innovative business models that could significantly contribute to the electrification of the maritime sector, potentially leading to a similar trend as that seen in the automobile sector in recent years.

To explore the topics noted earlier, data collection was carried out to identify user behaviors, type of boats, and battery capacities. Discussions were held with stakeholders involved in current projects to better understand the present conditions, and a battery degradation model was developed to assess the potential increased wear on batteries. Ultimately, the study results in tangible results for a marina using BD-charging in half of its boats, along with discussions that propose other profitable approaches for marinas and provide further explanations.

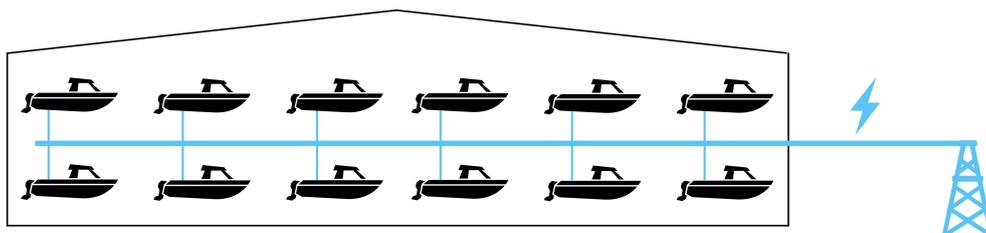


Figure 10: Multiple vessels charging and providing ancillary services in a marina

### 3.1.4 Case 4: Electric Ferries

Back in 2018, Ferry Operators Öresundslinjen gained a substantial amount of media attention for electrifying both of their large vehicle ferries [34]. With a large scale electrification of personal EVs in Denmark and Sweden [35], [33], the countries in which the Ferry operates, the fraction of the Ferry's onboard cars being electrified is set to grow substantially. This opens the door of investigating the potential uses of a onboard BD-system, which could do anything between extending the ferries electric range by purchasing electricity from the EVs onboard, to provide the passengers with an opportunity of charging while commuting to work.

In this case, the possibilities of installing a BD-charging system between the passenger batteries and the ferry's propulsion system is investigated, in order to draw general conclusion to which additional incentives there could be to electrify passenger ferries throughout the world. Öresundslinjen's Ferry M/S Aurora is used as a baseline for the installation and operation, and two specific scenarios are investigated.

1. M/S Aurora uses diesel generators during a portion of it's operational time to prevent longer charging stops. Could these generators be replaced with a BD-charging system? How many EVs would be necessary and can it remain profitability during operation?
2. Could the BD-charging system be utilized as a Vehicle To Load (V2L) system, in which the cars can buy and sell electricity from each other? Can this model be profitable both for the passenger which sells its electricity, while providing provision to the ferry operators?

The answers to the subsequent questions are analyzed to form a conclusion on how this application can offer extra benefits to operators opting to electrify their ferry fleets.



Figure 11: A BD-system onboard a Ferry to provide the Ferry battery with additional power

## 4 Foundational Outcomes Common to all Cases

The following section provides the common results used throughout the different cases, such as finalized models for battery degradation, returns for ancillary services, etc.

### 4.1 Finalized Battery Aging Model

The following subsection provides information on how the finalized battery degradation works, which assumptions are made and how each degradation factor is returned.

#### 4.1.1 Battery Aging Models

All the different cases implies a change in how the battery of the vehicle is being used, therefore a tool was developed to simulate how different simplified daily cycles effects the battery capacity loss. The model allows two different cycles with the same C-rate to be simulated and compared. The model was based on the theory behind battery degradation specified in section 2.2.

#### 4.1.2 Combining the Empirical Models

The two models were combined dynamically in the script which used Eulers Method to do so. By choosing whether the battery was idle, charging or discharging, the script switched between the two models accordingly.

#### 4.1.3 Determining the Value of each Degradation Factor

Definition of the variables was done dynamically by the script. Some of the variables were set to constant values, while some change depending on the battery usage conditions. This section describes each variable in Equation 5-7 and how the model determines their value.

- **Time [t]** - The simulation's time is crucial and utilized in all equations. Consequently, the time value is established using a `np.linspace()` command, with an interval which depends on the step size in Euler's Method. The duration of the time vector corresponds to the number of simulation days, calculated as  $24 \cdot \text{days}$ .
- **SOC** - The SOC is used during calendar aging, and is calculated from the base SOC given, and adjusted according to each hour's charging status and the c-rate. The model makes sure that the last SOC value is equal to the base SOC, in order to make the daily battery cycle enclosed. It also makes sure it does not surpass 100% or fall short of 0%. If any of these conditions are not fulfilled, an error message is given.
- **a<sub>1</sub>-a<sub>6</sub>** - Modeling parameters  $a_1$ - $a_6$  were set according to table 1, which is the values determined by Rechkemmer et. al [13].
- **Voltage [V]** - According to Rechkemmer et. al [13], the battery voltage of the cell varies non-linear with respect of the SOC. Therefore, the nominal battery voltage of the cell, 3.7, was used. This was determined experimentally, as it perfectly recreated the results presented in [13].
- **Temperature [T]** - Although the calendar aging model have fixed values, the cyclic does not. This value is set in the Python code, and has a constant value throughout the simulation. The unit is Kelvin.
- **Throughput Current [I<sub>0</sub>]** - The throughput current determines the stress level of the battery and is directly correlated with the C-rate. This is a quite simple correlation described in Equation 10, since the model is based on a LFP-cell with a 12 [Ah] capacity, it can be described as

$$I_0 = C_{rate} \cdot 12 \tag{10}$$

which is calculated in the Python code. One of the biggest assumptions made in this model is the constant C-rate, which correspondingly makes  $I_0$  a constant value.

- **DOD** - DOD is considered during cycling and, as previously mentioned, varies based on the depth of battery discharge. This complexity makes determining the DOD one of the most intricate processes in the simulation, as cycling patterns may vary. The model calculates the DOD by monitoring the duration the battery remains continuously in the charging or discharging state upon entry.

Using these parameters, it is possible to compute the degradation over a series of consecutive days involving repeated daily cycles. Nevertheless, the models exhibit sensitivity to shorter simulation durations, and it is noted in the report that no simulation lasted fewer than 30 days.

As mentioned in 2.2, the results are exaggerated due to being based on single battery cells. All uses of the model will therefore simulate until EOL is reached, as the value of the x-axis (time) will be an exceedingly rough approximation.

#### 4.1.4 Calculating Full Equivalent Cycles

While the timing of EOL is crucial, equally important is the battery's efficient usage over its lifespan. Therefore, the model calculated the full equivalent cycles per day. This calculation allows for a comparison at EOL of the full equivalent cycles between a battery using BD and one cycled solely for its primary function.

Additionally, the daily full equivalent cycles were assessed by determining the total SOC points discharged throughout the day.

#### 4.1.5 Different Uses throughout the Cases

The application of the model varied across the various case studies. Each case implemented a 20-minute resolution for the model, which corresponds to a step size of  $\frac{1}{3}$  in Euler's Method.

The method of inputting data into the degradation function differed across the scenarios. In case 1, the driving cycle was condensed into a 96-hour period that could be replicated as needed. For case 4, the minimum cycle duration was 24 hours. Case 3, however, presented a distinct pattern due to the irregular usage of recreational boats compared to commuting electric vehicles. Consequently, two distinct two-week discharge patterns were developed: one for a typical summer week involving cruising, charging, and ancillary service discharges, and another for winter, utilizing only ancillary services. These patterns were combined into an annual cycle and input into the model, which then repeated this cycle over several years.

## 4.2 General Result from Ancillary Services

In this section, the general return from ancillary services are presented. Investigation of what affects the compensation is shown, and potential earnings is calculated with the help of an expert on the subject.

### 4.2.1 Introduction to Ancillary Services

According to a business developer from CheckWatt [36], the markets for ancillary services to the power grid are new and immature markets with very different compensation earnings. Calculating future earnings in such new markets is difficult, almost impossible, to make a prediction. Market prices are subject to fluctuation and uncertainty prevails regarding their directional trend, with no definitive knowledge regarding potential upward or downward movements. Consequently, to get a valid assumption of what the compensation from the ancillary services, data are based on historical earnings for stationary batteries.

Supported by the theory in 2.3, FCR-D is considered the optimal ancillary service for an electrical battery due to its ability to discharge power to the grid within very short intervals, indicating a short activation duration for the service. Consequently, compensation is provided for the energy one can provide to the grid, regardless of the actual usage. The business developer from CheckWatt [36] says that FCR-D is the most used ancillary service for stationary batteries today and he suppresses that FCR is the most suitable ancillary services for batteries because it has low energy intensity.

### 4.2.2 Work Process to Estimate Earnings from Ancillary Services

The study had a starting point of gathering information on the general historical return for stationary batteries connected to the grid, to see what the possible return could be for V2G or Vessel to Grid.

Although SvK publishes the total volume and price of these services, there is no publicly available data regarding the prices at which subcontractors and aggregators compensate individual customers for ancillary services of batteries. Hence, it became difficult to acquire data of what the return for ancillary services could be for an individual.

To formulate reasonable assumptions, inquiries were made to aggregators regarding how much they compensate individuals with stationary batteries with, yet they directed attention to their respective websites. Eventually, data was obtained from a customer of an aggregator in Sweden electrical area 4 (SE4). Ultimately the compensation data stemmed from the two major commercial companies providing compensation for ancillary services to individual customers with stationary batteries, Varberg Energi and CheckWatt. In addition, information was obtained from a client of one of these firms to facilitate triangulation of reasonable assumptions about the compensation. The data from CheckWatt and the aggregator customer was for a 10 [kWh] battery. To match the data from Varberg Energi, the linear proportions of the battery power and compensation were used. This assumption was made to match the data between the sources. A comprehensive analysis of the compensation data was the original idea. The lack of data points and uncertainty in the field lead to a simpler investigation of the price structure of the compensation from the ancillary services.

Information was collected on the volume and price for FCR-D to better understand how much SvK purchases. Then, the three different data sets of estimated returns for ancillary services were compared. A simple linear analysis was performed to determine the correlation between data points using the built-in function in MATLAB. The 'polyfit' function was used to perform a polynomial regression analysis. Specifically, a first-degree polynomial was fitted to the data. This function calculates the coefficients of the polynomial that best fit the data using the least squares method. The function 'polyval' was used to generate predicted values of the dependent variable based on the fitted line. The predicted values were then compared to the actual observed values to assess the precision of the model.

The same steps were also performed to visualize the difference in daily earnings from an aggregator. The different months were plotted to visualize the variation.

Public data from Mimer [37] of average bidding prices for FCR-D were gathered on an hourly basis to see if there was any variation during the time of day. FCR-D was chosen because it is best suited for batteries and is the main source of compensation for stationary batteries according to a business developer from CheckWatt [36].

The biggest factor for an aggregator to bid mobile battery energy on the frequency regulation market is knowing when the vehicle is connected to the grid. The business developer from CheckWatt [36] pointed out that there will always be an uncertainty factor associated with the potential compensation since a battery is not always connected to the grid. For that reason, three uncertainty factors were determined to make an appropriate assumption of what the losses in earnings from ancillary services would be for V2G users compared with the earnings for stationary batteries.

The result for potential earnings for V2G in the ancillary services markets was presented on seasonally averages to make an easier calculation of what the earnings could be for V2G.

### 4.2.3 Data of Historical Compensation for Ancillary Services

Svenska kraftnät has developed an estimate of future volume requirements for frequency regulation markets for the years 2024-2026 in Figure 12. The upcoming years are anticipated to witness growth in these ancillary services markets.

2024-01-19

## Preliminära framtida volymbehov kapacitetsmarknader för balansering



Figure 12: Estimation of the prospective volume needs in the capacity markets for reserves spanning from 2024 to 2026, gathered from SvK [38]. Reproduced with permission.

Table 4 displays the cumulative expenditure by Svenska Kraftnät on FCR-D over the recent years.

Table 4: Total money spent on FCR-D services in recent years. [39]

Year	The total amount spent on ancillary services
2023	6,1 billion [SEK]
2022	5,1 billion [SEK]
2021	2,9 billion [SEK]

SvK predicts an increase in the total cost of ancillary services in the coming years, estimating that the aggregate expense for all ancillary services in 2024 will reach approximately 8 billion [SEK] [40]. This provides a clear indication that these ancillary service markets will continue to be significant in the future and may even yield higher returns than they do today. Historical returns for ancillary services provide a justified depiction of how profitable it can be for individuals to connect energy storage to these ancillary service markets.

In order to make an assumption of compensation for ancillary services, data was collected from three different sources. Varberg Energi, CheckWatt and a customer to an aggregator. All based on a stationary battery where the compensation earnings is linear to the power of the battery, in this case the data is calculated for a battery with a power of 20 [kW]. In Figure 13 the compensation earnings from the different sources are presented. The data from aggregator customer are only from July 2023 to February 2024, therefore, the compensation is only presented in that range. The compensation from Varberg Energi [41] is distributed into monthly earnings and from CheckWatt [42] the data is presented on a yearly basis, hence an equal monthly compensation.

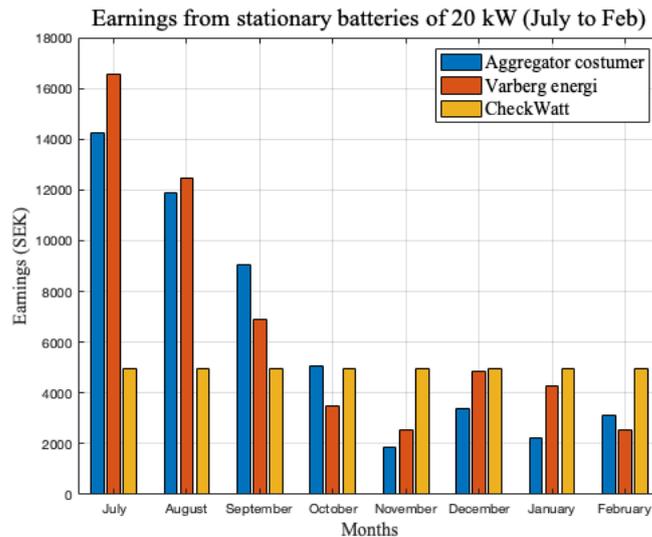


Figure 13: Compensation of ancillary services from three different sources during July 2023 to February 2024 [41], [42].

The main takeaway from Figure 13 is the pronounced seasonal dependency of compensation for ancillary services. Compensation is sometimes 3-4 times higher during the summer. According to the business developer from CheckWatt [36] this is due to the fact that hydropower contributes the majority of the volume to ancillary services during winter [38], especially FCR-D, which is the most frequently procured service for batteries.

To compare the annual compensation from the different sources, the total earnings from the aggregator customer is divided into an average monthly compensation based on the data for July to February and times the number of months per year. The result is presented in Table 5.

Table 5: Yearly compensation from ancillary services where it shows that the daily compensation varies between 176-275 [SEK]

Source	Yearly compensation	Monthly	Daily
Varberg Energi	99 006 [SEK]	8 251 [SEK]	275 [SEK]
CheckWatt	59 470 [SEK]	4 956 [SEK]	165 [SEK]
Aggregator Costumer	71 191 [SEK]	5 273 [SEK]	176 [SEK]

#### 4.2.4 Standard Deviation of Daily Compensation from Aggregator

The companies providing compensation for ancillary services do not show the variance between daily compensations over a month, thus enabling us to solely compare variance of the data from the aggregator customer. In Figure 14 the daily compensation for the customer to an aggregator is shown by circle dots. A red linear fitted line of the data point is also shown and calculated using a linear regression model in MATLAB. The mean value for each month and the standard deviation is also presented.

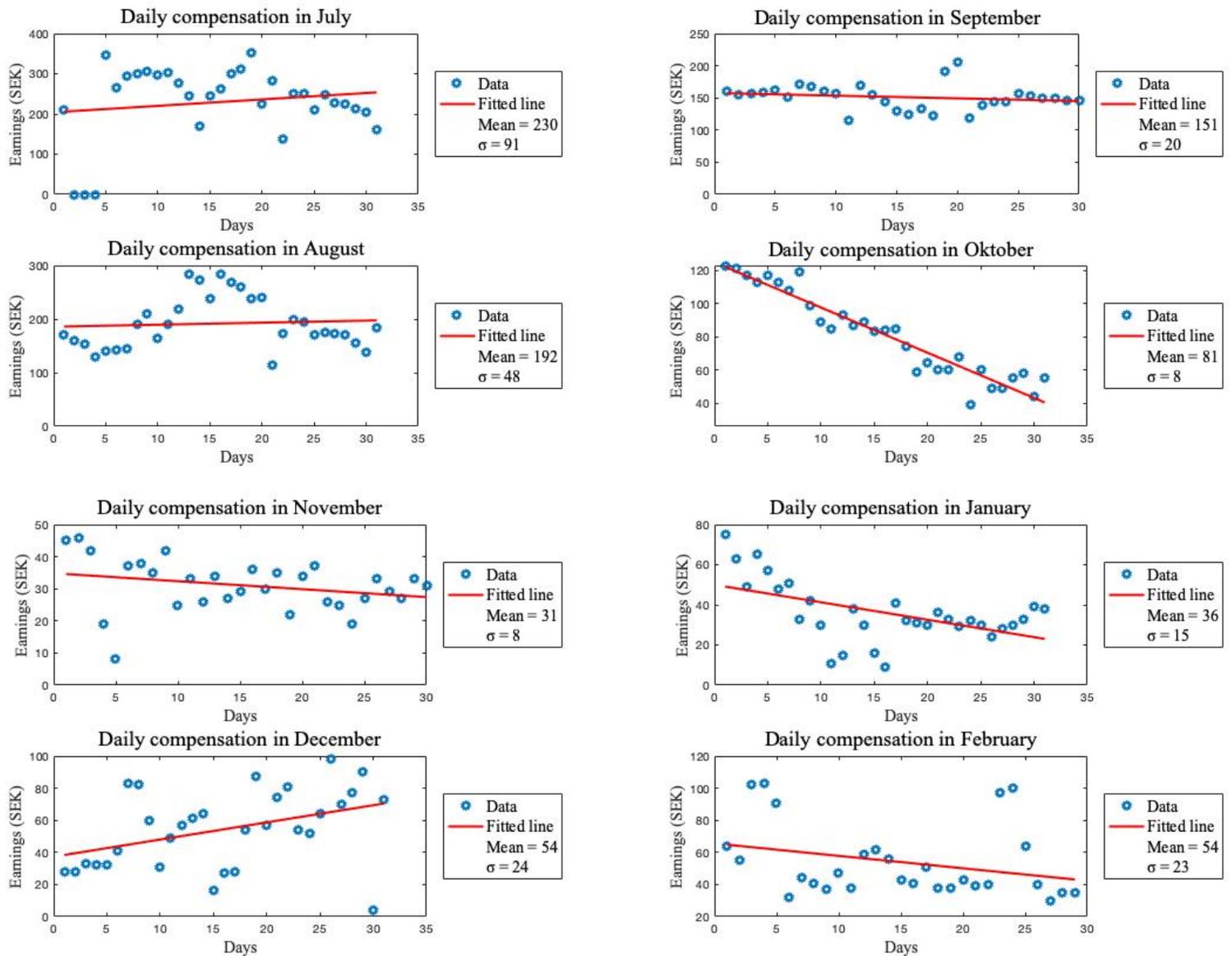


Figure 14: Daily compensation for an aggregator customer for the months from August 2023 to February 2024.

In Figure 14, it can be seen that daily compensation differs slightly over the months, mainly in the month of October. In general, the fitted line for each month exhibits a small slope and the standard deviation remains relatively small for every month except for July. The installation of the unit by the customer occurred towards the end of June, resulting in fluctuating data points for the compensation at the beginning of July, hence the significant standard deviation observed in July. Otherwise, the annual compensation is fairly consistent across days, with a few exceptions where the compensation may be slightly higher or lower. In general, this means that the day of connection does not make a significant difference, the compensation is quite consistent each month. The major variations in compensation are more seasonal dependent as shown in Figure 13.

### Hourly Variation in Bidding Price of FCR-D from Svenska Kraftnät

An aggregator does not display data on when a customer with an electric battery receives hourly compensation, instead, they provide daily compensation based on the prices at which SvK bids for

their ancillary services, according to the business developer from CheckWatt [36]. To determine whether there are fluctuations in SvKs bidding prices throughout the day, an analysis was conducted using data from Mimer [37]. The business developer from CheckWatt [36] explains that aggregators provide compensation to customers based on the prices at which SvK acquired ancillary services. In Figure 15 the variation in the average prices of FCR-D is shown with the time of day. The plot of the summer prices are an average of the prices bought at that time of the day during the summer period of the year, meaning April - September. The same process was used for the winter plot but for the winter period, October - Mars, shown in Figure 16.

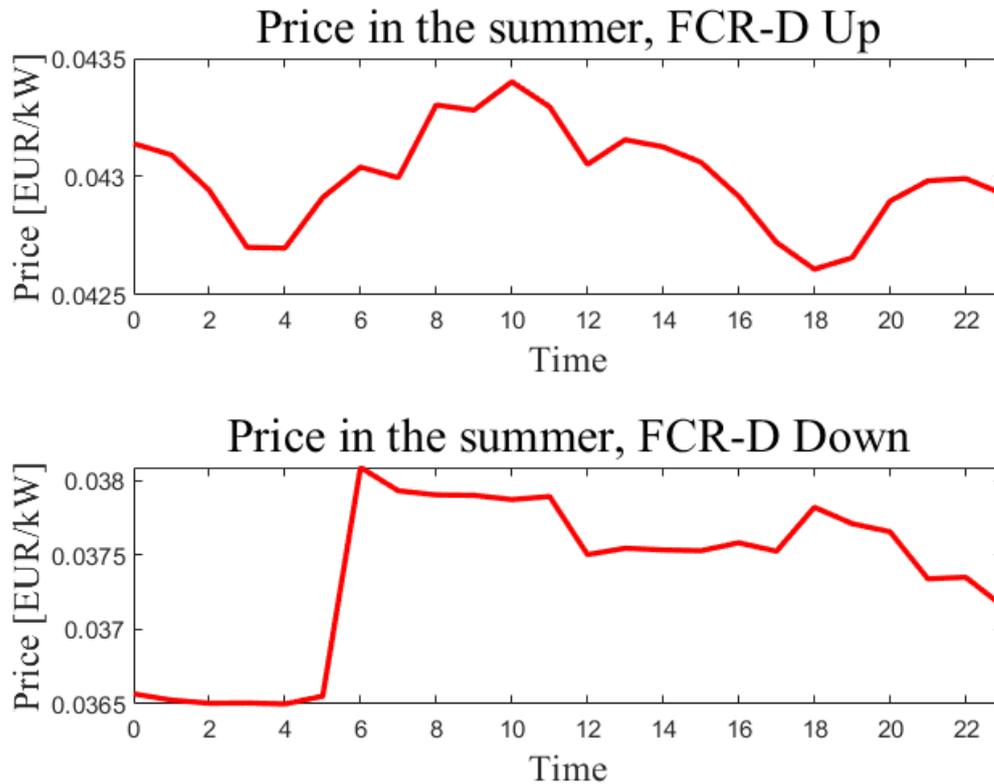


Figure 15: Graph showing varying bid prices throughout the day during the summer season, plotted using data from [37]. The upper graph is illustrating the regulation up and the lower is illustrating the regulation down.

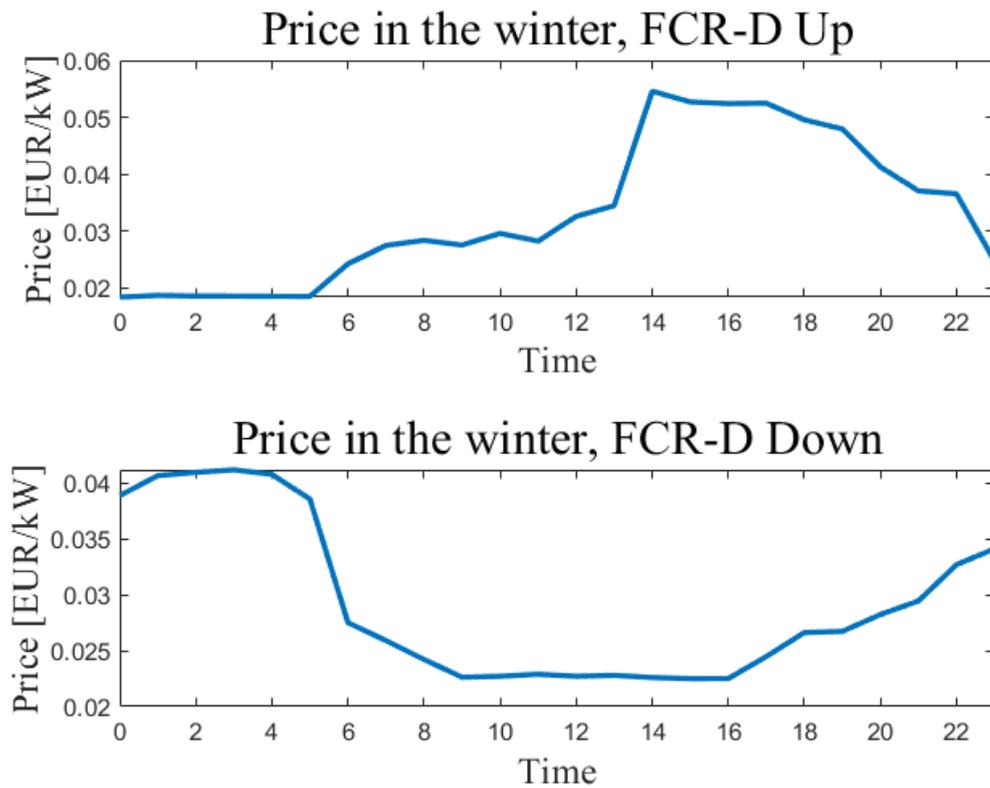


Figure 16: Graph showing varying bid prices throughout the day during the winter season, plotted using data from [37]. The upper graph is illustrating the regulation up and the lower is illustrating the regulation down.

In Figure 15, there is minimal variation in prices for both the upward and downward regulation, indicating that the returns throughout the day for FCR-D remain stable throughout the summer. Consequently, the timing of connection for providing ancillary services does not significantly impact the compensation received.

However, FCR-D bidding prices vary more during winter, as shown in Figure 16. That means that the time of day when you are connected to the grid may influence your compensation more. But as the general return for ancillary services is lower in the winter, the impact will be smaller on the total earnings over a year.

#### 4.2.5 Monthly Correlation Analysis Between Different Sources

The total amount of compensation for ancillary services is seasonally driven as seen in 13. The correlation analysis was performed between data from Varberg Energi and a customer of an aggregation company. To see how different the compensation was during the same time period, a linear regression model was implemented using MATLAB. The result and approximated functions are presented in Figure 17.

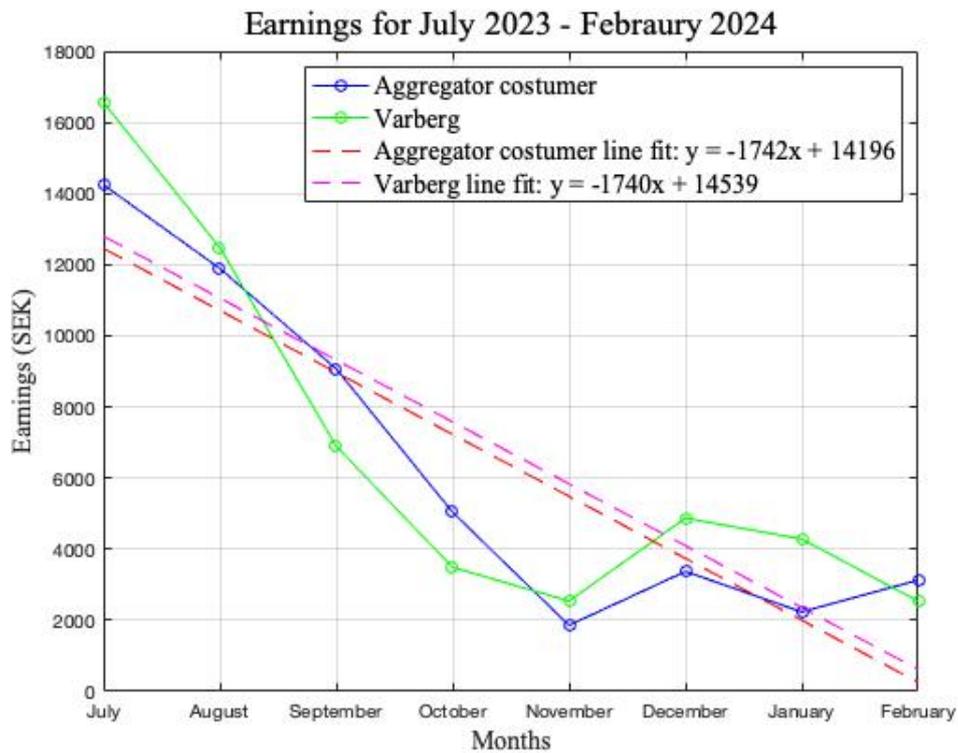


Figure 17: Linear regression plot between the compensation of ancillary services from Varberg Energi [41] and Aggregator customer during July 2023 to February 2024.

In the Figure 17 one can tell that the fitted functions between Varberg Energi and the aggregator customer are very similar and that they indicate very similar compensation from ancillary services during the same period. Consequently, the strong correlation between the two distinct sources provides a reliable estimate of the approximate compensation an individual could earn from the ancillary services using a stationary battery.

#### 4.2.6 General Compensation for Ancillary Services Related to the Cases

In order to make an assumption of what the compensation from ancillary services could be related to the different cases, some assumptions had to be made. To easier use the compensation earnings for each case, the earnings were divided into seasonally averages, one average compensation during the winter and one during the summer.

From the fitted functions in Figure 17, the following Equation 11-12

$$y_1 = -1742x + 14196 \quad (11)$$

$$y_2 = -1740x + 14539 \quad (12)$$

was used to calculate an average monthly compensation for the summer and winter period. The months considered summer period is April to September and winter period is October to Mars. In the fitted functions the first 3 integer is summer period and the last integers (4-8) is considered winter. These averages were then combined into a new average, one per season, and is displayed in Figure 18.

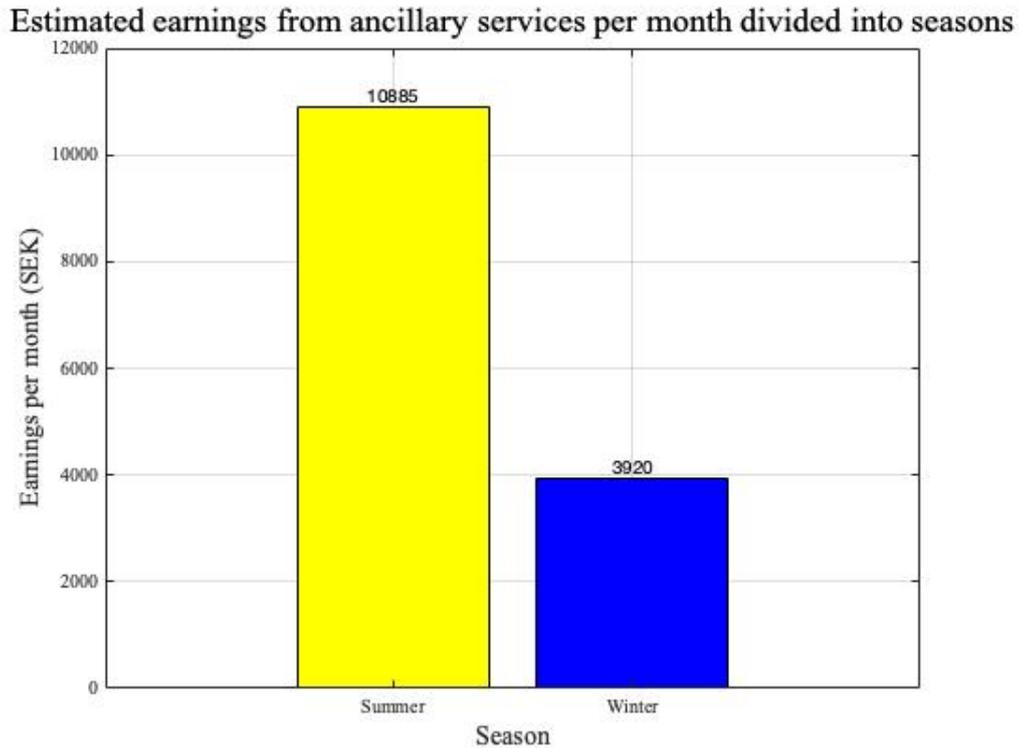


Figure 18: Approximated monthly average earnings for ancillary services divided into winter and summer season for a stationary battery.

#### 4.2.7 Analyze of Possible Revenue from Ancillary Services

The seasonally dependent averages displayed in Figure 18 are for stationary batteries. These batteries are constantly available to the power grid. Implementation of Bi-Directional charging for mobile batteries, for instance a car or a boat, entails an uncertainty factor for aggregators controlling the battery. It makes it more difficult for aggregators to bid planned capacity in the ancillary service markets. This uncertainty factor must be taken into account for potential compensation from the ancillary services. Hence, with increased scheduled utilization, such as that of your electric vehicle, aggregators gain a clearer understanding of the availability of one's EV battery and therefore they could plan their bidding on the ancillary markets easier. In other words, the more planned trips and usage of one's EV, the more one facilitates for aggregators controlling the battery, enabling its participation in ancillary service markets. This factor was important to consider in accordance with the business developer from CheckWatt [36].

To account for the uncertainty factor, three parameter of uncertainty in usage of the mobile battery and the uncertainty of availability to the aggregator, were implemented. To make a reasonable assumption for the uncertainty factor in the whole process, the normal distribution curve was used as a cornerstone. The values within the first standard deviation for a standard normal distribution curve are 68.3 %. Therefore, these parameters are used as a basis to estimate the uncertainty surrounding the amount of compensation a mobile battery can receive from ancillary services. There are 3 degrees of uncertainty.  $\alpha_1$  is the first order of uncertainty.  $\alpha_2$  and  $\alpha_3$  is the uncertainty raised to the power of 2 respectively 3. These parameters are presented in Table 6.

Table 6: Uncertainty parameters for the availability of mobile batteries as energy storage for ancillary service markets.

Uncertainty parameters	The degree of uncertainty in availability of mobile battery	Percent
$\alpha_1$	There will always be some uncertainty of when a mobile battery will be connected to the grid.	68,3 %
$\alpha_2$	Uncertainty parameter of one degree of more unpredictable usage of a mobile battery	46,6 %
$\alpha_3$	Highest degree of uncertainty in usage of the mobile battery. High variation in availability.	31,9 %

Compensation reimbursement from ancillary services regarding the uncertainty in the availability of mobile batteries is presented in Figure 19.

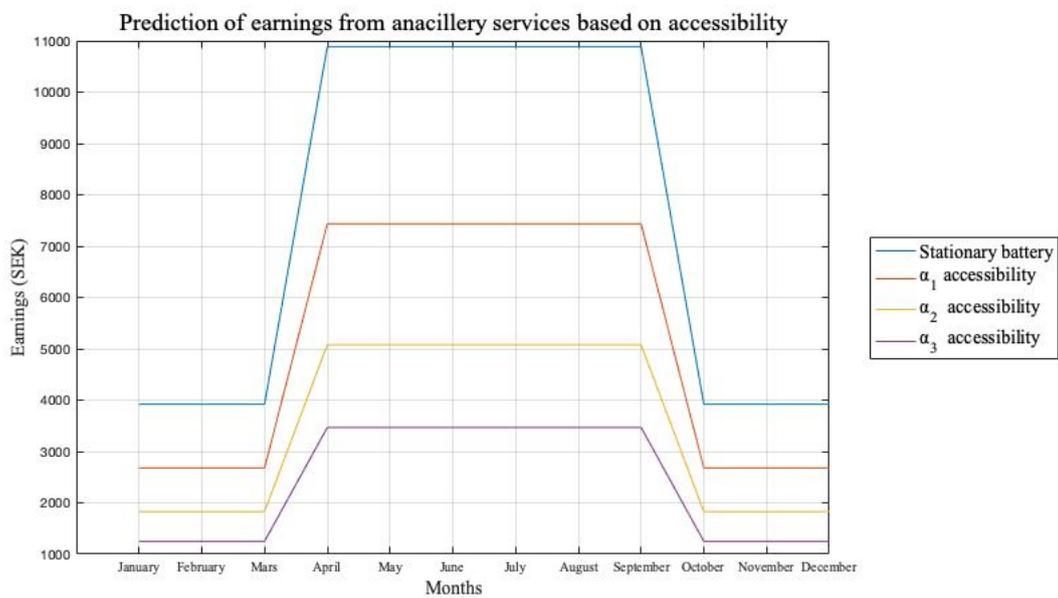


Figure 19: Graph of the compensation from ancillary services in consideration of uncertainty parameters

The total compensation regarding the uncertainty factors are summarized in Table 7 to provide a clearer picture of what the compensation could be with regards for uncertainly parameters.

Table 7: Summarization of compensation for ancillary services with regard to availability to the grid with uncertainty factors.

Type of compensation for a 20 [kW] battery	Average monthly compensation during winter season	Average monthly compensation during summer season	Yearly return
Stationary battery	3 920 [SEK]	10 885 [SEK]	88 827 [SEK]
$\alpha_1$ availability	2 677 [SEK]	7 434 [SEK]	60 666 [SEK]
$\alpha_2$ availability	1 829 [SEK]	5 078 [SEK]	41 442 [SEK]
$\alpha_3$ availability	1 249 [SEK]	3 468 [SEK]	28 302 [SEK]

The compensation values presented in Table 7 are based on if one unit is connected to the power grid around the clock all year round. In the specific cases one also have to take into account the

amount of time a unit is connected to power grid, which will have an impact of the compensation from ancillary services.

#### **4.2.8 Summary of Chapter regarding result from ancillary services**

This chapter presented historical earnings from ancillary services for stationary batteries. Compensation was combined with an uncertainty factor to address the availability factor of mobile batteries. The results serve as a starting point for estimating the compensation for ancillary services in the various cases.

## 5 Case Results

In this chapter the work process and results is presented for each selected case individually.

### 5.1 Case 1: Vehicle to Grid

The investigation into Vehicle to Grid (V2G) explores the potential for various car owners to utilize BD-charging and assesses its profitability.

#### 5.1.1 Work Process

The case study began with a literature study of BD-charging in general to obtain a better understanding of the subject and what the uncertainties are today.

The objective of this case was to combine driving pattern for EV users and historical earnings from ancillary services to see what the potential market could be for V2G. The results were then discussed considering the current state of the technology and the limitations of V2G.

Next step was to identify the user pattern to get a representative image of when this could be applied. Both a quantitative and a qualitative method were used to obtain a reliable result. A survey was sent out to get a larger number of responses, but both EV users and non-EV cars users answered. With sufficient amount of responses from the EV survey, the decision was to only comply the EV users answers, because it seemed more relevant to the project. To confirm the results of the more quantitative research, five interviews with EV users were held, to verify the result of the interviews, the summary was sent back to the respondent for approval.

To determine the potential profit of V2G, values for historical earnings from the ancillary services were used. Since the values presented were on a monthly or yearly basis, more specific data with daily precision were collected from an aggregator customer with a 10 [kWh] battery. The data process method is described in the same section as the general result from ancillary services 4.2.

An interview with the aggregator company Checkwatt were also held to get a better understanding of the Swedish energy market and the potential for V2G. Specified in section 3

To connect the user pattern and the possible profit for V2G, three example users were produced, based on the information from the survey and interviews. These users were complied to give a better understanding of what the result can be, so the reader can easier interpret and to identify oneself with the example users. Three users were established to view the different spectrum of the survey respondents and the interviewed.

The result of the possible return for a V2G system was summarized in tables to present the return based on peoples driving pattern for EVs.

A battery degraded simulation was also made based on the driving patterns of the EV users. Two different scenarios was made, one without BD-charging and one with BD-charging. The extra energy usage to provide the ancillary services was based on an example from Svk.

In order to discuss business models, literature studies were made to understand the future market for V2G. A study of future estimations regarding the number of EVs was conducted to be able to compare with the potential excess energy all the EV will have. Other cases and research were presented to compare the profitability of the V2G system.

#### 5.1.2 User Pattern for Electric Vehicle User

The first survey got 92 responses and the second got 256, the answers for both have the same tendencies and since the second had a bigger quantity of answers, the second was presented. The assumption is made that there is enough responses from EV users that only these responses would be evaluated.

For the case V2G the most important question is when the car is parked to be able to evaluate if it would be possible and profitable for the user to use V2G. The survey shows that most of the users keep their car parked from 18:00 to 07:00. It is assumed that the cars are parked at home during this time. In the figure 20 the parked time is shown as the colored parts.

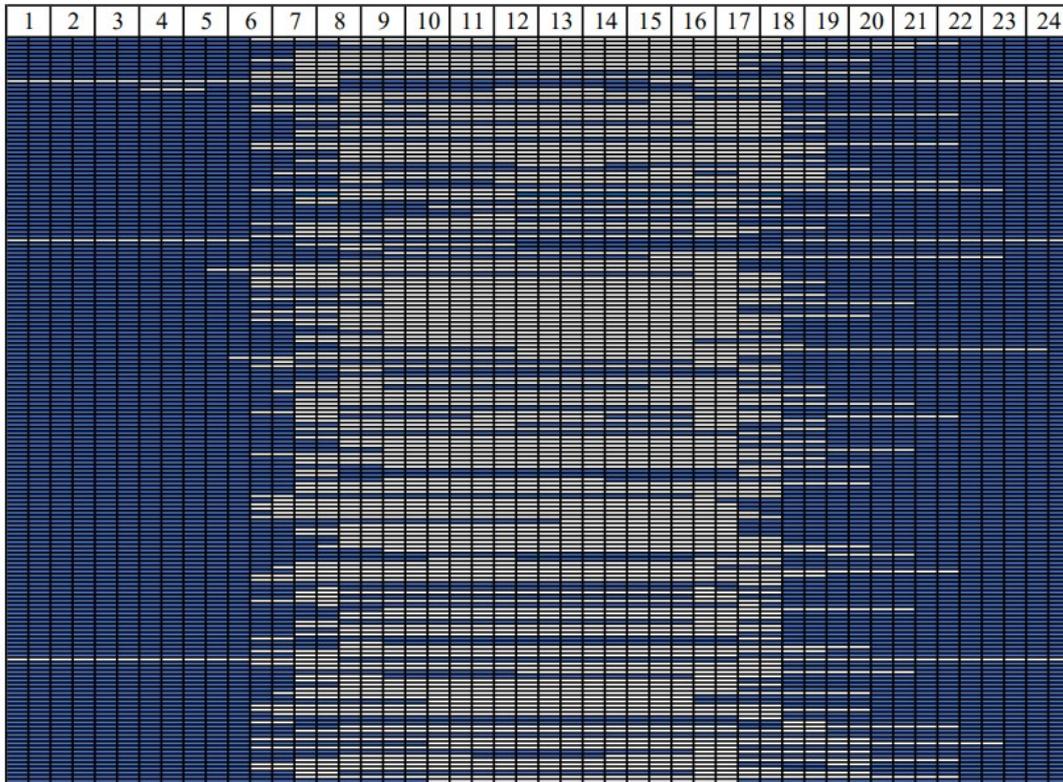


Figure 20: A visualization of when the car is parked with the blue colored parts being the time parked.

Other relevant questions for this case is "How far do you drive each day" and "How many hours do you drive each day". The answers are evenly distributed between the distances, and the highest option is "higher than 91 [km]". This graph can be seen in Figure 21. The evenly distributed answers correspond to the average driving distance each day for vehicles in Sweden in 2023, which is approximately 31 [km]. This validates the answers from the survey.

How many hours the respondents drive each day was mainly between 0-2 hours as seen in Figure 22.

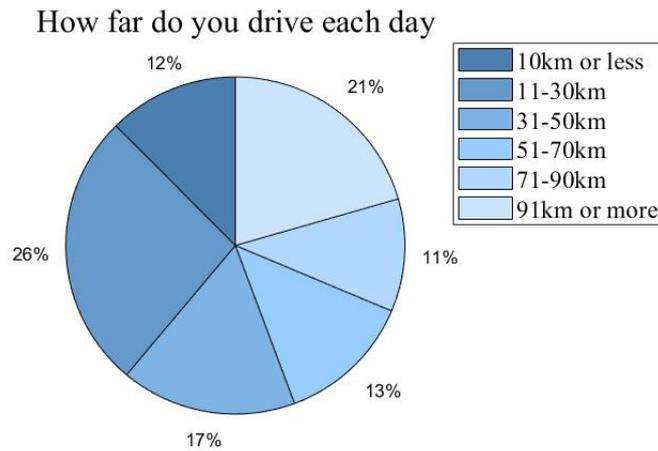


Figure 21: Survey results of the question "How far do you drive each day" indicating an evenly distributed result.

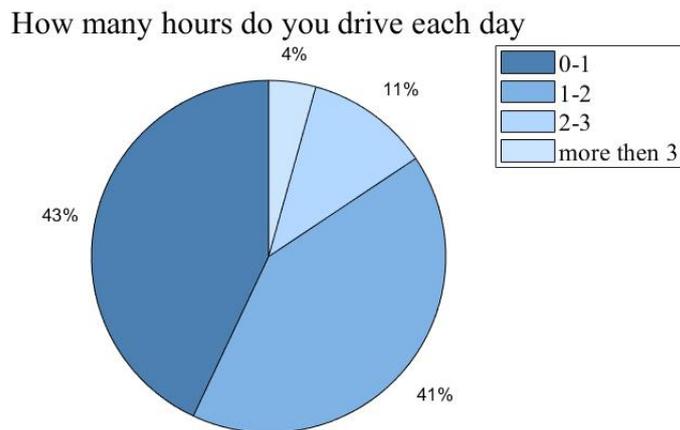


Figure 22: Survey results of the question "How many hours do you drive each day" showing that most users drive between 0-2 hours a day.

The questions "How many hours is your car parked at home" shows the result that 30 % is parked 9-12 hours a day at home and 41% is parked 13-16 hours a day. The graph illustrating these answers is presented in figure 23. There is also a question about where you charge your car which can be found in Figure 24 and 77% answers that they charge it at home and 13% that they do it at work.

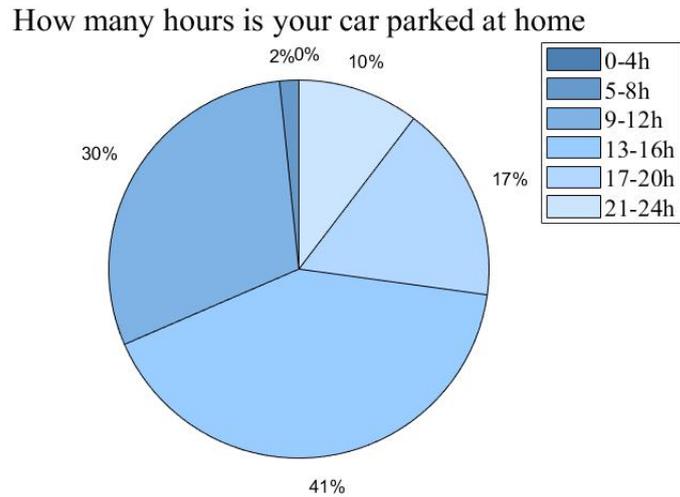


Figure 23: Survey results of the question "How many hours is your car parked at home" where it indicates a majority of the users is parked 9-16 hours a day.

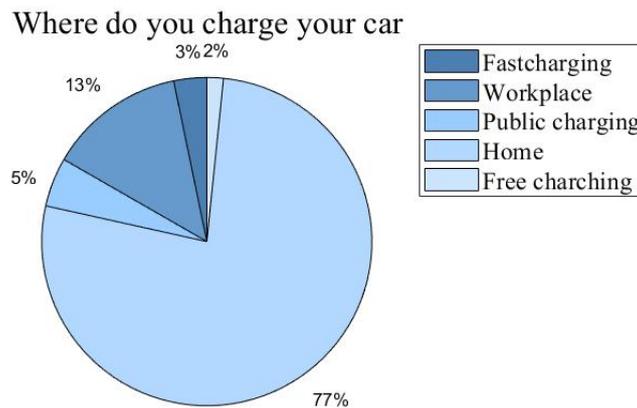


Figure 24: Survey results of the question "Where do you charge your car" showing that most users charge their car at home.

The results of the battery size is presented in figure 25 and 46% answered that their battery has a capacity of 71-80 [kWh].

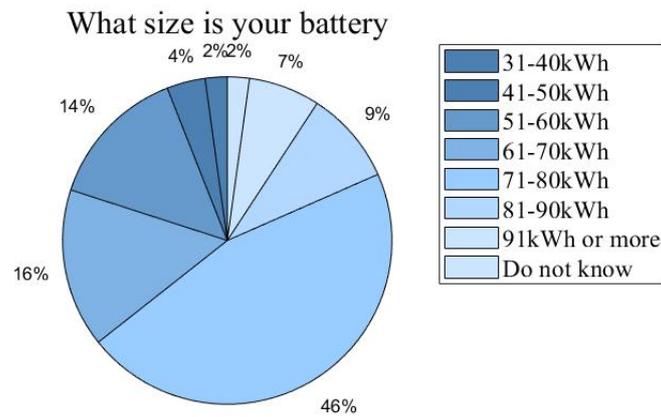


Figure 25: Survey results of the question "What size is your battery" showing that almost half of the respondents have a battery capacity between 71-80 [kWh].

The interviews gives more elaborated answers on what the car is used for but confirms the results of the survey that the car was not being used most hours of the day. One example from the interviews is presented in the table 8.

Table 8: Example Interview

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Distance [km]	13	13	13+8	13	13	50	0
Comment	Work and picking up children	Work and drop off children	Work, picking up children and grocery shopping	Work and drop off children	Work and drop off children	To fjällberget (skiing)	-

Most of the interviewed people that are working are using their car for transportation to work each day and the ones that work from home or are retired are mostly using it for visiting friends, shopping and/or different activities. Some of the activities seems to be happening every week and can therefore be assumed to be planned just as the trips to and from work. Three out of five respondents says they are charging their car at home most of the time, one of them are mostly using the charger at work and one is only using free fast chargers. This also confirms the results of the survey.

### 5.1.3 Example Users and their compatibility to Vehicle to Grid

Using the data collected from both the interviews and the survey three example users is produced to make it easier to visualize. These example users will be the basis of how much return an individual can earn for ancillary services and also the calculations of payback time for the investment in V2G.

For all the example users it is assumed that 10 [km] uses 2 [kWh] from the battery [43].

The first example user is based on the survey answer where people commute relatively far to work or other occupations. This user travels to work each day a normal week and has one main activity

on the weekend when they use the car, that activity lasts six hours away from home. The user pattern is presented in Table 9. Since this user is assumed to be driving to work in rush-hour, the average speed is assumed to be higher on the weekend than on the weekdays and therefore the distance is longer. The distance 91 [km] each weekday is chosen because it was the highest possible answer from the survey.

Table 9: Weekly usage pattern of example user 1, Long Commute.

Example user 1: Long Commute								
Capacity of car battery [kWh]	80							
Example Week	Mon	Tus	Wed	Thur	Fri	Sat	Sun	Sum
Daily driving hours [h]	2	2	2	2	2	2	0	12
Daily driving distance [km]	91	91	91	91	91	160	0	546
Hours the car is parked [h]	22	22	22	22	22	22	24	156
Hours the car is parked at home [h]	13	13	13	13	13	18	24	107
Used energy during driving [kWh]	18.2	18.2	18.2	18.2	18.2	32	0	123
Remaining capacity of car battery [%] (maximum SOC 80 %)	57.25	57.25	57.25	57.25	57.25	40	80	
Percentage of the time the car is parked [%]	92.9							
Percentage of the time the car is parked at home [%]	63.4							

The next example user is the opposite to the first one. It is based on the number of people in the survey who travel short distances each day. A sample week is also shown in Table 10, where each weekday consists of short travel distances and on the weekends one major activity, which last six hours away from home. The average driving speed for weekdays is shorter than the average driving speed on weekends, as it is assumed that the user travels in rush hour to and from work. The value of 15 [km] per workday is chosen since the survey shows that 26 % of the users drive between 11-30 [km] a day. 0.75 hours are chosen since 43% of the answers is between 0-1h.

Table 10: Weekly usage pattern of example user 2.

Example user 2: Short Commute								
Capacity of car battery [kWh]	80							
Example Week	Mon	Tus	Wed	Thur	Fri	Sat	Sun	Sum
Daily driving hours [h]	0.75	0.75	0.75	0.75	0.75	1.5	0	5.25
Daily driving distance [km]	15	15	15	15	15	50	0	125
Hours the car is parked [h]	23.25	23.25	23.25	23.25	23.25	22.5	24	162.75
Hours the car is parked at home [h]	14.25	14.25	14.25	14.25	14.25	18	24	113.25
Used energy during driving [kWh]	3	3	3	3	3	10	0	25
Remaining capacity of car battery [%] (maximum SOC 80 %)	76.25	76.25	76.25	76.25	76.25	67.5	80	
Percentage of the time the car is parked [%]	96.9							
Percentage of the time the car is parked at home [%]	67.4							

The last example user is based on the survey responses and the interviewees where the people who drive an EV are retired or work from home. For those instances they drive their car far less and does not commute to an occupation every weekday. The last example user is based on that extreme case, and also have one main activity on the weekend six hours away from home. In table 11 the user pattern for this user can be seen. Since the trips are supposed to not be done in rush hour, the average speed is higher than for the other users on weekdays.

Table 11: Weekly usage pattern of example user 3.

Example user 3: Work from home / Retired								
Capacity of car battery [kWh]	80							
Example Week	Mon	Tus	Wed	Thur	Fri	Sat	Sun	Sum
Daily driving hours [h]	0	1.5	0	1.5	0	1.5	0	4.5
Daily driving distance [km]	0	50	0	50	0	50	0	150
Hours the car is parked [h]	24	22.5	24	22.5	24	22.5	24	163.5
Hours the car is parked at home [h]	24	18	24	18	24	18	24	150
Used energy during driving [kWh]	0	10	0	10	0	10	0	30
Remaining capacity of car battery [%] (maximum SOC 80 %)	80	67.5	80	67.5	80	67.5	80	
Percentage of the time the car is parked [%]	97.3							
Percentage of the time the car is parked at home [%]	89.3							

All example users have an EV battery capacity of 80 [kWh] because it was the most common answer in the survey, and 3 out of 5 interviews had battery sizes of 80 [kWh].

#### 5.1.4 Return for Ancillary Services

To calculate the potential earnings an individual might obtain from ancillary services by utilizing their EVs battery, the example users are used. Potential earnings are assessed by comparing the return data from section 4.2 with the user pattern of these example users, excluding any consideration of investment expenses. Other tariff cost are already included in section 4.2.

The equation used to derive a compensation result for ancillary services for all example users is as depicted in 13.

$$Return\ per\ month = AMC \cdot \frac{365}{12} \cdot \alpha \cdot t_{available} \quad (13)$$

Where AMC is the average monthly compensation in [SEK] and  $t_{available}$  is the percentage of time that the car is available. The period is then divided into two seasons, summer and winter.

An important factor to consider is the uncertainty parameter of when the EV's battery is available for an aggregator to bid for their provides power to the ancillary services markets. According to a business developer from CheckWatt [36], the uncertainty factor will be the most decisive for the return of ancillary services from an aggregator. The more scheduled driving and planned usage of the car, the easier it is for an aggregator to bid and control the car battery. In the example user scenarios, the weekdays with planned commute trip to work are considered scheduled, and therefore obtains the  $\alpha_1$  uncertainty factor. This applies to example user 1 in figure 9 and 2 in figure 10. For example, user 3 in figure 11 the whole sample week is considered quite unpredictable, therefore, every day of the week is degree  $\alpha_2$ .

In all example user scenarios, the V2G charging system is installed at their residence, implying that whenever the car is parked at home, it is consistently connected to the charging unit, enabling the electric vehicle to supply energy to the grid.

#### Example User 1

The sample week, for example user 1 is presented in Table 12. The first row presents the percentage of the day the battery is available to the ancillary services. It also shows the duration the car remains parked at home, the uncertainty factor for that day, and the returns from ancillary services throughout the two different seasons. The table also includes the annual earnings from ancillary services for a V2G scenario.

Table 12: Estimated earnings from ancillary services for V2G for example user 1.

Example User 1: Long Commute	Weekday	Sat	Sun
Percent available to the grid each day [%]	54.2	75	100
Uncertainly factor [%]	$\alpha_1$	$\alpha_3$	$\alpha_3$
Return per day summer [SEK]	132	86	114
Return per day winter [SEK]	48	31	41
Return for one example week in the summer [SEK]	860		
Return for one example week in the winter [SEK]	312		
Total return for ancillary services for one year [SEK]	30 472		

One factor to consider is the SOC of the EV battery when returning home after a day of driving. When SOC is low, the user does not want to deplete energy to contribute to ancillary services upon arriving home. Instead, one prefers to charge the car. However, according to Table 9, it can be seen that User 1 never has less than 40 % SOC upon returning home and with 40 % of battery capacity for a 80 [kWh] battery, it is possible to drive 160 km, assuming a consumption of 2 [kWh] per 10 [km] [43]. Because of that the user should feel safe knowing that enough energy is left in the car for spontaneous trips. Therefore, User 1 has sufficient battery charge level to gradually recharge the battery in the evening while being available to support the power grid with ancillary services.

This reasoning is equally applicable to the other two sample users, for whom the minimum SOC upon returning home on any given day of the sample week is 67.5% for each.

### Example User 2

For user 2 the same uncertainty parameters as user 1 were assumed since the pattern is comparable but with shorter distances, as shown in Table 13.

Table 13: Estimated earnings from ancillary services for V2G for example user 2.

Example User 2: Short commute	Weekday	Sat	Sun
Percent available to the grid each day [%]	59,4	75	100
Uncertainly factor [%]	$\alpha_1$	$\alpha_3$	$\alpha_3$
Return per day summer [SEK]	145	86	114
Return per day winter [SEK]	52	31	41
Return for one example week in the summer [SEK]	925		
Return for one example week in the winter [SEK]	332		
Total return for ancillary services for one year [SEK]	32 682		

### Example User 3

For user 3, the same data as the other users is presented but the uncertainty factor is constantly  $\alpha_2$ . This is because each day would be equally uncertain, either only staying at home or a more spontaneous trip than the ones to work for user 1 and user 2. For user 3 each day is different and because of this each day is presented in Table 14.

Table 14: Estimated earnings from ancillary services for V2G for example user 3.

Example User 3: Work from home / Retired	Mon	Tis	Wed	Thu	Fri	Sat	Sun
Percent available to the grid each day [%]	100	75	100	75	100	75	100
Uncertainty factor [%]	$\alpha_2$						
Return per day summer [SEK]	165	124	165	124	165	124	165
Return per day winter [SEK]	60	45	60	45	60	45	60
Return for one example week in the summer [SEK]	1032						
Return for one example week in the winter [SEK]	375						
Total return for ancillary services for one year [SEK]	36 582						

### Net Result for Vehicle to Grid combined with Ancillary Services and Driving Costs

Table 15 displays the net outcome for V2G for home usage derived from historical earnings data. The cost of electricity for charging is assumed to be 2,18 [SEK], inclusive of taxes and additional charges, which was the average price of electricity for the household spring of 2024 in Sweden [44].

Table 15: Net result of V2G earnings over 1 year.

Result for 1 year	User 1	User 2	User 3
Return from ancillary services [SEK]	30 472	32 682	36 582
Cost for energy used when driving [SEK]	13 943	2 834	3 401
Sum [SEK]	16 529	29 848	33 181

The result of a V2G charging station at home shows that the profit from the V2G earnings for a year will cover the cost of driving the electric car for one year. This means that all example scenarios result in several thousand [SEK] in profit each year with a V2G system at home. This does not take into account a V2H system in which renewable energy sources such as solar panels are utilized. The profitability of such a system is described in detail in Section 5.2.

### Payback of Vehicle to Grid Investment

The cost of a V2G charging station is difficult to determine because it is such a new and untested technology. Since the majority of electric vehicles today do not support BD V2G charging [5], actors say V2G technology will be standard in a few years.

There are two options for the charger; either the converter is placed inside the car or in the charger, and in this case it is assumed to be integrated in the charger, allowing for DC-to-DC energy transfer. One possible BD-charger soon to be launched is the Quasar 2 [45] with a power of 11.5 [kW] for 4 000 [\$]. The company FerroAmp is testing a new 20 [kW] V2G charger which will soon be ready for the market [46]. In Table 16 we assumed that the Quasar 2 charger price will be approximately the same for a 20 [kW] charger from FerroAmp but since there is a cost for installation, the total will be assumed as 50 000 [SEK].

Table 16: Payback time for V2G system disregard to driving costs.

Payback of a 20 [kW] V2G system	
Average earnings from example users [SEK]	33 245
Cost and installation of V2G charging box [SEK]	50 000
Payback Time [years]	1,5

The pay back time is calculated to be 1.5 years. With the assumed lifespan of a normal EV charger, which ranges between 10-15 years [47]. The V2G charger will generate net profit of 8.5 - 13.5 years. Resulting in potential net earnings of 282 582 - 448 807 [SEK] for the average user in Table 16.

### Business Model Example for a Parking Garage

For a scaled-up business model example one can consider a parking garage. A garage with 50 slots with 50 V2G chargers, assumed to cost similarly to the Quasar two. If the parking garage has an average capacity of 75 % of EVs around the clock and does not charge the parked vehicle for the parking spaces, it instead takes 50 % of the compensation generated from the ancillary services that each EV produces. If we assume the first uncertainty parameter ( $\alpha_1$ ) for all EVs in the garage, the general result of the parking garage is presented in the table 17. This example does not account for the profit of charging the EVs in the garage and does not account for the cost of battery degradation when the EVs provides some energy to the ancillary markets.

Table 17: Simplified business model for a parking garage with V2G charges.

Business model parking garage	
Number of parking slots	50
Number of V2G chargers	50
Average capacity in garage [%]	75
Cost for V2G chargers [million SEK]	2.5
Earnings from the cars each year [million SEK]	1.14
Pay back time for V2G charges in the garage [years]	2.19

In this example, the EV owner still gets 50 % of the return from the ancillary services. That means if a person parked their car there every working day for a year, that is, 260 days, 8 hours parked each day. If the same uncertainty parameter is assumed ( $\alpha_1$ ), the return from the ancillary services will be 7 195 [SEK] per year for that person. That amount of money sometimes exceeds the cost of driving the EV, according to Table 15.

### Financial Result of US Perspective and other Research of Vehicle to Grid

A summarizing of other reports about the profit using V2G shows in [48] that the earnings in the U.S. can differ between around 0 to 4300 [EUR] per year. The difference in the structure of the market between the states in the U.S. is also brought up and that the research about V2G started earlier because of the regulations in California about zero emissions.

Fermata Energy gives possible earnings from V2G for a household and it differs depending on the state and how many chargers are being used [49]. For a household using one charger in New Jersey, the estimated earnings are 2 709 [USD], the highest of the possible states to choose from. The lowest is Colorado which gives 0 [USD]. The option international gives 977 [USD]. Fermata Energy has investigated how profitable it would be to use V2X in Texas and used a battery with 70 [kWh] and a charger with two different options for the effect, 7.7[kW] and 11.5 [kW] [50]. They also used two markets for selling and buying energy and four ancillary services for the calculations. One

vehicle using one charger and being active on all the possible markets, the profit can differ from 300 [\$] to 3 000[\$].

A report from the Australian renewable energy agency (ARENA) shows that an average EV could earn from 2 000[\$] to 12 000 [\$], depending on which ancillary service market they were bidding, using V2G technology [51]. The analysis delves into the role of EVs in frequency control ancillary services markets, called FCAS, utilizing V2G technology to contribute to the stabilization of the energy grid system. The trial consisted of an EV fleet of 51 cars and 51 V2G chargers from Quasar connected together, this case showed a business model potential for how a V2G concept could look like in the future. An important note this study discussed was the practical implementation of V2G technology necessitates careful and strategic management. As V2G technology experiences rapid growth and gains popularity in the future, there is a possibility of saturation in the FCAS market due to the abundance of EV battery capacity. This saturation may reduce the attractiveness of participating in FCAS markets for both EV owners and aggregators, according to the study.

### 5.1.5 Vehicle to Grid Impact on Vehicle Battery Degradation

The effects on the battery for all three example users are calculated by using the battery degradation model presented. Two different driving cycles per user are defined, one with V2G and the other without V2G. To obtain an appropriate comparison between the users one day of the example week is used in the model as a basis of reference; the day is Monday. The model uses the same effect for charge and discharge and because of this the driving time was used for the different users. To account for how much energy activated in the V2G scenario, the probability of energy activation in Svk calculation example for FCR-D down is used [52] which is the assumption of 1.5 % of the available energy is activated. This is assumed to be the same for FCR-D up since 2022 there was 1.02% of the time a higher frequency than wanted and 0.81% lower than wanted [53]. For the simulation, the full 20 minutes [54], [55] for each activation was used and an activation of FCR-D up was assumed to be followed by an activation of FCR-D down and the other way. To make it more realistic every other activation was started with FCR-D up and followed by FCR-D down and the rest was the opposite. The model operates for a 24-hour period with 20 minute intervals, indicating that energy activation aligns with these intervals. The C-rate in the model was set by the previous assumption of a 20 [kW] charger. For a Volkswagen ID.4, this corresponds to a C-rate of 0.25, roughly equal to the discharge rate during highway driving at 23 °C at 110 km/h [56]. That makes a C-rate value of 0.25 valid both during charging and discharging.

The driving cycle for user 1 is presented in Table 18.

Table 18: Normal driving cycle on a Monday for User 1 without V2G

Driving cycle User 1		
Hours	Cycle for a Monday	SOC
00:00 - 07:00	Idle	80 %
07:00 - 07:20	Discharging	71.7 %
07:20 - 07:40	Discharging	63.4 %
07:40 - 08:00	Discharging	55.1 %
08:00 - 17:00	Idle	55.1 %
17:00 - 17:20	Discharging	46.8 %
17:20 - 17:40	Discharging	38.5 %
17:40 - 18:00	Discharging	30.2 %
18:00 - 18:20	Charging	38.5 %
18:20 - 18:40	Charging	46.8 %
18:40 - 19:00	Charging	55.1 %
19:00 - 19:20	Charging	63.4 %
19:20 - 19:40	Charging	71.7 %
19:40 - 20:00	Charging	80 %
20:00 - 24:00	Idle	80 %

The driving cycle with V2G adds an additional 20-minute interval of discharging, respectively, charging during the night every other day. Since 1.5 % of the time user 1 has the EV parked at home is approximately 12 minutes, the energy activation in this case is every other day because the model uses intervals with 20-minutes.

The battery degradation for user 1 can be seen in Figure 26 when using V2G respective not.

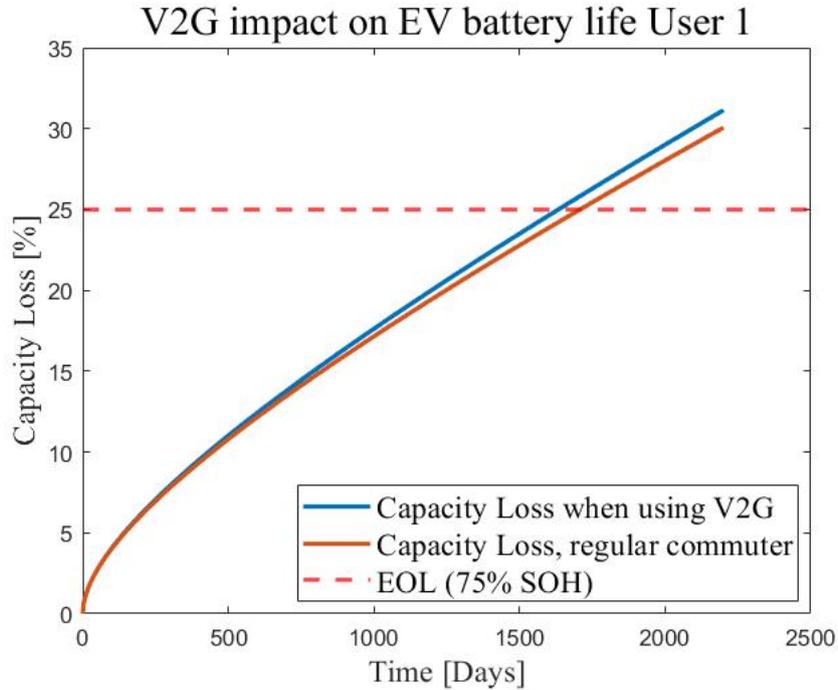


Figure 26: Battery degradation for user 1 with V2G and without during one year.

In Figure 26 - 28 the x-axis represents the degradation of the defined number of cycling days for a new battery and the y-axis represents the capacity loss in percentage. In this graph, it indicates that cycling the battery for one year with normal commute routes and incorporating BD-charging does not significantly age the battery. The battery ages 4.4% faster using BD-charging compared to regular commuter. It is important to clarify that this model only simulates one weekday with the same user pattern for an entire year.

The driving cycle for user 2 is presented in Table 19.

Table 19: Normal driving cycle on a Monday for User 2 without V2G

Driving cycle User 2		
Hours	Cycle for a Monday	SOC
00:00 - 07:00	Idle	80 %
07:00 - 07:20	Discharging	71.7 %
07:20 - 07:40	Discharging	63.4 %
07:40 - 17:00	Idle	63.4 %
17:00 - 17:20	Discharging	55.1 %
17:20 - 17:40	Discharging	46.8 %
17:40 - 18:00	Charging	55.1 %
18:00 - 18:20	Charging	63.4 %
18:20 - 18:40	Charging	71.7 %
18:40 - 19:00	Charging	80 %
19:00 - 24:00	Idle	80 %

The same argument for the V2G case is applicable for user 2. The V2G driving cycle adds an additional 20-minute interval of discharging, respectively, charging during the night every other day. Because 1.5 % of the time user 2 has the EV parked at home is approximately 13 minutes, the energy activation in this case is every other day because of the 20-minute interval. This represents 0.0415 more cycles per day with BD-charging.

In Figure 27 the battery gets 5.6 % shorter life using BD-charging than without. Note that user 2 has notably less driving miles per year than user 1. It is important to clarify that this model only simulates one weekday with the same user pattern for an either year. As user 2 has approximately the same hours parked at home, the same assumption for energy activation was made for user 2, indicating that with BD-charging, the battery undergoes an additional 0.0415 cycles per day.

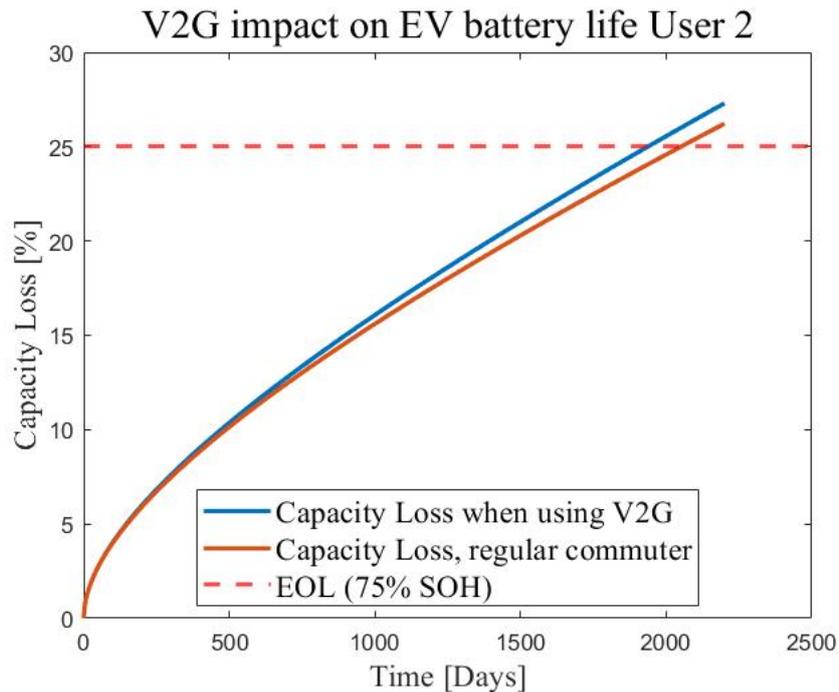


Figure 27: Battery degradation for user 2 with V2G and without during one year.

In Table 20 the driving cycle for user 3 an ordinary Monday is presented. Since this user is parked at home all day there is one activation of FCR-D up and FCR-D down each day and this is varied the same way as user 1 and user 2. In Figure 28 the degradation of the battery can be seen and the extra degradation using V2G for user 3 gives a 22.5% shorter life of the battery.

Table 20: Driving cycle for User 3 assuming Monday for the whole simulation namely EV is Idle for one year.

Driving cycle User 3		
Hours	Cycle for a Monday	SOC
00:00 - 24:00	Idle	80 %

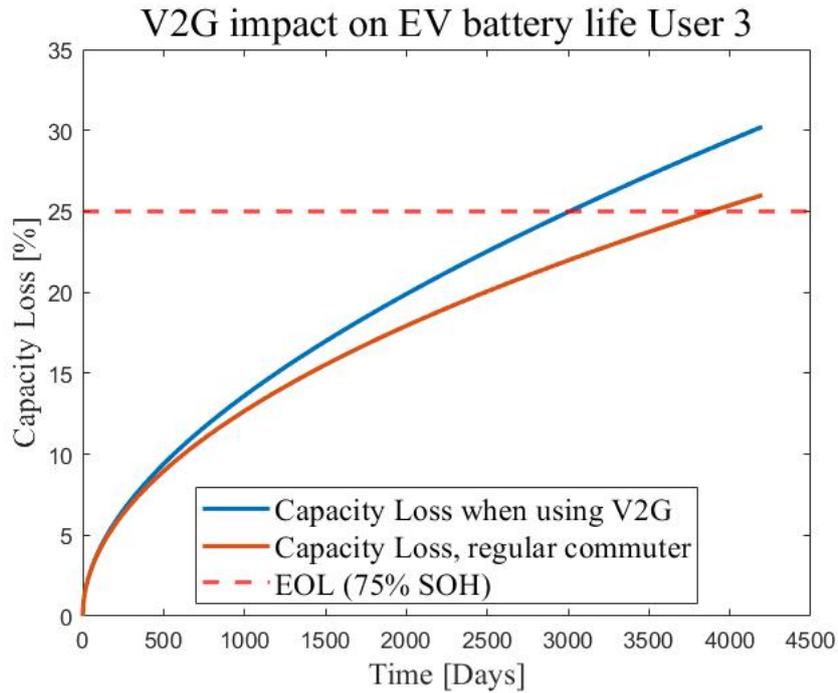


Figure 28: Battery degradation for user 3 with V2G and without during one year.

The amount of full equivalent cycles the battery does before EOL is presented in the table 21 for each user, both for using BD-charging and not.

Table 21: The amount of full equivalent cycles the battery does before EOL using BD respective not

	Full equivalent cycles with BD	Full equivalent cycles without BD
User 1	881	850
User 2	723	681
User 3	1213	0

### 5.1.6 Market for Vehicle to Grid

Numerous implementation possibilities do exist for V2G technologies, offering significant future advantages for both energy utilization for an EV battery and grid stabilization. According to section 5.1.4, the overall returns across various user scenarios involving V2G can be profitable. The potential for V2G to unlock flexibility in the electricity system is significant. According to the survey, 84 % drives less than two hours a day, which means that the car is standing still almost 92 % every day. This coincides with what a report from KTH [57], where around 96 % of the time, private vehicles in Stockholm remains parked. As detailed in the survey, 81 % drives less than 90 [km] per day and the average capacity of the EV batteries was approximately 80 [kWh]. This implies that if one assumes that the EV driving efficiency is 2 [kWh] per 10 [km]. The vast majority of survey respondents only use 22,5 % of the car battery each day. Leaving 78,5 % of the capacity unused which could be used in more efficient ways.

The market for EVs is rapidly growing; according to Power Circle [58] the number of full EVs in Sweden was approximately 290 000 by the end of 2023. Based on the survey result for driving distance, battery size, and the excess energy stored in all EVs during one day is approximately 18 [MWh] of energy that could help balance the grid and cut power peaks. A long-term forecast from Power Circle also indicates that by 2030, there could be 3 million EVs in Sweden. With the same user pattern, battery size and excess energy as before, by 2030 the flexible energy of all the EV will be approximately 188 [MWh] each day. The Swedish energy agency [59] estimates that 10 % of

Sweden's EV fleet will adapt V2G technology by the year 2030, and by 2050 the entire EV fleet in Sweden will have V2G technology. Their results predict that the energy flexibility potential with V2G in 2030 will be around 200 [MWh/h], which correlates with this study. The excess energy can facilitate local power balancing for DSOs and global power balancing for TSOs.

#### **5.1.7 Summary of Case 1: Vehicle to Grid**

The main conclusion of this study is that currently, EV owners do not utilize their vehicle's battery to its full potential. This unused energy could potentially be employed in V2G systems. It has been shown that V2G systems can produce profits for individuals and other stakeholders, given the historical earnings from ancillary markets. Importantly, it has been observed that diverting a portion of the EVs energy to these services does not hasten the degradation significantly of the battery. The findings suggest that, based on historical evidence, V2G systems are economically viable.

## 5.2 Case 2: Vehicle to Home

The following section will firstly explain the work process for the investigation of Vehicle to Home (V2H), see Figure 29. Afterwards significant data will be presented with reasonable explanations. Lastly the outcome of the investigation will be presented.

### 5.2.1 Work Process

The V2H study explores the potential benefits of integrating Bi-directional charging into residential settings. It examines the implications for homeowners from both an energy efficiency and a financial point of view. To ensure the accuracy of the findings, the study primarily relies on a simulation using collected real-world data from a household in Sweden. The home is equipped with solar panels and a battery. The simulation looks at two different scenarios for the home, one with V2H and one without V2H. The following case looks at the opportunities of replacing the expensive battery and instead using V2H with an electric vehicle. A visualization of the work process can be seen in Figure 29.

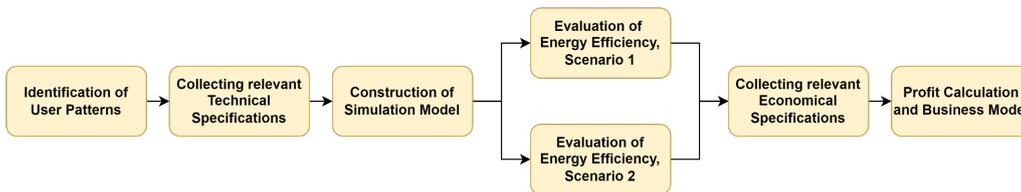


Figure 29: Illustration of the work process for Vehicle to Home.

To initiate the simulation model, the process starts with an analysis of user behavior through a distributed survey. This survey is designed to gather details on the availability of the EV for V2H usage.

The simulation model utilizes data from July 2023 and January 2024, which represent the warmest and coldest months in Sweden, respectively. This selection is strategic to evaluate the effectiveness of V2H during both high and low demand periods throughout the year. Essential data and information were necessary to develop and construct the simulation model. The collected data and information included the following:

- Hourly values of the home electricity consumption.
- Hourly values of the solar production.
- Information about main fuse and maximal power output and input.

The MATLAB-based simulation model computes hourly electricity surpluses or deficits by analyzing solar output and residential power usage, with regard of dynamic load balancing in the home charger. In the V2H scenario (later referred to as first scenario), these surpluses or deficits either charge or deplete the car battery. The model incorporates a maximum power threshold and monitors the SOC of the battery, where there is a maximum and a minimum SOC. Any surplus or deficit beyond the maximum power limit is subsequently traded with the grid. The same occurs if the battery's SOC reaches its upper limit or lower limit, and there is still a surplus or deficit, the electricity is directly traded with the grid. This also applies when the car is not available, typically during work hours. Assumption of how much energy is consumed during commutes to and from work during both summer and winter will be made.

In the setup without V2H (second scenario), the model represents a basic household equipped with solar power and an electric vehicle. The vehicle battery does not adjust its charge state based on a surplus or shortage of electricity. Rather, depending on whether there is a surplus or shortage, electricity is either purchased from or sold to the grid. The battery only depletes its charge during commutes to and from work. Upon depleting to a minimum SOC, the vehicle will undergo normal charging, contributing to the household's power usage and an additional expense.

The business model relies on economically comparing two scenarios. For calculation purposes, the necessary data included:

- The average price for buying electricity from the grid and additional expenses.
- The average price for selling electricity to the grid and additional commissions.
- Profit from ancillary services from an aggregator.

An average for the purchase and sale price of electricity was given by the homeowner for both July and January. As the homeowner had a monthly deal with the local electricity supplier, there were additional variables needed to consider for the purchase and sale price, as in a variable fee, a fixed fee and also grid benefit commission. The fixed fee will be disregarded as it will not make a difference in the comparison between the two scenarios. Tax was included in the variable fee and was added to get a final purchase price. Regarding the sale price, the grid benefit commission was added to get a final price. Lastly, the total volume of purchased and sold electricity was summarized, then multiplied with the respecting price. Data on profits of using ancillary services were also given, which were included in the final overall profitability of the scenarios with V2H. The overall profitability included the total sale price, total purchase price and total ancillary services price (excluded for the second scenario).

The outcomes for both scenarios will be depicted in charts illustrating the car battery's SOC and grid usage. The business model will be displayed using a bar chart detailing the volume of sold and purchased electricity transactions and overall profitability, both in the currency [SEK].

### 5.2.2 Technical Specification for Simulation Model

The simulation model focuses on a residence located in Electric Area 4 in Laholm, Sweden. This home is outfitted with 96.7 [m<sup>2</sup>] of solar panels which produce about 20 600 [kWh] of renewable electricity each year, while the household's electricity annually usage is roughly 20 000 [kWh]. A 10 [kWh] battery is also incorporated into the solar power system to provide ancillary services, aiding in both the storage and distribution of electricity either for use within the residence or for export to the electrical grid. An inverter, integrated within the home charger, will be utilized in the simulation to facilitate the conversion of electricity from AC to DC (to charge the EV) and from DC to AC (to discharge the EV). The specific data employed in the simulation model are as follows, refer to Table 22:

Table 22: Established Technical Specifications required in the simulation model.

Technical Specifications	
Electric Vehicle Battery Capacity [kWh]	75
Maximum SOC [%]	80
Minimum SOC [%]	20
Power Input [kW]	17
Power Output [kW]	11

### Electric Vehicle Battery Capacity

To determine the suitable battery capacity, both survey results and statistical analysis were utilized. The survey showed that the battery capacities of most electric vehicles fall between 71-80 [kWh], as depicted in Figure 25. According to the statistical analysis, the battery capacities varied from 57.5 to 72.8 [kWh], further details are provided in the Appendix A.1. Observing the most frequent battery size across all EV models listed, it was noted that the larger battery size was more prevalent. Considering both the survey and statistical insights, the battery capacity was initially established at 75 [kWh].

### Maximum and Minimum State Of Charge (SOC)

The maximum and minimum SOC is set at 80% and 20%. Reason being as explained in the theory section about battery degradation, see Section 2.2.

### Power Input and Output

The power input specification for the EV battery is established at 17 [kW] due to the household's main fuse being rated at 25 [A], which imposes a maximum power capacity of 17 [kW] [60]. The output power is set to 11 [kW], as the majority of EVs that are capable of V2H have a maximum output power of 11 [kW] [61].

### Work Hours and Electricity Consumption of Commute

Survey findings show that most people in Sweden depart for work at 07:00 and return at 18:00, as referenced in Figure 20. Consequently, within the simulation, the EV cannot be used for V2H during these hours on weekdays (assuming a typical Monday to Friday work schedule). Battery usage for daily commutes to and from work is estimated at approximately 7% in the summer and 15% in the winter.

#### 5.2.3 Economical Specification for Business Model

For the business model, the following specifications are used, gathered from the residence in Electric Area 4, see Table 23:

Table 23: Established Economical Specifications required for the Business Model.

Economical Specification	January 2024	July 2023
Average Purchase Price [SEK/kWh]	1.29	0.7279
Variable Grid Fee - including Tax [SEK/kWh]	0.6	0.6
<b>Final Average Purchase Price [SEK/kWh]</b>	<b>1.89</b>	<b>1.3279</b>
Average Sale Price [SEK/kWh]	0.798	0.3767
Grid Benefit Commission [SEK/kWh]	0.036	0.036
<b>Final Average Sale [SEK/kWh]</b>	<b>0.834</b>	<b>0.41274</b>
<b>Ancillary Services Commission [SEK]</b>	<b>1058</b>	<b>7123</b>

#### Average Purchase Price

The average purchase price, which is 1.29 and 0.7279 [SEK/kWh] respectively, represents the mean cost of electricity purchased from the grid during those months. A variable charge (inclusive of tax) of 0.6 [SEK/kWh] was applied, resulting in a total purchase price of 1.89 [SEK/kWh] and 1.3279 [SEK/kWh].

#### Average Sale Price

During those months, the average selling price for electricity fed back into the grid was 0.798 and 0.3767 [SEK/kWh]. After adding a grid benefit fee of 0.036 [SEK/kWh], the final sale prices were revised to 0.834 and 0.41275 [SEK/kWh].

#### Ancillary Service Commissions

The ancillary service commission amounts of 1 058 and 7 123 [SEK] represent the majority of the total earnings for the household in those respective months. It is important to note that these commissions are associated with the 10 [kWh] battery installed in the household, which is accessible at all times. However, the simulation model will exclude a portion of these commissions since the EV battery will not be accessible during work hours.

### 5.2.4 With and Without Bi-Directional Charging during Summer

The following section will present the result of using Bi-directional charging or not during July 2023 in Sweden.

#### Battery State Of Charge and Volume of Sold and Purchased Electricity

The simulation model gave the following result for the SOC of the EV battery and the volume of sold and purchased electricity during July 2023.

The findings indicate that V2H in the summer maintains the vehicle's SOC between 50% and 80%, as illustrated in Figure 30. Additionally, Figure 31 demonstrates the feasibility of disconnecting from the grid in the summer months through V2H.

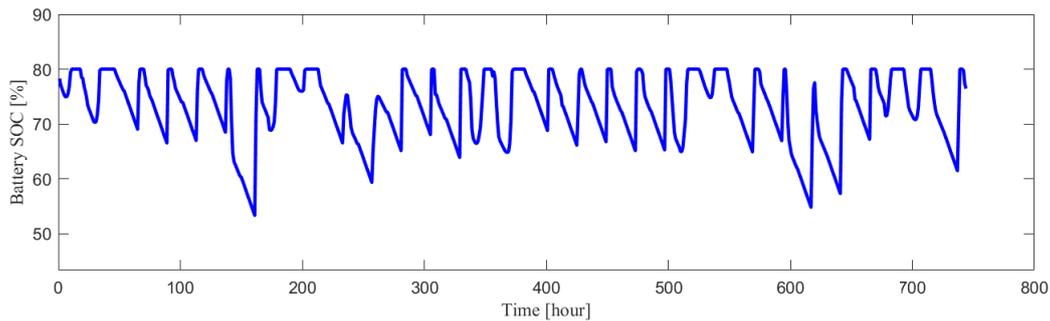


Figure 30: Battery SOC with V2H.

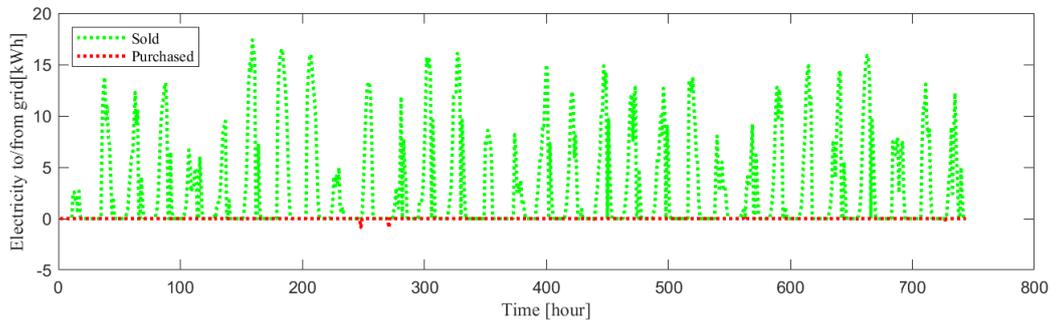


Figure 31: Sold (green) and purchased (red) electricity with V2H.

The outcome of the second scenario, without V2H, indicates a continuous decrease in the EV's SOC until it reaches below the limit of 20% and recharges, as illustrated in Figure 32. The EV recharges 2 times during the month. Figure 33 highlights the primary distinction from the V2H scenario, which is the need to buy electricity from the grid during evening and nighttime hours.

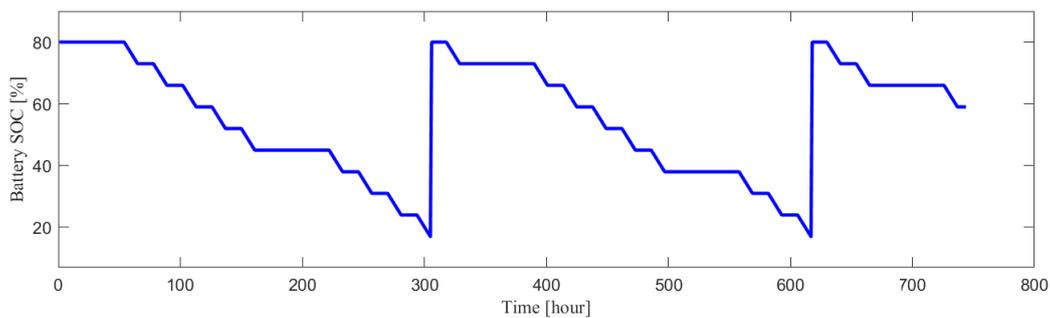


Figure 32: Battery SOC without V2H.

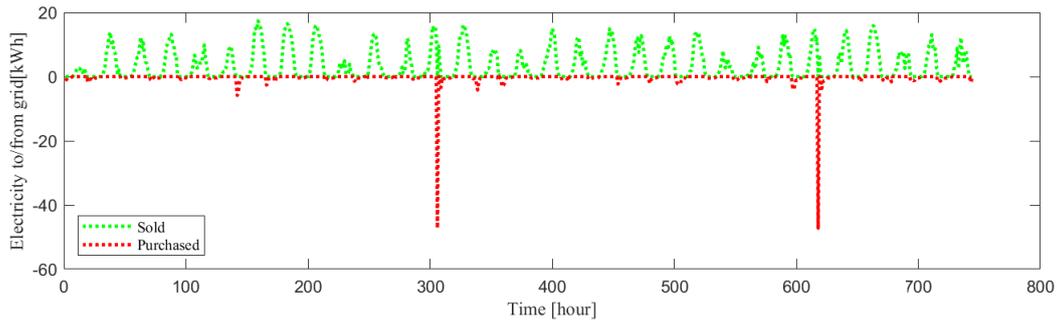


Figure 33: Sold (green) and purchased (red) electricity without V2H.

Summarizing the total volume of sold and purchased electricity gave the following result for both scenarios, see Table 24. The 3 [kWh] of purchased electricity from the grid in the first scenario was always during weekdays when the EV was unavailable. For the second scenario, the 300 [kWh] purchased electricity was during early morning and nighttime. The case for the sold electricity was the opposite, namely during daytime (work hours).

Table 24: Summary of total volume electricity from the grid.

Volume of Sold & Purchased electricity from the grid		
	Purchased [kWh]	Sold [kWh]
With V2H	3	2247
Without V2H	300	2631

### Business Model during July

Considering the sale and purchase prices, the outcome is presented in Figure 34. Predictably, the total sales profit was predominant for the first scenario.

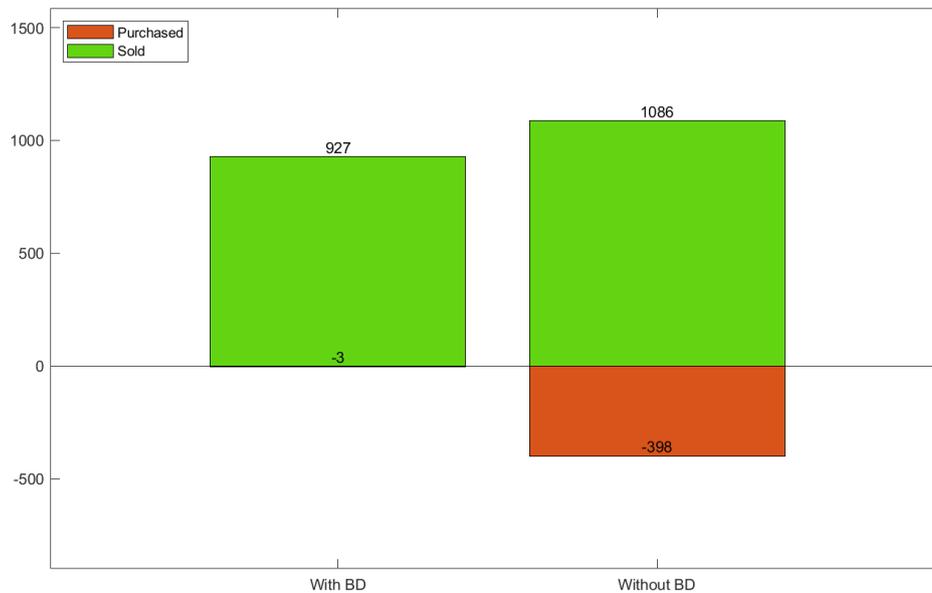


Figure 34: Amount earned and spent on electricity, July 2023.

Finally, ancillary services were to be included in the equation to finalize the total profits during July 2023, see Figure 35. The ancillary service commission comes in at 4 911 [SEK] for the month and is the biggest factor for the difference in profitability between the two scenarios.

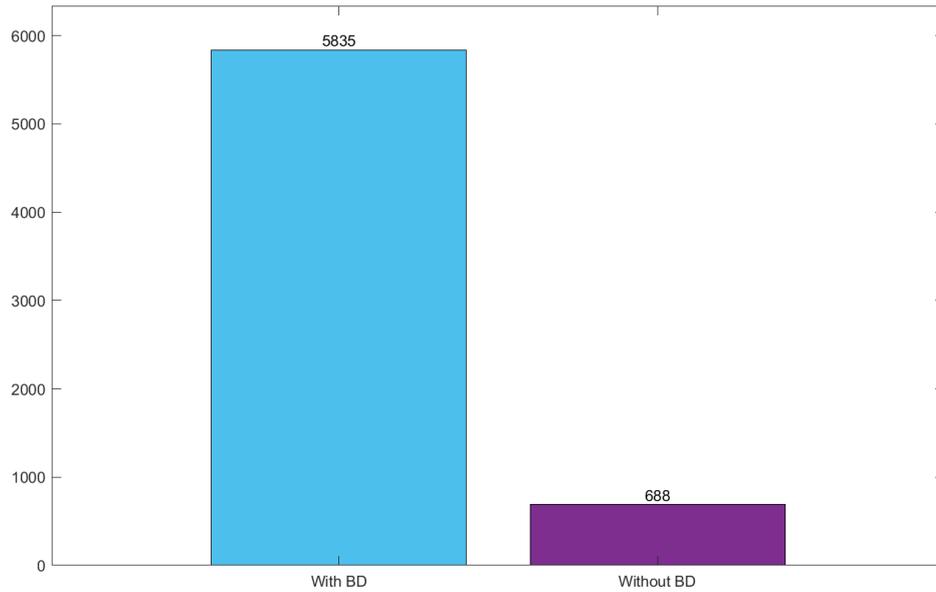


Figure 35: Profitability of both scenarios.

### 5.2.5 With and Without Bi-directional Charging during Winter

The following section will present the result of using Bi-directional charging or not during January 2024 in Sweden.

#### Battery State Of Charge and Volume of Sold and Purchased Electricity

The simulation model gave the following result for the SOC of the EV battery and the volume of sold and purchased electricity during January 2024.

The result shows that using V2H during winter depletes the car battery very quickly. After three days the EV battery is completely depleted, see Figure 36. The grid is for the majority used for purchasing electricity, as shown in Figure 37.

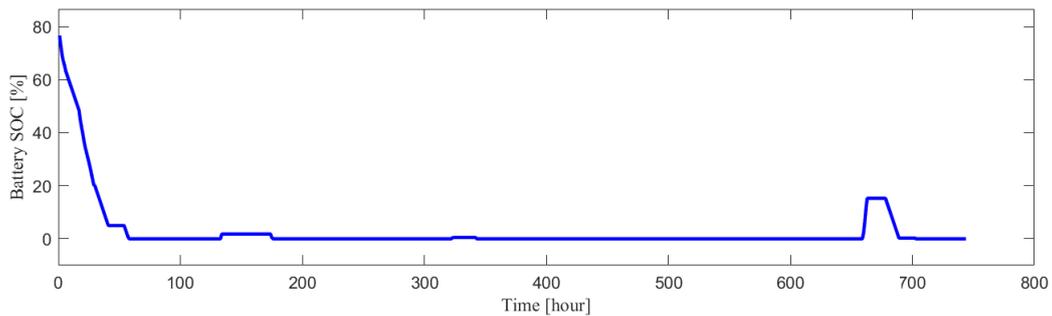


Figure 36: Battery SOC with V2H.

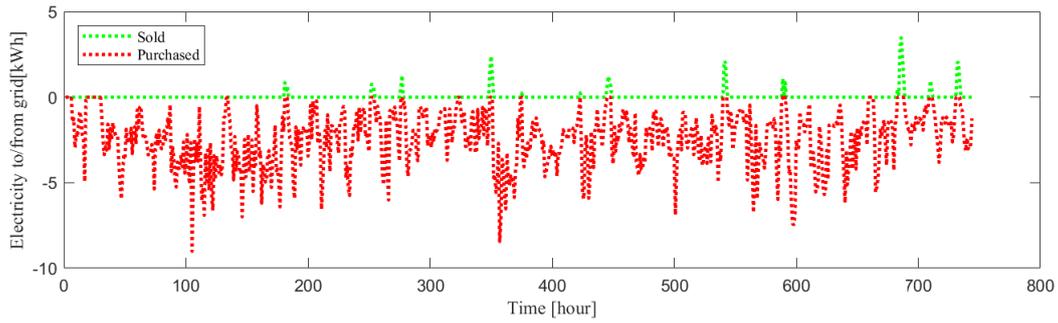


Figure 37: Sold (green) and purchased (red) electricity with V2H.

The results from not using V2H does not differ a lot from when using V2H, as the exceptions are at the beginning (when the EV has battery capacity), see Figure 38. Occasional peaks on the purchasing side corresponds to when the EV recharges, see Figure 39.

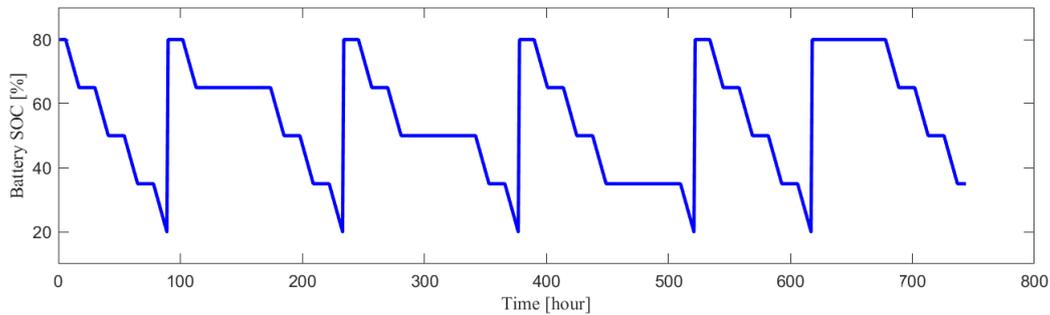


Figure 38: Battery SOC without V2H.

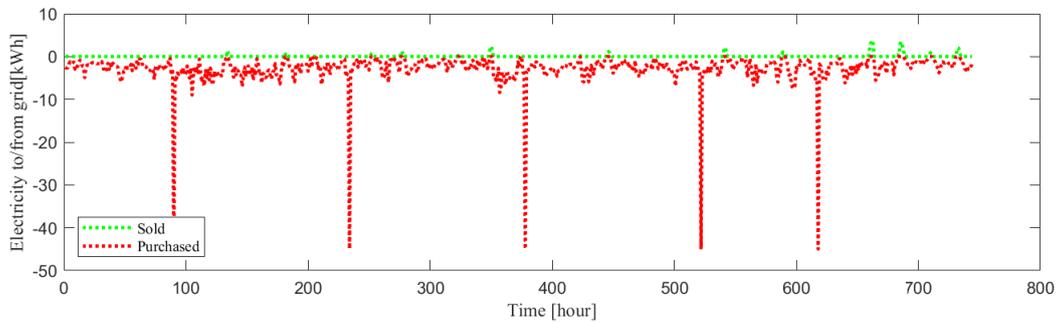


Figure 39: Sold (green) and purchased (red) electricity without V2H.

A summary of the total volumes of electricity sold and purchased for both scenarios is presented in Table 25. In both cases, the electricity that were sold to the grid, was primarily during work hours. Conversely, the electricity that were purchased, occurred at various times throughout the day.

Table 25: Summary of total volume electricity from the grid.

Volume of Sold & Purchased electricity from the grid		
	Purchased [kWh]	Sold [kWh]
With V2H	1 811	39
Without V2H	2 051	52

### 5.2.6 Business Model during January

Considering the sale and purchase prices, the outcome is presented in Figure 40. Predictably, the total purchasing cost was predominant.

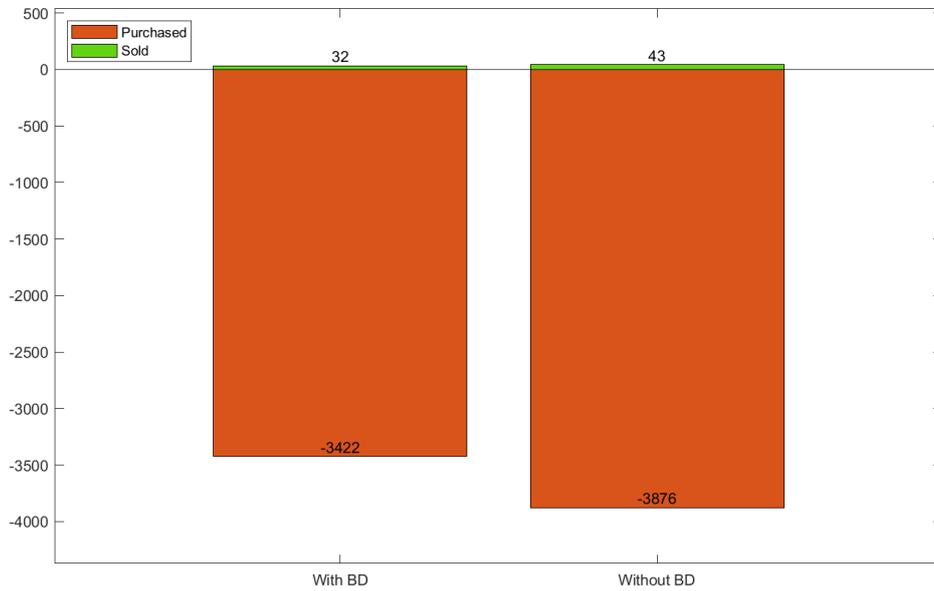


Figure 40: Amount earned and spent on electricity.

Finally the ancillary services has to be included in the equation to finalize the total profits for January 2024, see Figure 41. The ancillary service commission comes in at 37 [SEK] for the month, as the EV battery only was available for ancillary services for the first three days. In the second scenario, the EV is recharged five times (a charge of around 50 kWh), leading to an additional cost of 472.5 [SEK]. If the cost of recharging is excluded in the total profits for the second scenario, the difference is a value of 7.5 [SEK].

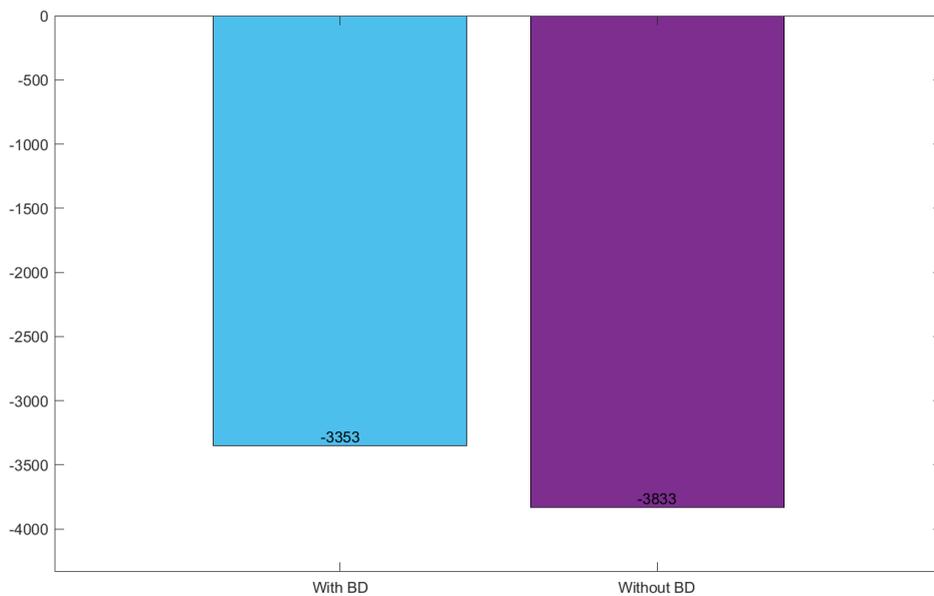


Figure 41: Profitability of both scenarios.

## Investments and Additional Costs

To integrate V2H into the electricity infrastructure of a household that contains solar panels, some investments will be needed. At first a home charger with a inverter will be needed to convert electricity AC-DC and DC-AC. A Bi-directional compatible home charger available in the market is the Quasar 2 with a price of approximately 50 000 [SEK] [45] including installation. As the home charger today cost around 12 000-18 000 [SEK] [62], V2H will need an additional cost of 32 000-38 000 [SEK].

As the result indicate, the only profits are made in the summer months. The difference of profits made with V2H and without V2H are 5 147 [SEK]. Assuming that a year includes 2 summer month with profits of 5 147 [SEK/month], 7 winter months where no profits are made, 3 months with 2 573.5 [SEK/month] of profits (half of a summer month), the yearly profit ends with 18 014 [SEK]. With that assumption, the payback time is approximately under 2 years.

### 5.2.7 Summary of Case 2: Vehicle to Home

To shortly summarize the provided results for July 2023:

- With V2H the EV battery's SOC stayed in a span of 50-80%, see Figure 30. Without V2H, the SOC decreased constantly until the need to recharge, which occurred two times, see Figure 32.
- The electrical grid was mainly used for feeding back the excess electricity, see Figure 31 and 33. With V2H only 3 [kWh] of electricity was purchased and 2 247 [kWh] sold fed back the grid. While without V2H, 300 [kWh] was purchased and 2 631 [kWh] was fed back into the grid, see Table 24.
- With V2H the profitability ended in 5,835 [SEK], while without V2H the profitability ended in 688 [SEK], see Figure 35.

To shortly summarize the provided results for January 2024:

- With V2H the EV battery's SOC completely depleted after 3 days, see Figure 36. Without V2H the SOC depleted constantly and needed recharging five times, see Figure 38.
- The electrical grid was mainly used for purchasing the deficit for both scenarios, see Figure 37 and 39. With V2H 1 811 [kWh] was purchased and 39 [kWh] was sold, while without V2H 2 051 [kWh] was purchased and 52 [kWh] was sold, see Table 25.
- With V2H the profitability came to be -3 353 [SEK], while without V2H the profitability came to be -3 833 [kWh], see Figure 41. Take in consideration that an addition of 472.5 [SEK] was included in the second scenario as the EV was recharged five times. If the additional cost is excluded in the profitability for the second scenario, the profit is -3 360 [SEK].

### 5.3 Case 3: Vessel to Grid

In the upcoming chapter, the focus shifts to the Vessel to Grid scenario, where various aspects related to the integration of maritime vessels into the electrical grid are explored. This case study aims to provide insight into how vessels can contribute to the grid's stability and efficiency through innovative solutions such as ancillary services and BD-charging.

#### 5.3.1 Work Process

To gain insight into boat usage patterns and boat archetypes, this study investigated the ongoing electrification of the Swedish maritime and created a targeted survey for boat owners and operators in Sweden. The survey was crafted to extract data on various aspects, such as typical usage patterns, energy storage capacity onboard, and storage preferences for the vessels. Using survey data, the aim was to acquire an understanding of how boat owners used and managed their vessels, thus forming the design and optimization of Vessel to Grid strategies. In addition, a comparative analysis was conducted between the gathered data and available data sets to ensure coherence and validity.

Drawing on insights from the survey and supported by data from Transportstyrelsen [63], along with additional calculations presented in the results section, a standard boat archetype, user behavior, and projected battery capacity for future electric boats in Sweden was developed. This effort aimed to explore potential individual profits from BD-charging, possible battery degradation on boat batteries, the availability of capacity throughout the year, the most suitable ancillary services for the boat battery and boat usage patterns, and other challenges or opportunities associated with BD-charging for boats. Ultimately, this enabled us to develop business models and calculate profits for larger applications.

#### 5.3.2 Electrification of the Swedish Maritime

The process of charging an electric boat largely mirrors that of an electric car; you simply connect a portable charger at a docking spot. Commonly known as shore power, this method uses a standard 16/32[A] 230[V] outlet, available in single- and three-phase versions.

The boat producer Candela [64];

”Electric boats can be charged using a regular household current or a standard Level 2 electric vehicle fast charger. This method is both simple and convenient. Additionally, three-phase outlets are available in most marinas. Marinas are equipped with shore power since many fossil fuel boats also use it to recharge their batteries.”

Nevertheless, utilizing these conventional outlets for charging may require a significant amount of time, as demonstrated by XShore, which employs the portable charger Juice Booster 2 and offers information on the charging times for their boats via shore power [65].

- 3 Phase 32[A] 400[V]: Delivers 22 [kW] and charges the bot from 0-100% in 6 hours
- 3 Phase 16[A] 400[V]: Delivers 10.5 [kW] and charges the bot from 0-100% in 12 hours
- 1 Phase 16[A] 230[V]: Delivers 3.5 [kW] and charges the bot from 0-100% in 36 hours

This makes charging with standard outlets inefficient for long-distance travel that requires charging along the route, as it generally takes too long to charge.

Recognizing this, the initiative go:Leif plans to establish 400 new rapid charging stations along the Kattegatt coast [66]. These stations will primarily include DC units with capacities between 25-75 [kW], and AC units with a maximum power output of 22 [kW]. During an interview with Peter Berg [67], the leader of innovations at go:Leif, it was confirmed that there are currently 26 charging stations for electric boats along the Kattegatt coast from Gothenburg to Strömstad in Sweden. These stations offer 25-75 [kW] DC Fast charging and 22 [kW] AC charging. Furthermore, the eastern coast of Sweden currently offers five Candela-sponsored charging stations [68], each with a maximum output power of 22 [kW], located in the Stockholm Archipelago. Detailed data on specific charging locations in the Swedish archipelago remain difficult to map, but a 2021 report by

EkoMarina [69] indicates that approximately 10.6% of Swedish harbors are equipped with chargers specifically designed for electric boats, while 69% possess standard electrical outlets. The report also notes that harbors with more than 400 boat slips typically have more advanced infrastructure, the report indicated that 29% of these harbors were equipped with electric boat charging facilities, suggesting that these harbors are likely to lead the transition to electric powered maritime.

In the most recent issue of Båtlivsundersökningen [63], released in 2020, it is stated that Sweden has a fleet of 864 200 boats, of which 34 568 are electric, constituting only 4% of the entire boat population. In the same report, it is also mentioned that the number of boats along the west coast of Sweden was 13% of the total number of boats. Given that 4% of these boats are electric, it results in 4 493 electric boats utilizing the 26 fast chargers mentioned above, indicating that there are 172 electric boats per fast charger along the west coast. Peter Berg mentioned in the interview that the difficulty in encouraging the use of fast chargers arises from the supply exceeding the demand. This claim is backed by Candela [70], stating;

”While fuel stations for boats have become less common in the Swedish archipelago, electrical outlets can be found almost everywhere. Since boats generally go shorter trips and stay longer at their destinations than cars, fast charging is not needed. Instead, the challenge for electric boat owners has been to know where they are allowed to plug in.”

The findings demonstrate that while Sweden’s charging infrastructure is still evolving, its expansion is aligned with demand. This includes the potential addition of 400 charging units from the go:Leif initiative, reflecting market projections that anticipate a 10-13% annual growth in the electric boat sector through 2030 [71] [72] [73], leading to a market valuation between 10 and 13 billion by the same year. Furthermore, a Statzon report highlights that Europe leads this growth [74], contributing 34.5% to the overall increase, further supporting the increasing demand for rapid charging stations in Sweden.

### 5.3.3 Boating User Habits Survey

The subsequent section presents the results of the conducted survey investigating boating user habits in Sweden and typical boat archetypes.

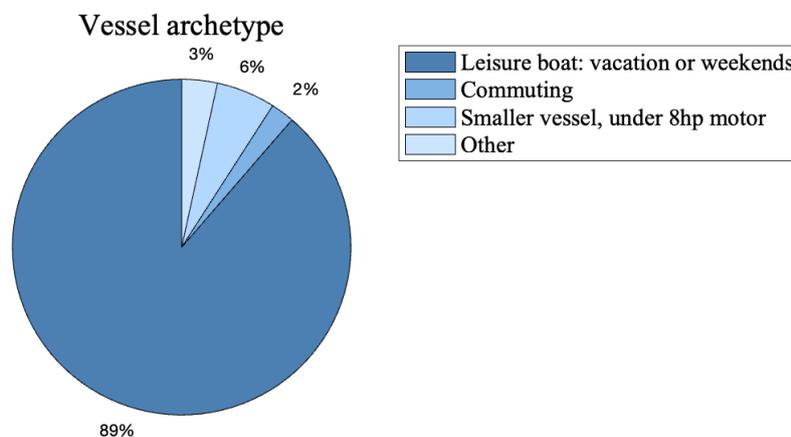


Figure 42: This figure illustrates the prevalent vessel types in Sweden, highlighting the predominance of leisure boats

The initial investigation aimed to determine the predominant type of boat. The survey reveals, as seen in Figure 42 that 89% of boat users own a type of leisure boat, defined as a vessel mainly used for vacations, holidays, or weekends. The Transportstyrelsen report categorizes vessels differently, including several types not covered by the survey, such as kayaks, non-motorized boats, small boats, etc., accounting for 31.4% of the total [63]. However, boats that fit the survey category of leisure boats constitute 51% of the total in the study.

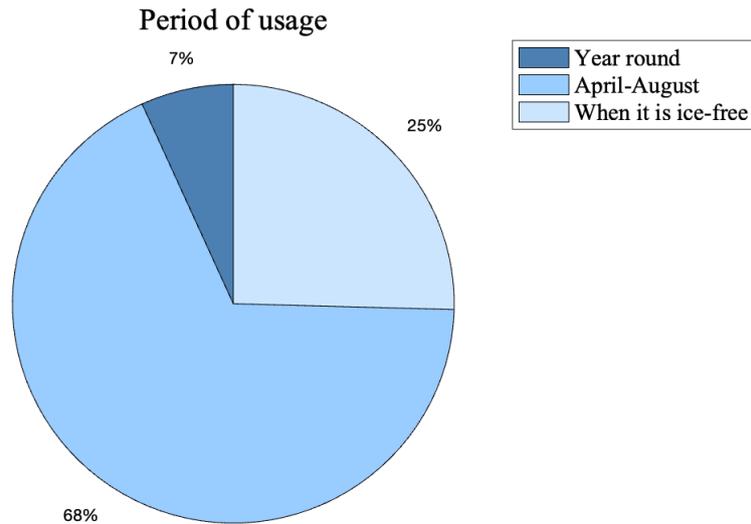


Figure 43: This image displays the times of the year when people typically use their boats.

Considering the cold weather in Sweden, it is important to determine the peak season for boating. The survey reveals as seen in Figure 43 that 68% of boat owners use their boats between May and September. 25% percent begin boating when conditions allow, particularly once the ice has melted. About 7% boat all year round. Although the Transportstyrelsen study did not use exactly the same phrasing, it noted that 83% of the boating days occurred from May to September, suggesting a trend similar to what was observed in the boating user pattern survey [63].

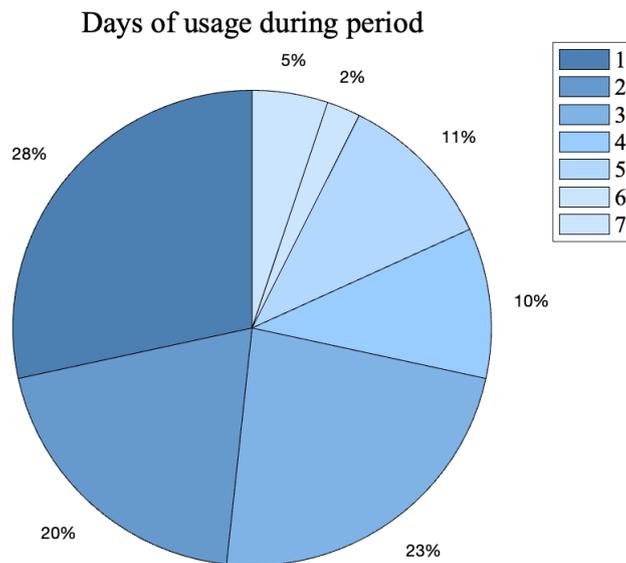


Figure 44: Illustrating the number of days per week that individuals operate their boats within their boating season

Understanding the frequency of boat usage in this particular time frame was crucial. The third question provides a clear answer as seen in Figure 44, revealing that 71% of the boat owners use their boats only 1-3 times a week during the usage period. Similarly, the Transportstyrelsen study indicates an average usage of 19.6 days from May to September, equivalent to about 1.9 days per week during the period [63].

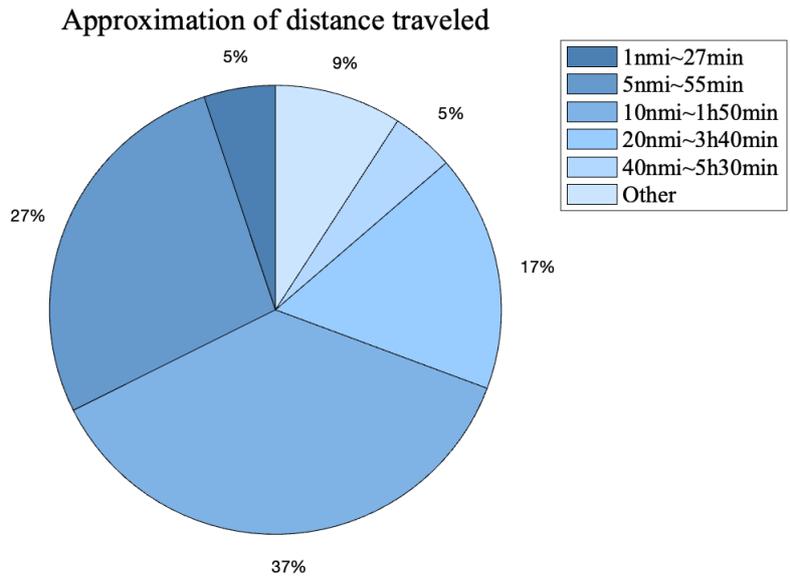


Figure 45: Illustrates the usual travel distance of the boat in nautical miles. 1 [nmi] equals 1.852 [km]

Question four seeks to determine the duration for which the boat's driver actively consumes fuel or energy, see Figure 45. This assessment helps to estimate the necessary battery capacity for boats. It is crucial to acknowledge the difficulty in measuring fuel or energy usage based solely on the duration and nautical miles traveled, as consumption heavily relies on the speed, the boat's hull design, weight, and other variables. According to the survey, 69% of the participants typically operate their boats for no more than 1 hour and 50 minutes per use. Transportstyrelsen research indicates that the type of boat significantly influences this behavior, and also one-quarter of boat owners struggle to estimate the distance they travel [63]. Among those who have an approximate idea of the duration of their usage, 89% travel about 12.5 nautical miles a week, which corroborates the survey findings, see Figure 45.

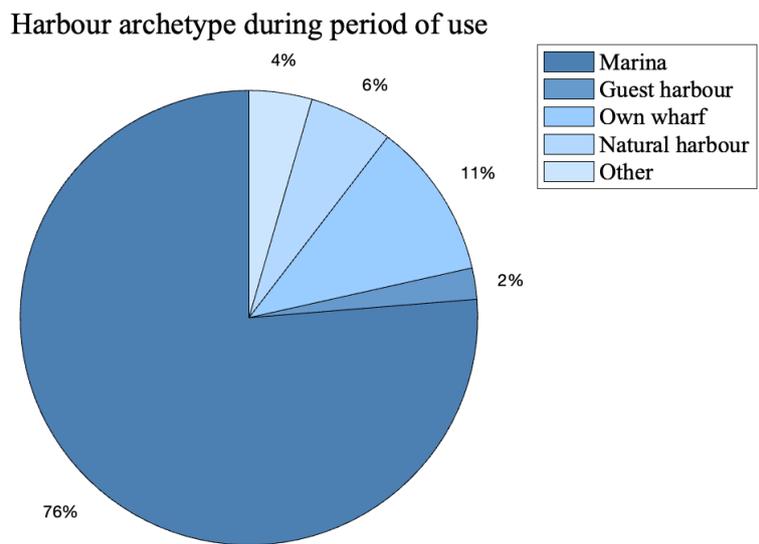


Figure 46: Illustrates the preferred types of harbors for mooring, with a significant 78% choosing marinas.

This question focuses on determining the primary storage locations for boats during usage, see Figure 46. Such data is crucial for analyzing storage trends to enhance profitability and pinpoint

regions in need of increased Bi-Directional charging facilities. Notably, 76% of respondents keep their boats in marinas, while 11% have their boats at private docks separate from marinas. These findings contradict the research documented in [63], which indicates that 47% of boat owners use a wharf or marina for storage, and 35% opt for storage on land or trailers.

**Time that the vessel is away from the harbour when used**

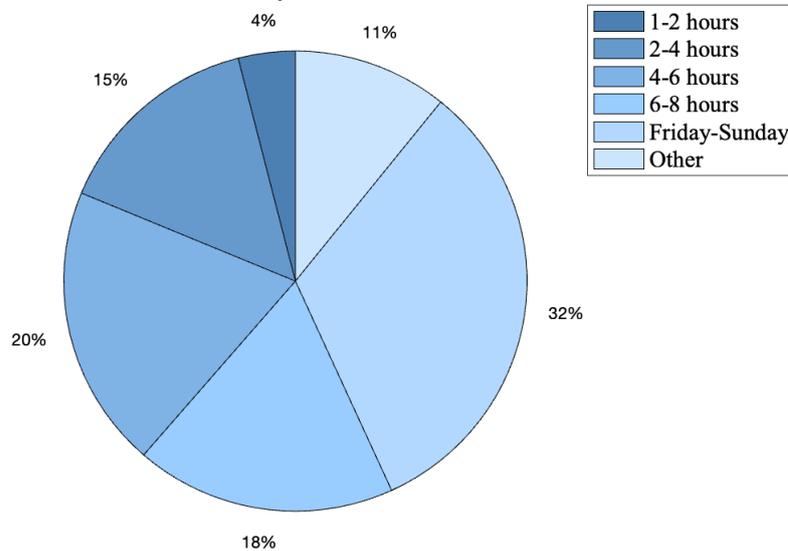


Figure 47: This figure illustrates the prevalent vessel types in Sweden, highlighting the predominance of leisure boats

To gain a deeper understanding of when boats are available for Bi-Directional charging, it is crucial to investigate how long a boat is away from its storage location during operation. This examination is separate from the earlier question of the "time of active use", as it focuses on the typical duration of a boat trip. The survey reveals that 57% of the trips last between 1-8 hours, while 32% continue throughout the weekend, see Figure 47. The 'other' category makes up 11% and uses up a considerable amount of the data. Further analysis shows that most individual responses fall into the durations of 1-8 hours or over the weekend, which collectively gathered the most votes. The Transportstyrelsen report does not include the corresponding data.

**Paying for port location during high season**

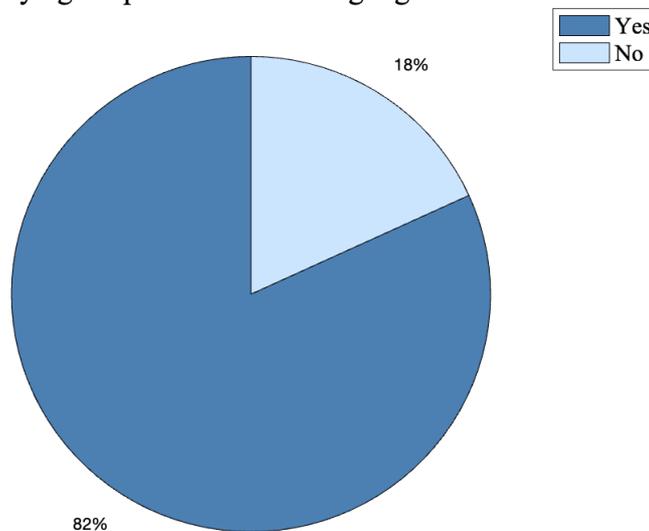


Figure 48: 82% pays for their berth during the season, whereas 18% does not.

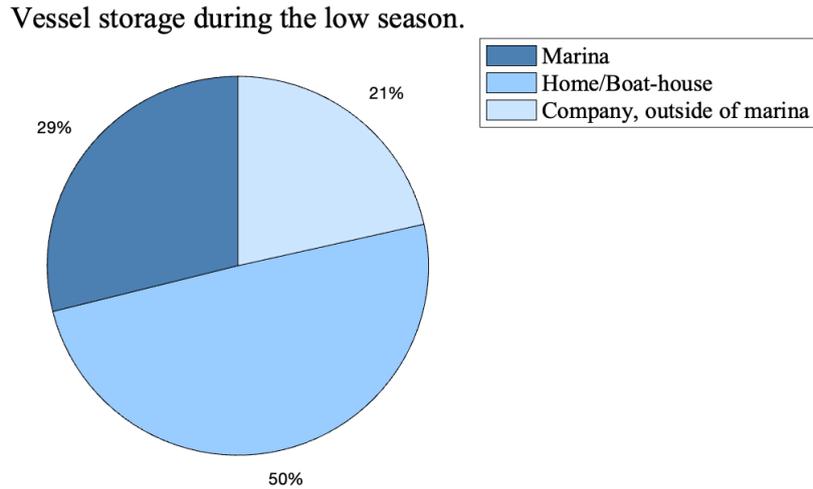


Figure 49: Vessel storage location, winter months.

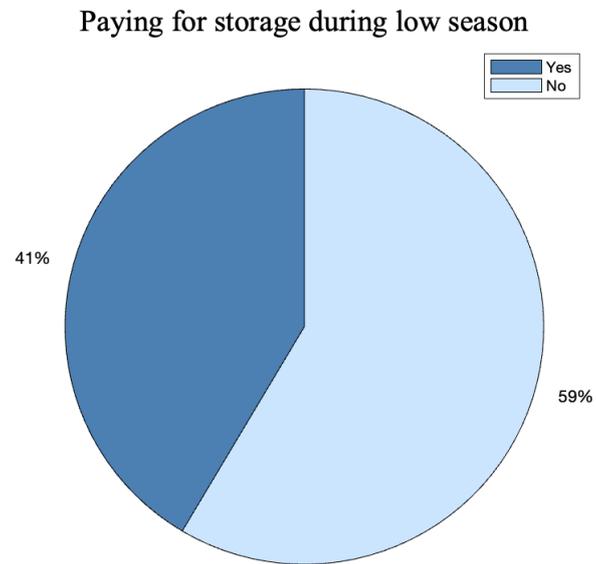


Figure 50

The survey additionally revealed information about mooring fees during the peak and off-peak seasons, along with the locations where boats are stored in the off season, see Figure 48, 49, 50.

### 5.3.4 Most Common Boat-User and Boat Archetype

Survey data suggests that a significant portion of Swedes own a leisure boat, and according to [63], nearly half of these owners possess a decked motorboat or daycruiser. Reflecting this trend, we constructed the typical Swedish boat, which is a motorboat or daycruiser designed to accommodate 6-8 individuals primarily for leisure purposes. Swedish electric boat manufacturers primarily produce such boats [75], [76], implying a similar consensus.

Usage patterns from the survey and [63] reveal that most Swedes operate their boats during the peak season from May to September. In this period, usage typically spans 1-3 days per week, not exceeding 8 hours per use. These data points lay the foundation for the calculation of docking time in marinas. Over five months, or 153 days, using the upper limit of 3 days weekly, boats are

utilized for 65 days. Considering that 68% of boat owners operate their boats up to 8 hours each day, it results in the boats being docked for 16 hours on the days they are utilized, totaling 3 148 hours docked during the season, which is approximately 85.5% of the time. Additionally, the boats require recharging post-journeys. Given the variability of factors influencing the State of Charge (SOC) upon return from voyages and the scarcity of reliable data, pinpointing the exact SOC after a journey is challenging. Consequently, this report adhered to recommendations regarding battery life longevity [77], resulting in a scenario where the boat consistently returns with a minimum of 20% SOC, the recharge duration is estimated at about 1 hour for a 60 [kWh] battery and roughly 2 hours for a 120 [kWh] battery using a 45 [kW] charger. For the 60 [kWh] battery, this leads to 3080 hours available for ancillary services throughout the summer. During the off-season, the boats are stored and inactive, allowing the batteries to be fully available 100% of the time. Thus, the annual availability of the boat for ancillary services via BD-charging is 93.3%. In the scenario with the 120 [kWh] battery, there are 3 020 hours available for use during the summer months, which sums 92.8% of the time when accounting for the winter months.

- The typical Swedish boat is designed to accommodate 6-8 individuals and used primarily for leisure purposes.
- Calculations based on usage patterns show that boats remain in berth for approximately 85.5% of the time during the summer months.
- The overall duration for which the boat can be utilized for ancillary services through BD-charging amounts to 92.6 - 93.8% annually depending on the battery capacity.

Furthermore, survey usage data indicated that the boat was rarely used actively for more than two hours at a time, see Figure 47. Taking this into account, and comparing with the current capacity and effect of electrical boats, it is projected that the battery capacity for electric leisure boats for most Swedes will range between 60-120 [kWh]. The span of 60 [kWh] is due to several factors, including design, top speed, and maximum power output of the motor. However, the range is supported by the current battery capacities of electric boat producers such as Candela and XShore, which are within or near this range [78], [76]. Furthermore, this view was supported by engineers at Volvo Penta [79].

- Battery capacity range from 60 [kWh]-120 [kWh]
- The wide range is attributed to the design and function of the boat, with lighter hydrofoil models falling into the lower range and heavier daycruisers occupying the upper range.

### 5.3.5 Results of Potential Revenue Streams

By assessing the economic benefits that a private boat owner could achieve through BD-charging and the optimal ancillary service, it is possible to gain insight into the financial rewards and associated energy production. With the archetype boat described in Section 5.3.4, it is assumed that the Vessel to Grid (Vs2G) income for a single boat aligns with the historical figures provided by the aggregator CheckWatt [42]. The service from CheckWatt enhances profitability by utilizing all available ancillary services, nevertheless CheckWatt reports that 95% of the earnings derive from FCR-D up and FCR-D down. Detailed descriptions of these services are provided in Section 4.2, highlighting that they commence minimal battery cycling, thus enhancing battery life. This is supported by the independent nonprofit organization CENEX [80], which analyzed various boat archetypes and found that for leisure boats, stabilizing services yield the highest returns. To estimate revenue, the number of hours the boat is available for ancillary services during the summer is first determined, subtracting the hours the boat is in use, the duration needed to recharge post-trip and fully charge the battery before trips.

It was also assumed that there is a direct linear correlation between the impact of the charger power and the profits, an assumption validated by a business developer from CheckWatt [36], and endorsed by the electricity provider Varberg Energi [41]. The linear correlation is illustrated by Equation 14

$$\text{Profit/kW/day} = \frac{S_{\text{profit}} \cdot S_{\text{month}}}{\text{Days} \cdot \text{kW}} = \frac{10\,885 \text{ [SEK]} \cdot 5}{153 \text{ [D]} \cdot 20 \text{ [kW]}} = 17.7 \frac{[\text{SEK}]}{[\text{kW}][\text{Day}]} \quad (14)$$

where  $S_{\text{profit}}$  represents the average profit per month during the summer period, and  $S_{\text{month}}$  the number of months, as discussed in the final part of Section 4.2.

In the analysis, chargers is utilized with capacities of 10, 20, 30, and 45 [kW], demonstrating the variability in profits based on the power of the charger. The decision to limit the power of the chargers to 45 [kW] was aimed at reducing the duration of charge and preventing considerable battery degradation during the implementation of ancillary services. The results are showcased in Table 26. These findings are corroborated by the CENEX study, which suggested that the maximum potential annual income for a recreational boat could reach up to 284 [GBP] per [kW] effect of the charger per year, amounting to 175 000 [SEK] at a currency conversion rate of 13.67, suggesting a similar profit potential. It is crucial to note that neither the Cenex study nor this example takes into account any uncertainty factors. This omission is likely to affect the results, as the ancillary service market is highly unpredictable. The assumption that the market operates consistently from day to day does not hold true in practice. Consequently, this leads to the exclusion of days with minimal or no profits, as well as days with substantial profits, thereby skewing the results.

Table 26: Potential Earnings.

	10 [kW]	20 [kW]	30 [kW]	45 [kW]
May-Sept	175 [SEK/D]	355 [SEK/D]	531 [SEK/D]	795 [SEK/D]
Rest of the year	92.5 [SEK/D]	185 [SEK/D]	277.5 [SEK/D]	415 [SEK/D]
Annual	46 400 [SEK]	93 500 [SEK]	140 000 [SEK]	209 500 [SEK]

### 5.3.6 Battery Degradation

Frequent usage of the battery through BD-charging and ancillary services could impact its total life length. In this simulation, it is assumed that the battery is used for the ancillary service FCR-D while the boat is stationary and not charging, since this service offers the highest financial returns. SvK mentions that FCR-D down operates for approximately 1-2% of the batteries' total available time [52], this was assumed for FCR-D up as well, supported by Fingrid [53]. This translates to 18 minutes of daily activation for the 60 [kWh] battery and 17.7 minutes of daily activation for the 120 [kWh] battery spread over the whole year. Due to the slight difference in these times, the simulation was performed using the 90 [kWh] battery. Moreover, as mentioned in [81] [82], both types of FCR-D has an activation time of 20 minutes; hence, the simulation incorporated 20-minute intervals. The discharge from boat usage was also assessed, leading to a 45 [kW] discharge during a drive time of 1 hour and 36 minutes, which is in line with the results from the survey 5.3.3. This effect reduces the battery's SOC to 20% upon return to the dock. Additionally, a 45 [kW] charger was chosen for this simulation since of its higher profitability as shown in the previous chapter 5.3.5, however it also causes more significant battery wear by intensifying the charge/discharge cycles for FCR-D. Thus highlighting the balance between economic benefits and battery life. The daily charging cycle for summer operation was designed assuming the boat docks with 20% battery left, charges to around 60%, uses ancillary services just before leaving, and then charges fully to 100%. Although it is best for the battery's health to maintain its charge between 20% and 80% [77], in this simulation, the battery is fully charged each time before departing, allowing for the assessment of more extreme degradation scenarios. During the winter season, it was presumed that the battery would be continuously accessible for FCR-D and would not be employed for regular boating activities.

Table 27 below illustrates the charging and discharging cycle during a typical summer week of boating, with all charging processes utilizing a 45 [kW] capacity and discharges typically below 25 [kW]. The period from May to September defines these summer weeks. Conversely, Table 28 details the patterns for the winter weeks, covering the remainder of the year.

Table 27: Summer Charging Cycle.

	Mo	Tu	We	Th	Fr	Sa	Su
FCR-D Discharge [min]	20	20	20	20	20	20	20
FCR-D Recharge [min]	20	20	20	20	20	20	20
Normal Discharge [min]					100	100	100
Normal Recharge [min]					40	40	40

Table 28: Winter Charging Cycle.

	Mo	Tu	We	Th	Fr	Sa	Su
FCR-D Discharge [min]	20	20	20	20	20	20	20
FCR-D Recharge [min]	20	20	20	20	20	20	20

Figure 51 presented below illustrates the simulation outcomes. It is evident that adhering to the demonstrated charging cycle reduces the overall lifespan of the battery by about 3.4 years, resulting in a total lifespan of 6.8 years. This is in contrast to a battery not utilizing ancillary services, which has a lifespan of 10.2 years. Indicating that employing ancillary services with a 45 [kW] fast charger cuts down the battery's lifespan by by a 33%.

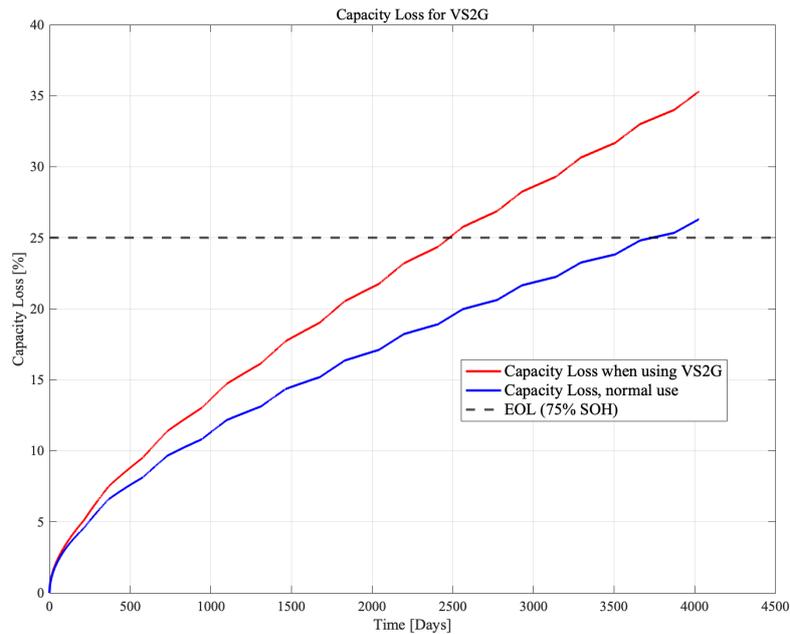


Figure 51: Battery Degradation Simulation.

Evaluating the average full equivalent cycles reflects the extent of battery utilization throughout its lifespan. Considering that calendar aging is a constant factor in battery life, it is common for a battery that ends its service early to have undergone more total cycles than another comparable battery. This implies that despite its premature end of life, the battery's actual use is more advantageous as it enables more effective contribution to the electricity grid and allows for greater overall usage compared to its longer-lasting counterpart. The findings of this analysis indicate that the battery operating with FCR-D was utilized 68% more in total than its counterpart.

- Using FCR-D; 785 Full Cycles

- Not using FCR-D; 540 Full Cycles

### 5.3.7 Vessel to Marina Results

As stated in the Transportstyrelsen report [63], as well as the EkoMarina report [69], Sweden is home to 2 654 leisure harbors that house approximately 400 000 boats that fit the archetype described in section 5.3.4, resulting in an average of 150 such boats per harbour. Nevertheless, the EkoMarina research indicates a diverse range of boat capacities across Swedish harbors, with the majority of harbors accommodating between 2 and 50 boats, representing approximately 26% of all harbors. This is further elaborated in 5.3.2. The report also states that harbors possessing more than 400 berths generally have a more developed infrastructure, 29% of these harbors are already equipped with electric boat chargers. This facilitates the easy integration of the electrical systems necessary for future electrification, which is crucial given the significant installation costs summarized in Table 37. In addition, these harbors accommodate a greater number of boats, enabling the utilization of services associated with electrification and BD-charging by a broader audience, generating greater profits whilst optimizing grid stabilization. Hence, it is considered most suitable for this model to focus on larger harbors.

Referencing above, the modeled harbor accommodates a total of 400 boats, half of them conforming to the archetype described in 5.3.4, which is motorboats measuring 6-8 meters in length and a passenger capacity of eight. These specifications align with the Candela C-8 or XShores Eelex 8000 models [78], [76], which have battery capacities ranging from 69 [kWh] to 126 [kWh]. For simplicity and clarity in this model, the battery capacity is set to 90 [kWh] for all boats. The selection of charging power is influenced by the existing charging stations in Sweden, which offer a range of 10.5-75 [kW], but also due to an evaluation of the advantages and disadvantages of higher versus lower power charging options, while also considering the varied behaviors of boating individuals. Since these fast chargers will have an increased effect on battery wear, as demonstrated in 5.3.6, considerations must be made on how this will affect people's charging habits. In this model, it is presumed that individuals will avoid using fast charging power over 45 [kW] for ancillary services or post-trip charging. Rather, they will opt for these fast chargers during voyages when rapid charging is necessary, considering the substantially higher impact on battery health. In addition, people may still use regular outlets when they anticipate not using their boats for extended periods and are concerned about extra battery wear when using high-power chargers. Following this reasoning, this model posits that one-third of the electric boats utilize chargers with power output of 10.5 [kW]. One-third of the electric boat owners opt for a 22 [kW] charging station, and the remaining third use a 45 [kW] charger. For simplicity reasons, the model assumes that the chargers are all DC chargers. This setup illustrates the varying degrees of battery degradation, profitability, and charging durations.

When designing the harbor, it was essential to consider the maximum potential power output, not only to estimate the costs of various components and electricity but also to address safety regulations. In this scenario, the harbor hosts 198 fully electric boats, each with a 90 [kWh] battery capacity, operating under three distinct loading cycles. Boat owners are presumed to behave consistently ideal, ensuring that the battery level never drops below 20% and avoiding charges above 80% to prolong the battery lifespan [77].

The harbor was also modeled after the event that all boats required simultaneous charging, which would result in the highest peak of power demand. The estimation of the various charging times was conducted utilizing Equations 15 and 16

$$Battery = 90 \cdot 0.2 + 90 \cdot 0.8 = 54 [kWh] \quad (15)$$

$$Time = \frac{Battery}{Power} = \frac{54}{45} = 1.2 [h] \quad (16)$$

for each level of power output, while Equation 17

$$Total\ power = Power \cdot nr_{boats} = 45 \cdot 66 = 2970 [kW] \quad (17)$$

was applied to calculate the power output for all boats using the charging stations. Subsequently, the cumulative power demand for just the boats was calculated to be approximately 5.16 [MW] for the first 1.2 hours, then 2.15 [MW] for the subsequent 1.25 hours, and ultimately 700 [kW] for the remaining 2.69 hours.

It is important to note that these calculations only account for the charge of the boats and do not include the usual operational load of the marina. When planning the marina infrastructure, a peak power output of 10 [MW] was assumed based partly on equations 15-17 but also by taking into account the occasional use of 75 [kW] charging stations for quick recharge, the potential expansion of the charging infrastructure, daily operational needs, and the anticipated growth and electrification of the maritime sector.

As BD-charging is an emerging technology, accurately determining the cost of compatible chargers is challenging. Nevertheless, a thorough analysis by recognized solar and battery expert Jason Svarc [83] indicates that prices for lower-power EV BD-chargers range from 16 200 to 75 600 [SEK]. Regarding higher-capacity BD-chargers, products from Aqua Super Power were considered, specifically the Aqua Pod for 22 [kW] and their 75 [kW] charger, accounting for the 45 [kW] effect and occasional 75 [kW] charging [84], [85].

To handle the expected output effect, it is crucial to dimension the electrical components accurately. To facilitate this, reasonable simplifications were implemented in our calculations. This included assuming a 95% efficiency for both the Aqua chargers, as specified in the documentation [86], and the transformer, a standard practice in electrical engineering. The presence of a 10.5 [kV] main power supply connection at the marina was assumed to be directly connected to the regional grid, following the practice of Öresundslinjen in managing their power output [87], which is also designed for 10 MW. Moreover, it was assumed that a transformer is capable of converting 10.5 [kV] to 400 [V] to be able to handle the otherwise large currents needed when multiple boats use the 45 [kW]. According to Båtlivsundersökningen, 2022 [63], the recommended berth width is approximately 3 [m] for boats similar in size to the Candela C-8 and Xshore Eelex 8000 [78], [76], this is incorporated into the model. Taking these assumptions in account, the proposed electrical design is illustrated in figure 52.

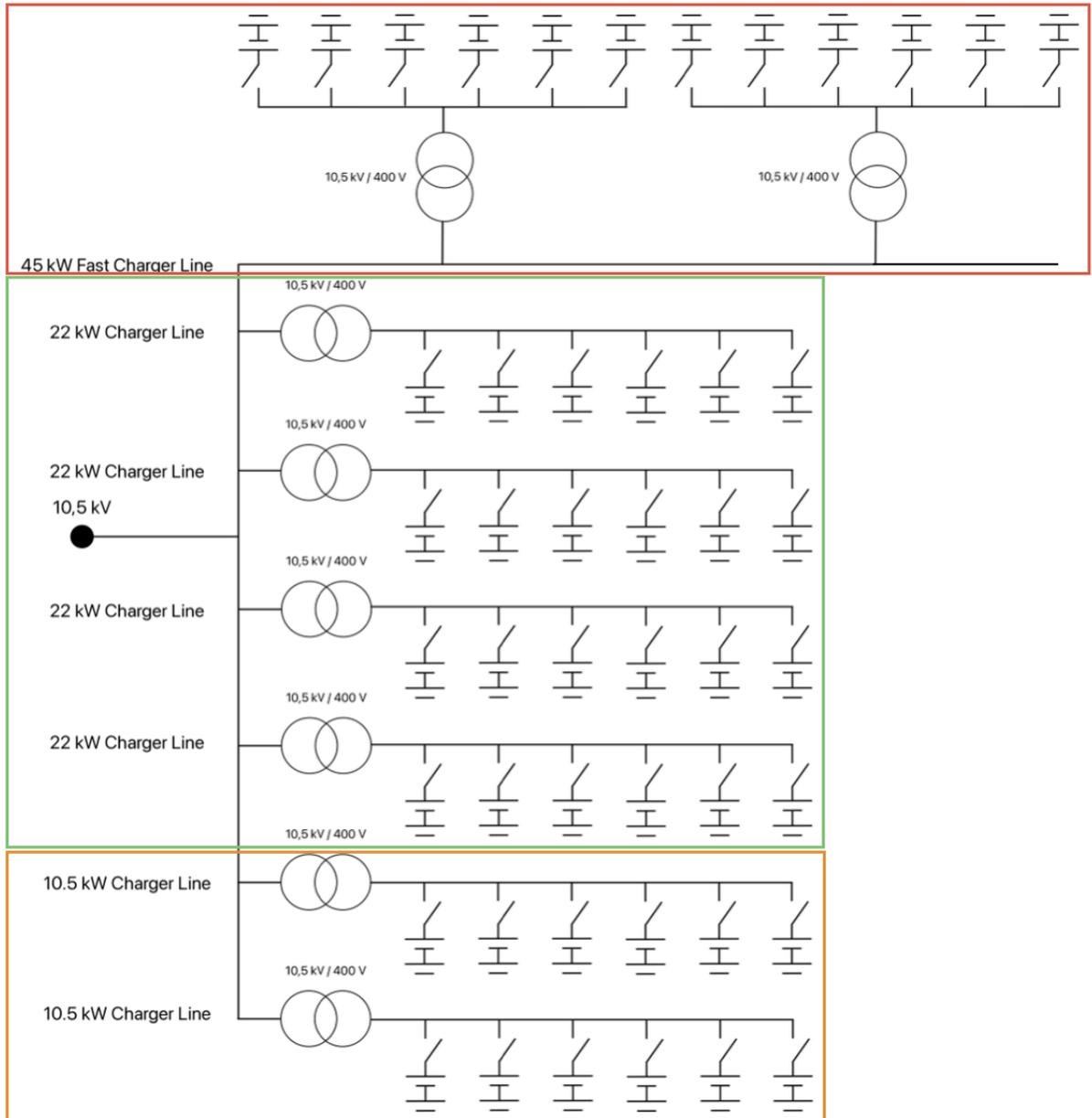


Figure 52: A single line diagram of the three different charging areas in the marina. Red marks the 45 [kW] section, green the 22 [kW] section and yellow the 10.5 [kW] section.

Given that systems employing multiple transformers and high-power transmissions can experience significant efficiency losses, it is crucial to evaluate the actual proportion of power delivered to the grid. The model segregates the marina into three distinct sections: 45 [kW] for fast charging, 22 [kW] for regular charging, and 10.5 [kW] for slow charging. The efficiency of each segment is computed to determine the amount of power each contributes to the grid, as efficiency losses will differ depending on the architecture.

### Power Calculations

To enhance the arrangement of the marina, the chosen parameters for the sections with 45 [kW], 22 [kW], and 10.5 [kW] are detailed in 29- 31.

Table 29: Configuration parameters to the Marina's 45 [kW] BD-system.

Parameter	Value	Unit
$n_{boats}$	66	[-]
$n_{links}$	1	[-]
$n_{transformers/link}$	11	[-]
Cable area	150	[ $mm^2$ ]
$\rho_{al}$	$282 \cdot 10^{-6}$	[ $\Omega m$ ]
$L_{berth}$	3	[m]
$\eta_{trans}$	0.95	[-]
$\eta_{charger}$	0.95	[-]
$P_{boat}$	45000	[W]
U	10500	[V]

Table 30: Configuration parameters to the Marina's 22 [kW] BD-system.

Parameter	Value	Unit
$n_{boat}$	66	[-]
$n_{links}$	4	[-]
$n_{boat/link}$	16.75	[-]
Cable area	150	[ $mm^2$ ]
$\rho_{al}$	$282 \cdot 10^{-6}$	[ $\Omega m$ ]
$L_{berth}$	3	[m]
$\eta_{trans}$	0.95	[-]
$P_{boat}$	22000	[W]
U	10500	[V]

Table 31: Configuration parameters to the Marina's 10.5 [kW] BD-system.

Parameter	Value	Unit
$n_{boat}$	66	[-]
$n_{links}$	2	[-]
$n_{boat/link}$	33	[-]
Cable area	150	[ $mm^2$ ]
$\rho_{al}$	$282 \cdot 10^{-6}$	[ $\Omega m$ ]
$L_{berth}$	3	[m]
$\eta_{trans}$	0.95	[-]
$P_{boat}$	10500	[W]
U	10500	[V]

The following calculations were performed to assess the total power, resistance and efficiency of each section of the marina. The purpose was to accurately evaluate the profits and expenses associated with power output and input, and to ensure that the marina's design was feasible without the risk of overheating cables or other electrical systems. Equations 18 - 23 pertain to the 45 [kW] section, while Equations 24 - 30 detail the specific calculations for the 22 [kW] section. The analysis for the 10.5 [kW] section mirrors that of the 22 [kW] section, but with adjustments including two links instead of four, 33 boats per link instead of 16.5, and 10.5 [kW] instead of 22 [kW].

Total power output for a 10.5 [kV] transformer point was calculated as

$$P_{TP} = n_{boats/point} \cdot P_{charger} \cdot \eta_{Tran} \cdot \eta_{charger} = 6 \cdot 45000 = 270\,000 \text{ [W]} \quad (18)$$

In Equation 18  $P_{TP}$  is the power for the transformer point in [W]

There is eleven transformer points for the 45 [kW] link pictured in red in Figure 52, the total power for this link can then be described as

$$P_{link} = P_{TP} \cdot n_{TP/link} = 270\,000 \cdot 11 = 2\,970\,000 [W] \quad (19)$$

where  $P_{link}$  is the maximum power output onto the AC line expressed in [W].

To determine the resistance of the aluminum cable, the number of boats were multiplied by their spacing, and then the resistance was computed as follows

$$R_{cable} = L_{cable} \cdot \frac{\rho_{al}}{A} = (L_{berth} \cdot n_{boats/link}) \cdot \frac{\rho_{al}}{A} = (66 \cdot 3) \cdot \frac{2.82 \cdot 10^{-8}}{1.5 \cdot 10^{-4}} = 0.0062 [\Omega m] \quad (20)$$

where  $R_{cable}$  denotes the resistance of a single AC link in [ $\Omega m$ ],  $L_{cable}$  represents the total length of the aluminum cable per link, calculated as the product of the length of each boat space (assumed to be 3 meters) and the number of boats for the link.  $A$  refers to the cross-sectional area of the aluminum cable in [ $mm^2$ ], and  $\rho_{al}$  [ $\Omega m$ ] indicates the resistivity of aluminum.

Equations 19-5.3.7 can be combined to calculate the losses due to the cables efficiency, which can be calculated as

$$P_{link,loss} = \left( \frac{P_{link}}{U} \right)^2 \cdot R_{cable} = \left( \frac{2\,970\,000}{10.5 \cdot 10^3} \right)^2 \cdot 0.0062 = 496 [W] \quad (21)$$

Where the fraction represents the current flowing through the cable, with  $U$  denoting the voltage across the link and  $P_{link}$  representing the power along the line, expressed in [W]. The power output from the link, post losses, can be calculated by taking into the account of efficiency losses, noted as 95% for both the transformer points and the chargers as per Aqua [86]. Consequently, the overall losses can be computed as

$$P'_{link} = (P_{link} - P_{link,loss}) \cdot n_{trans} \cdot n_{charger} = 2\,680\,300 [W] \quad (22)$$

where  $P'_{link}$  denotes the power output from the cable post-losses, measured in [W]. It is important to observe that the minimal losses are attributed to the high voltage, resulting in an efficiency of

$$\eta = \frac{P'_{tot}}{P_{tot}} = 0.902 \quad (23)$$

Total power output per link was calculated as

$$P_{link} = n_{chargers/link} \cdot P_{charger} = 16.5 \cdot 22000 = 363\,000 [W] \quad (24)$$

In 24  $P_{charger}$  is the total effect for one charger, which in this example is 22 [kW].

There are four links housing 22 [kW] chargers pictured in Green in Figure 52, the total power for these links can then be described as

$$P_{TL} = P_{link} \cdot n_{links} = 363\,000 \cdot 4 = 1\,452\,000 [W] \quad (25)$$

Where  $P_{TL}$  is the total power output onto the AC line expressed in [W].

To determine the resistance of the aluminum cable, first multiply the number of boats by the berth spacing, and then compute the resistance as follows

$$R_{cable} = L_{cable} \cdot \frac{\rho_{al}}{A} = (L_{berth} \cdot n_{boats/link}) \cdot \frac{\rho_{al}}{A} = (16.5 \cdot 3) \cdot \frac{2.82 \cdot 10^{-8}}{1.5 \cdot 10^{-4}} = 0.0093 \quad (26)$$

where  $R_{cable}$  denotes the resistance of a single AC link in  $[\Omega m]$ ,  $L_{cable}$  represents the total length of the aluminum cable per link, calculated as the product of the length of each boat space (assumed to be 3 meters) and the number of boats for the link.  $A$  refers to the cross-sectional area of the aluminum cable in  $[mm^2]$ , and  $\rho_{al}$  indicates the resistivity of aluminum.

Again, equations 25 and 26 can be combined to calculate the losses in the cabling, which can be calculated in a similar fashion as did in equation 21, using the  $P_{TL}$  and  $R_{cable}$  calculated above.

$$P_{TL,loss} = \left(\frac{P_{TL}}{U}\right)^2 \cdot R_{cable} = \left(\frac{1452000}{10.5 \cdot 10^3}\right)^2 \cdot 0.0093 = 178 [W] \quad (27)$$

where the  $R_{cable}$  represents the current flowing through the cable, with  $U$  denoting the voltage across the link and  $P_{TL}$  representing the power along the line, expressed in  $[W]$ . The power output from the link, post losses, can be characterized as

$$P'_{TL} = P_{TL} - P_{TL,loss} = 1\,451\,822 [W] \quad (28)$$

Where  $P'_{TL}$  denotes the power output from the cable post-losses, measured in  $[W]$

Ultimately, the 95% efficiency of the 10.5 [kV] transformer must be considered. The charger, however, is assumed to be ideal in this case with no efficiency losses, as there is no available data to suggest otherwise.

$$P'_{tot} = P'_{TL} \cdot \eta_{Trans} = 1\,451\,822 \cdot 0.95 = 1\,379\,230 [W] \quad (29)$$

Again, the minimal losses are attributed to the high voltage, resulting in an efficiency of 95% as depicted in equation 30

$$\eta = \frac{P'_{tot}}{P_{tot}} = 0.95 \quad (30)$$

### Calculations of Cost

Although Aqua currently does not state the cost of its chargers, a price range of 300 000 to 500 000 [SEK] was used for these chargers, as estimated by a project leader at Innovatum involved with the Go:Leif project mentioned in 5.3.2. Given the considerably elevated expenses associated with the Aqua Super Power chargers, designed for marine usage, this model selects the upper price bracket for the less powerful chargers, factoring in the extra development costs for those chargers to include BD-charging in maritime settings. Leading to the following price assumptions for each charger presented in Table 32. Note that this does not include installation costs.

Table 32: Cost of chargers.

	10.5 [kW]	22 [kW]	45 [kW]
Per charger	75 600 [SEK]	300 000 [SEK]	500 000 [SEK]

To estimate the cable expenses, this model relied on the assumption that each berth measures 3 meters across the width, and each section of the marina accommodates 66 boats, which collectively require a cable length of 594 meters for the three sections combined. Since this measurement only includes the cables needed for the chargers, it also also considered the cost for extra cabling, thus adding an additional 150 meters of cable. This brings the total cable length required for the marina to 744 meters. The cable cost estimation utilized the categorized cost per kilometer listed in the EBR cost catalog from 2020 [88], which indicates that the standard cost per meter for high voltage cables is approximately 130 [SEK].

- Total cost for cables: 96 720 [SEK]

The results of the calculated data for output power, efficiency and chargers in the three different segments of the marina system are shown in table 33 below. Note the significant efficiency difference of nearly 5% in the 45 [kW] section. This occurs due to the designed architecture in this model, which varies from the 10.5 and 22 [kW] chargers to accommodate the power requirements.

Table 33: Power Output, Charger Costs and efficiency

	Input [kW]	Output [kW]	Charger cost [MSEK]	Efficiency
45 [kW]	2 970	2 680	16,5	90.2%
22 [kW]	1 452	1 379	20,1	95%
10.5 [kW]	690	659	4,9	94%
Total	4 822	4 702	41,5	

Additionally, the installation of eleven 10.5 kV transformers for the red section, four for the green section, and two for the yellow section adds certain costs. These costs typically range from 1 000-10 000 [USD] according to multiple websites [89], [90] and the final costs used culminated in a cost of 5 000 [USD] or 54 000 [SEK] per transformer, and 918 000 [SEK] for the whole marina.

### Calculation of Revenue

To estimate the ancillary services revenue for this model, the input and output power data from Table 33 were used on various chargers. The model also adhered to the assumptions outlined in Sections 5.3.5 and 5.3.4, which describe the archetype, user behavior, and per [kW] revenue from ancillary services. Additionally, the analysis covers only 153 days, specifically from May to September, aligning with the peak marina occupancy by boats as indicated in the survey results in 5.3.3. Table 34 shows the revenue per boat for the different charging areas of the marina and table 35 shows the accumulated revenue for all boats in the marina, here the model assume that 66 boats inhabit each charging area summing up to a total of 198 boats.

Table 34: Revenue per boat based on type of charger.

Charger	avg Daily Revenue	Summer Period Revenue
45 [kW]	720 [SEK]	110 000 [SEK]
22 [kW]	365 [SEK]	56 000 [SEK]
10.5 [kW]	175 [SEK]	27 000 [SEK]

Table 35: Revenue for all boats.

Charger	avg Daily Revenue	Summer Period Revenue
45 [kW]	47 500 [SEK]	7 267 500 [SEK]
22 [kW]	24 000 [SEK]	3 672 000 [SEK]
10.5 [kW]	11 500 [SEK]	1 760 000 [SEK]
All	83 000 [SEK]	12 699 500 [SEK]

### Calculation of Electricity Fees

Additionally, the marina bears electricity expenses for its operations. Within this model, the marina is characterized as a production entity linked to a higher voltage and employs a effect-based electricity subscription of 10 [MW] from Nätkraft Borås. The costs are detailed in 36 below.

Table 36: Effect Subscription.

Fixed electricity grid fee	4 410 000 [SEK/year]
Base cost	22 000 [SEK]

It is assumed that there is no transfer fee for the marina, since the electricity they buy is sold to the boat owners, and at that price the transfer fee is paid for. Efficiency losses are not included in power calculations to maintain stringent margins. The assumptions for the duration of charge are based on the boats, each equipped with a 90 [kWh] battery, returning with 20% remaining battery capacity and not charging beyond 80%. Furthermore, it is assumed that there is no transfer fee for ancillary services.

The summer period, comprising 153 days, corresponds to 21.85 weeks, which is used to calculate the transfer fee for the whole summer in Table 37. The total costs and earnings for the marina are also summarized in the Table.

Table 37: Marina

	Cost	Profit
Fixed electricity grid fee	4 410 000 [SEK/year]	0
Base cost	22 000 [SEK]	0
Revenue from ancillary services	0	12 699 500 [SEK/summer]
Total cost for chargers	41 500 000 [SEK]	0
Total cost for cables	96 720 [SEK]	0
Total cost for transformers	916 000 [SEK]	0

### Yearly Energy Output

Using Equations 31-33, the daily energy output for each charger power can be determined for all boats. By multiplying this result by 365 in Equation 34, the yearly energy output from ancillary services is obtained, assuming a daily operation of 20 minutes.

$$\text{Energy output} = \text{Power} \cdot \text{time} \cdot \text{boats} = 45 \cdot 1/3 \cdot 66 = 990 [kWh] \quad (31)$$

$$\text{Energy output} = \text{Power} \cdot \text{time} \cdot \text{boats} = 22 \cdot 1/3 \cdot 66 = 484 [kWh] \quad (32)$$

$$\text{Energy output} = \text{Power} \cdot \text{time} \cdot \text{boats} = 10.5 \cdot 1/3 \cdot 66 = 231 [kWh] \quad (33)$$

$$\text{Yearly Energy Output} = (Eq\ 31 + Eq\ 32 + Eq\ 33) \cdot 365 = 622 [MWh] \quad (34)$$

- FCR-D down: 311 [MWh]
- FCR-D up: 311 [MWh]

This outcome highlights the capacity of BD-charging to stabilize the grid and facilitate the shift towards greener energy sources.

## 5.4 Case 4: Electric Ferries

The results of the electric ferries case, which investigated the possibilities of installing BD-chargers onboard electrified ferry lines. In order to provide concrete results, the study was based on the electrified ferries between Helsingborg and Helsingör.

### 5.4.1 Work Process

The Electric Ferry project began by reaching out to Öresundslinjen, the company managing the Electric Ferries operating between Helsingborg and Helsingör. This approach streamlined the work process and facilitated the identification of crucial investigation areas. It also established the primary research questions, enabling the definition of two scenarios.

Since the range an electric ferry can travel depends on many factors, such as the length of the stop between arrival and departure, the charging C-rate and how much cycling stress the battery is allowed to be exposed to, it was quickly determined to be the most realistic to investigate what a BD-charging system onboard the ferries operated by Öresundslinjen could offer. Making a concrete case study will allow for generalized results and conclusions that could be further applicable on ferry routes elsewhere.

The established collaboration with Öresundslinjen also provided the case with valuable data sources. The following data was provided by Öresundslinjen:

1. The Technical Specifications of the ferry, such as battery capacity, battery voltage, etc.
2. Blueprints of the boat, such as the stowage area for the passenger cars.
3. Single line diagram of the boat's Electrical System, including propulsion, batteries, DC-DC conversion, etc.
4. Ferry Usage Pattern, SOC upon arrival and departure, DOD, capacity loss per crossing, etc.
5. Charging Specification, such as charging power, current, voltage and average charging duration.
6. Passenger vehicle data, such as the distribution of electric cars

The data provided were sufficient to define two key scenarios, which in combination with each other could provide profitability. The two scenarios were defined as the following, all assuming the same kind of installation of a BD-system in the passenger vehicle stowage area.

1. Could the operating hours of the back-up diesel generators be decreased if the battery capacity deficit is restored from energy bought from passenger cars, rather than generated from diesel generators? Could this be profitable for both the passengers and the operators of the ferry?
2. Could a buy and sell system be implemented, were the operators take provision from passengers selling their electricity to other passengers?

These scenarios were chosen because they proved to be the most relevant to Öresundslinjen and their specific usage patterns. It is important to note that the ferries between Helsingborg and Helsingör have quite unique usage patterns, as their stops are only about 10 minutes, and the ferries operate throughout the entire day without any longer stops.

The proposal of installation was done by combining the current data of EVs onboard the ferries, with forecasts of the continued expansion of the EV fleet to decide how many chargers are necessary. The blueprints were then used to ensure that there were appropriate spaces to install these chargers, without losing any car capacity on board the ferry. Then, approximations of market prices were used to come up with an approximation of installation costs, which is a necessity in the business model. Basic laws of electricity and approximates of component efficiency from common rule-of-thumbs were implemented as a last step to calculate approximate losses and dimensions of the cable in the system.

Each scenario used the given data to establish each business model. The case integrated the standard driving cycle from the V2G case to determine the impact on the typical car user participating in

the Ferry BD-system, considering SOC at the time of arrival and expedited battery aging. The battery aging model was applied from a worst-case scenario.

#### 5.4.2 Data from Ferry Operator

The Technical Specifications are based on the M/S Aurora af Helsingborg and a compilation can be found in Table 38. There are currently two ferries operating the route, M/S Aurora af Helsingborg has the smaller battery system of the two and will henceforward only be referred to as M/S Aurora.

Table 38: Specifications and other data provided by the Ferry Operators.

M/S Aurora af Helsingborg - Technical Specifications	
Battery Capacity	4100 [kWh] [91]
Crossing Capacity	1050 [kWh] [91]
Vehicle Capacity	250 cars [87]
Charging Power	10000 [kW] [87]
Charging Current	600 [A] [87]
Average Charging Duration	7-9 [min] [87]
Diesel cost per cubic meter	8350 [SEK] [92]
Critical SOC lower bound	15 % [92]
Critical SOC higher bound	70 % [92]
Charging Voltage	10.5 [kV AC] [87]

#### Charging

Each charging takes approximately 7-9 minutes. The charging starts at 1 [MW] and increases with 1 [MW] per second until it reaches 10 [MW]. After reaching a 50% SOC, it slowly decreases. The charging cable is connected through a robot, and it takes approximately 45 seconds for the robot to connect to the ferry [87].

#### Crossing

Each crossing takes approximately 20 minutes and consumes 1 050 [kWh] of energy. The SOC is always kept between 66% and 39%. It can however go as low as 30% to avoid having to start the diesel generators. Approximately 27% DOD per crossing or lower [92].

#### The Electrical System

The single line diagram in Appendix A.2 shows the electrical system of the ferry. The AC charging current is first transformed to a voltage of 750 [V], and then rectified to a 1 000 [V] DC Voltage. This 1 000 [V] DC-Link is a central component and is also the link to which the BD system is to be connected onto. DC-DC converters separates the different battery modules from the DC-Link. The ferry has 4 motors, each at 1.5 [MW] which uses AC current. Each motor is therefore connected to the DC Link through an inverter [91].

#### Distribution of Onboard Cars

Data of the vehicle distribution of the passenger cars onboard the ferry was provided by Öresundslinjen, from June 2023 to February 2024. This data was used to calculate the fraction of electric cars, and can be found in Appendix A.3 [93]. The most important takeaways from this dataset, is that during the time period, 9.7% of the approximately 385 000 cars registered were 100% electric, and an additional 8.2% were plug-in hybrids. The part of 100% electric vehicles rose from approximately 8% on average in the first quarter to 11.6% on average in the last.

### 5.4.3 Installation of Bi-Directional Charging system

The data from the operator was used to settle an appropriate size and installation for the BD-system. Initially, the appropriate amount of chargers needed had to be decided.

The swift escalation in the number of electric vehicles underscores the necessity of integrating forecasts with existing data to ensure an adequate number of charging stations on the ferry. Data from the Swedish Central Bureau of Statistics (SCB) indicates that the number of electric cars has increased threefold from 2020 to 2022 [33]. This trend is expected to continue, with projections suggesting that electric vehicles will constitute about 50% of all vehicles in Sweden by around 2029, as per a study from 2020 [94]. Considering the present proportion of electric vehicles, a reasonable assumption is to equip about 30% of ferry parking spaces with charging stations to meet the anticipated demand over the next few years could be reasonable, equating to 75 charging spots. Given the layout constraints, with installations only feasible along the walls and not between parking slots, the maximum feasible number of charging stations is around 61. A total of 61 chargers could be installed using two parallel DC charging lines on the train deck and two on the platform deck. Since chargers in practice acts as DC-DC converters, and the DC-link needs conversion before it is connected to the main DC-link of the ferry, the voltage of the charging lines is not a crucial parameter. Since one of the companies utilizing 20 [kW] Bi-Directional chargers in pilot tests use a 760 DC grid, a voltage of 760 [V] DC is assumed [95].

Five separate DC-links are arranged in parallel, each accommodating between 14 and 20 vehicles. These lines merge at a single junction and are linked to a DC-DC converter that increases the voltage from 760 [V] (the output voltage of the BD charger) to 1000 [V] (the input voltage of the ferry's main DC-link). The arrangement of these parallel DC-links is illustrated in figure 53 as a single line diagram.

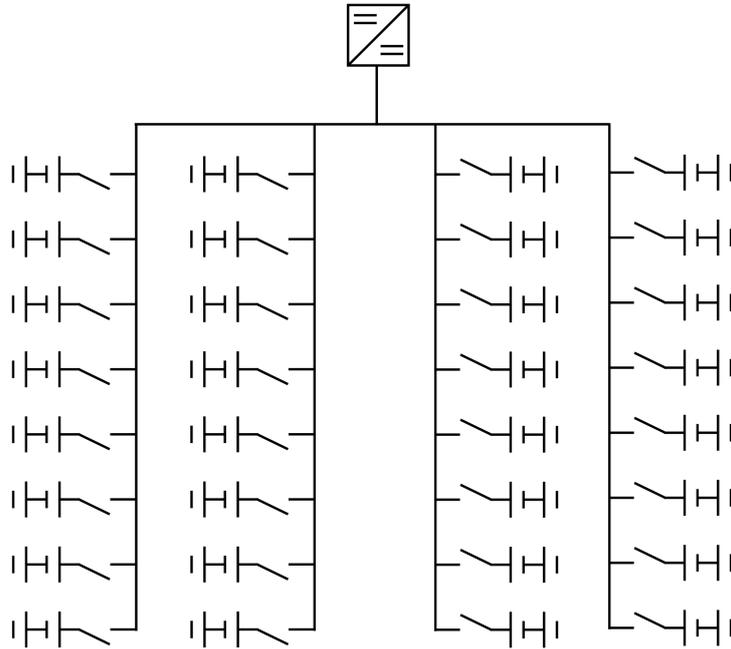


Figure 53: A single line diagram of a BD-system with 4 parallel DC-links, with 8 connected units each. Cars are depicted as voltage sources.

As depicted in figure 53, the values are  $n_{cars} = 32$ ,  $n_{cars/link} = 8$ ,  $n_{links} = 5$ , among others. In practical terms, each car charger functions as an individual DC/DC-converter that manages the flow of current. For the ferry, there will not be equally distributed chargers per line, as the possibility of installing chargers varies. The maximum capacity is set to be 61 for wall-mounted chargers, with

a configuration depicted in figure 54. The parameters for the ferry's setup are detailed in table 39.

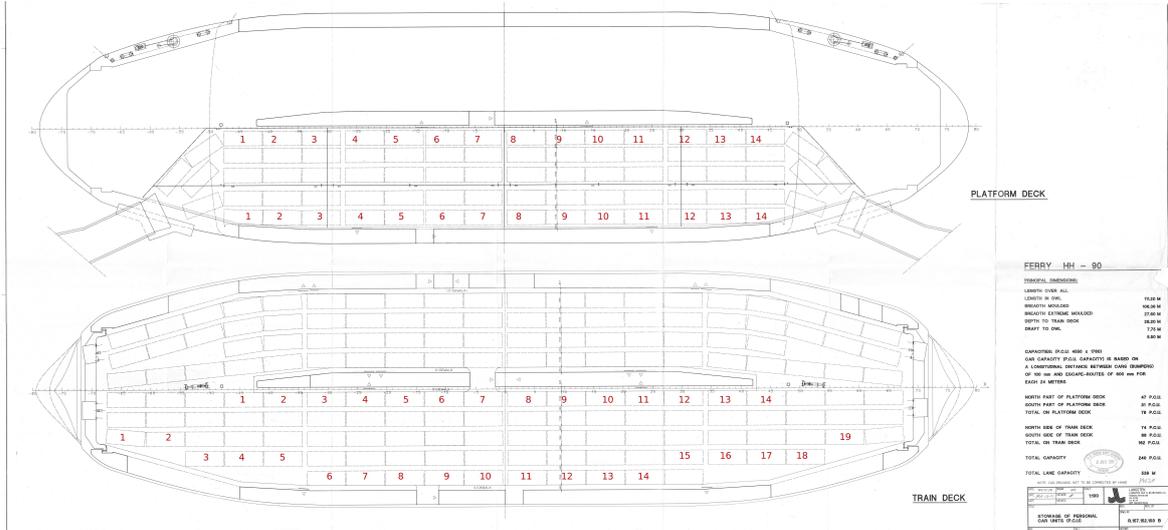


Figure 54: The vehicle stowage area with appropriate charger locations. The upper area of the Train deck is reserved for trucks.

Table 39: Configuration parameters to the ferry's BD-system.

Parameter	Value	Unit
$n_{cars}$	61	[-]
$n_{links}$	4	[-]
$n_{cars/link}$	15.25	[-]
$A$	120	$[mm^2]$
$\rho_{cu}$	$172 \cdot 10^{-6}$	$[\Omega m]$
$L_{parking}$	5	[m]
$\eta_{DC/DC}$	0.95	[-]
$P_{car}$	20 000	[W]
$U$	760	[V]

In Table 39,  $n_{cars}$  is the total number of charging spots, in this case determined to be 61.  $n_{links}$  is the number of parallel DC-links, in this case 4 (2 on the train deck, 2 on the platform deck).  $n_{cars/link}$  is set to 15.25 to get the average power output.  $A$  is the cross-section of the copper cable, set large enough to withstand the cumulative power from all the cars.  $L_{parking}$  is the length of the parking space.  $\eta_{DC/DC}$  is the efficiency of the DC/DC-converter, were 0.95 is a reasonable estimation.  $P_{car}$  is the power output from each car, and  $U$  is the voltage on the links.

It was assumed that the total cable length per link would equal the combined lengths of all parking spaces, plus an extra 20 meters to link all parallel connections to the Ferry's main DC-link. To reduce losses and prevent overheating, a copper cable with a 120  $[mm^2]$  cross-section was selected, as it will withstand the maximum current of 500 [A] of the lines with 20 connected cars just as good as any larger cable. The DC-DC converter's efficiency was estimated at 95%.

The total power output for a configuration with 15.25 cars per link can simply be described as

$$P_{tot} = n_{cars} \cdot P_{car} = 61 \cdot 20\,000 = 1\,220\,000 \text{ [W]} \quad (35)$$

where  $P_{tot}$  is the power output experienced cumulatively by the cars in [kW],  $n_{cars}$  is the total amount of cars, and  $P_{car}$  is the charger output power from each car, previously assumed to be 20

[kW]. Equation 35 does not take losses into consideration, which is relevant to approximate in order to determine the power input experienced by the ferry.

Average car per line is estimated to be 15.25, the total power per link can then be described as

$$P_{link} = n_{cars/link} \cdot P_{car} = 15.25 \cdot 20 = 305000 [W] \quad (36)$$

where  $P_{link}$  is the maximum power output onto the DC line expressed in [W]. The resistance of the copper cable can be calculated as

$$R_{cable} = L_{cable} \cdot \frac{\rho_{cu}}{A} = (L_{parking} \cdot n_{cars/link} + 20) \cdot \frac{\rho_{cu}}{A} = (15.25 \cdot 5 + 20) \cdot \frac{1.724 \cdot 10^{-8}}{1.2 \cdot 10^{-4}} = 0.0138 [\Omega] \quad (37)$$

where  $R_{cable}$  is the resistance of a single DC link expressed in Ohm,  $L_{cable}$  is the length of the copper cable on each link, which can be rewritten as the length of each parking space, assumed to be 5 meters, times the number of cars per link. The additional 20 meters are also included, which is to connect all the parallel links.  $A$  is the cross-section of the copper cable, and  $\rho_{cu}$  is the resistivity of copper.

Equations 36-37 can be combined to calculate the losses in the cable, which can be calculated as

$$P_{link,loss} = \left( \frac{P_{link}}{U} \right)^2 \cdot R_{cable} = \left( \frac{305\ 000}{760} \right)^2 \cdot 0.0138 = 2\ 227 [W] \quad (38)$$

where the fraction describes the current through the cable, with  $U$  as the link voltage and  $P_{link}$  as the power in the line, described in [W]. The output power from each parallel link, after losses can now be described as

$$P'_{link} = P_{link} - P_{link,loss} = 302\ 773 [W] \quad (39)$$

where  $P'_{link}$  is the Power output from the cable after cable losses expressed in [W]. Combining all these results with the efficiency of the DC-DC converter allows the overall efficiency and power output experienced by the ferry to be calculated as

$$P'_{tot} = n_{links} \cdot P'_{link} \cdot \eta_{DC/DC} = 4 \cdot 302\ 773 \cdot 0.95 = 1\ 150\ 500 [W] \quad (40)$$

where  $P'_{tot}$  is the total power input experienced by the ferry, expressed in [W], and  $n_{links}$  is the total number of parallel DC links. Moreover, this will correspond to an efficiency of

$$\eta = \frac{P'_{tot}}{P_{tot}} = 0.94 \quad (41)$$

which will be relevant throughout the different usage scenarios and business models.

Assuming one crossing takes 20 minutes, and the system can remain at maximum power for just as long, the maximum capacity that the ferry could receive would then be

$$E_{max} = t_{crossing} \cdot P'_{tot} = 0.33 \cdot 1\ 150\ 500 = 379\ 665 [Wh] \quad (42)$$

Which means only the remaining 670 [kWh] of the crossing capacity would have to be discharged from the battery.

#### 5.4.4 Scenario 1: Using Bi-Directional System to Become Diesel Independent During Charger Service Disruptions

The ferry operators states that the main occurrence which causes the most significant disturbance to the charging, and therefore creates a need of the diesel generators to be started, is the quarterly service of the charging robots. These service rounds are done during two 12 hour windows, for two consecutive days [92]. During these 12 hours, the ferry is dependent on either the diesel generators, or the BD-system to remain within the critical limits of SOC defined by the operators and their battery suppliers. The costs of operation of using the diesel generators is compared by

the BD-system by assuming a cost per [kWh] given to the passengers and an additional assumption of the efficiency of diesel-combustion. These are all given in table 38.

As the ferry sets sail from one harbor to another, coinciding with the onset of a service disruption at the destination harbor, the BD-system is triggered. This activation leads to a reduced depletion of battery capacity upon arrival at the harbor with the service disruption. Nonetheless, the ferry will exhibit a diminished SOC upon departure from this harbor compared to ordinary operation conditions. Departing towards the initial harbor, the BD-system continues to operate, ensuring that a substantial portion of the crossing's energy requirements are not drawn from the battery. Upon arrival at the starting harbor, the ferry utilizes the charging robot to fully restore its battery during the available charging period, achieving the SOC level targeted by the operators, around 66%. This process is repeated until the charging robot is once again operational, from which point the BD-system will be unnecessary.

This process is visualized in figure 55. In this figure, at the 9th crossing the BD-system turns on as the ferry heads towards the harbor with the non-operational charging robot. It prepares by activating the BD-system, and therefore it arrives with a higher SOC than the crossings before. It also leaves the harbor with the same SOC as upon arrival, as it has not been able to charge during the stop. After the 10th crossing it has reached the harbor with the functioning charger. The output power of the charger allows the battery to reach the desired SOC of 66% without extending the time of the stop.

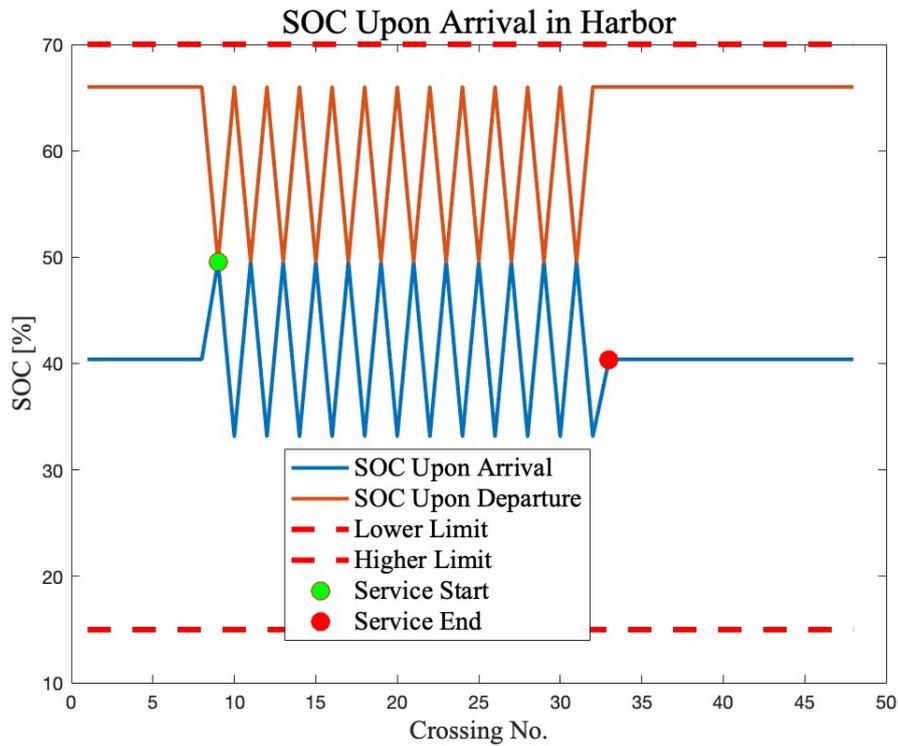


Figure 55: The SOC of the ferry during a day with service interruptions with an active BD-system of 61 cars.

This result means the ferry grows independent of using the diesel generators with 61 connected EVs, and includes an efficiency of the BD-system of 93%. Decreasing the number of connected cars make the ferry dependent of the diesel generators as the SOC reaches the critical levels. Figure 56a shows the SOC with 45 cars connected, whereas figure 56b shows the SOC with 40 cars connected.

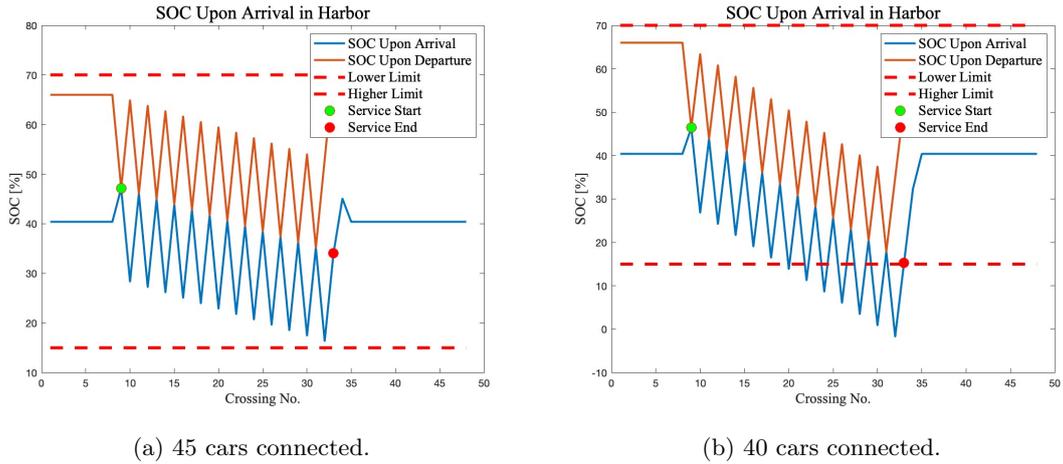


Figure 56: The SOC of the ferry with lower amounts of cars connected.

In figure 56, it can be noted that having 45 cars connected barely keeps the ferry from reaching the critically low SOC during the 12 hours of charger disruption, a lower bound to remain independent of the diesel generators. However, 40 cars means crossing the critically low SOC of 15%, which means the battery system will demand an activation of the diesel generators.

### Scenario 1: Costs of Operation

Assuming the previously stated cost per liter of buying diesel, efficiency of the BD-system, etc, the only variable parameter in the cost of operation is the rate to which the Ferry Operator buy electricity from the passengers. The efficiency of the diesel combustion is assumed to be 30%, and one liter of diesel is assumed to equal 9.96 [kWh] [96]. The cost per [kWh] diesel can then be calculated as

$$C_{diesel} = \eta_{diesel} \cdot C_{diesel/liter} \cdot 9.96 = 0.3 \cdot 8.35 \cdot 9.96 = 2.8 \text{ [SEK/kWh]} \quad (43)$$

were  $C_{diesel}$  is the net cost of one [kWh] diesel in [SEK]. As the ferry makes 2 crossing each hour, and the service interruption last for 12 hours, the BD-system is activated for 24 crossing. The amount of energy bought during one crossing was stated in equation 42. The total of energy bought during a day of service interruptions can then be calculated as

$$E_{bought} = E_{max} \cdot 24 = 9\,048\,480 \text{ [Wh]} \quad (44)$$

were  $E_{bought}$  is in [Wh] and equivalent to 9 048 [kWh]. Assuming that a passenger is willing to sell at a rate of 2 [SEK/kWh], the total cost of electricity would be 18096 [SEK]. The equivalent cost of diesel would be approximately 25 336 [SEK], not taking the saving of emission trading into consideration. Since service is done quarterly on each harbor, the 8 days of this operation each year would equal an annual net profit of 57 920 [SEK].

#### 5.4.5 Scenario 2: Incorporating a Buy-And-Sell System between the Cars

The second scenario uses the BD-system to buy electricity from cars at a set price, and selling it to cars in need of electricity at a higher rate. It makes a few assumptions, which are summarized in table 40.

Table 40: Main assumptions for the Buy-And-Sell Scenario.

Parameter	Value	Unit
$c_{buy}$	2	[SEK/kWh]
$c_{sell}$	4	[SEK/kWh]
$\eta_{bd}$	0.94	[-]
$n_{cars,day}$	30	[-]
$n_{cars,night}$	10	[-]
$n_{cross,day}$	24	[-]
$n_{cross,night}$	24	[-]

In table 40,  $c_{buy}$  is the rate to which electricity is bought,  $c_{sell}$  is the rate to which electricity is sold,  $\eta_{bd}$  is the previously calculated efficiency of the BD-system, and  $n_{cars,day}$  and  $n_{cars,night}$  is the number of cars participating on each side and  $n_{crossings}$  are the total amount of crossing made during the day or night. It is important to note that if the balance between buying and selling cars is perfect, the DC-DC converter between the BD-system and the ferry's battery does not have to be used, which will further increase the efficiency  $\eta_{bd}$ . In the following calculations, perfect balance will be assumed, which implies that 30 cars are selling to 30 cars during daytime, etc. Since traffic during night mostly consists of trucks, the number of participating cars is assumed to decrease [92]. The rate at which cars sell their electricity is the same as in scenario 1, which is a higher rate than paid by most to charge their car at home. The  $c_{sell}$  was chosen from what the ferry now charges for their fast chargers onboard (6.75 SEK/kWh) [91]. Since the BD-chargers cannot provide the same power (20 [kW] instead of the fast chargers 150 [kW]), the charging is chosen to be lower.

The costs can simply be described as

$$c = c_{buy} \cdot n_{cars,day} \cdot P_{car} \cdot t_{cross} \cdot n_{cross,day} + c_{buy} \cdot n_{cars,night} \cdot P_{car,kW} \cdot t_{cross} \cdot n_{cross,night} = 12\,800 \text{ [SEK]} \quad (45)$$

were  $c$  is given in [SEK]. To calculate the corresponding income, we use the same method but include the efficiency of the BD-system, which equals

$$i = c_{sell} \cdot n_{cars,day} \cdot P_{car} \cdot t_{cross} \cdot n_{cross,day} \cdot \eta_{bd} + c_{sell} \cdot n_{cars,night} \cdot P_{car,kW} \cdot t_{cross} \cdot n_{cross,night} \cdot \eta_{bd} = 24\,064 \text{ [SEK]} \quad (46)$$

were  $i_{electricity}$  is the total income given in [SEK]. Note that in both these equations, the unit of  $P_{car}$  needs to be changed from [W] to [kW]. The following results provides a net profit of 11 264 [SEK] per day in operation.

The net profit of different distributions of participating cars are presented in table 41.

Table 41: Different daily profits of Buy-And-Sell system based on participating cars.

$n_{cars,day}$	$n_{cars,night}$	Profits [SEK/day]
10	0	2 816
30	0	8 448
10	10	5 632
20	5	7 040
15	0	4 224

#### 5.4.6 Accelerated Battery Aging of Passenger Cars

The different usage scenarios impacts the battery life of the cars to a certain degree. Using the battery aging model presented, in can be approximated to which degree the changed usage patterns effects the lifetime of the battery.

The two different scenarios suggest that there is no extra utilization of the ferry's battery, although it affects the personal electric vehicles. This situation leads to increased cycling for the cars on board that are selling their energy back to the ferry operators. Employing a typical commuter's driving cycle from the survey, two distinct driving cycles were developed. One involves selling energy on the ferry, while the other does not. The C-rate was set by the BD-charger on the ferry, assumed to be 20 [kW]. For the Volkswagen ID.4, this corresponds to a C-rate of 0.25, roughly equal to the discharge rate during highway driving at 23 °C at 110 km/h [56]. Therefore a c-rate of 0.25 is a valid assumption both during charging and discharging. Each cycle spans 24 hours with intervals of 20 minutes. These cycles are detailed in table 42, showing the vehicle's status during each 20-minute interval and the SOC at the end of these intervals.

Table 42: A common commuter driving cycle, C=0.25.

Driving Cycles, Helsingborg-Helsingör Commuter				
Hour	Cycle 1 (BD)	SOC	Cycle 2 (no BD)	SOC
00:00-8:00	Idle	80%	Idle	80%
8:00-8:20	Discharging	72%	Discharging	72%
8:20-8:40	Discharging	63%	Idle	72%
8:40-9:00	Discharging	55%	Discharging	63%
9:00-17:00	Idle	55%	Idle	63%
17:00-17:20	Discharging	47%	Discharging	55%
17:20-17:40	Discharging	38%	Idle	55%
17:40-18:00	Discharging	29%	Discharging	47%
18:00-19:20	Charging	63%	Charging	80%
19:20-20:00	Charging	80%	Idle	80%
20:00-00:00	Idle	80%	Idle	80%

Table 42 demonstrates that the cycles are exactly the same, with the exception of cycle 1 which continues to discharge while on the ferry. Consequently, it will reach its destination, and then return to its starting point with a diminished SOC. The DOD will be elevated throughout all the cycles. The first cycle is equivalent to 0.5 full equivalent cycles per day, and the cycle 2 corresponds to 0.32 full equivalent cycles per day. The application of this driving cycle in a 20-minute resolution adaptation of the battery aging model yields the results depicted in figure 57.

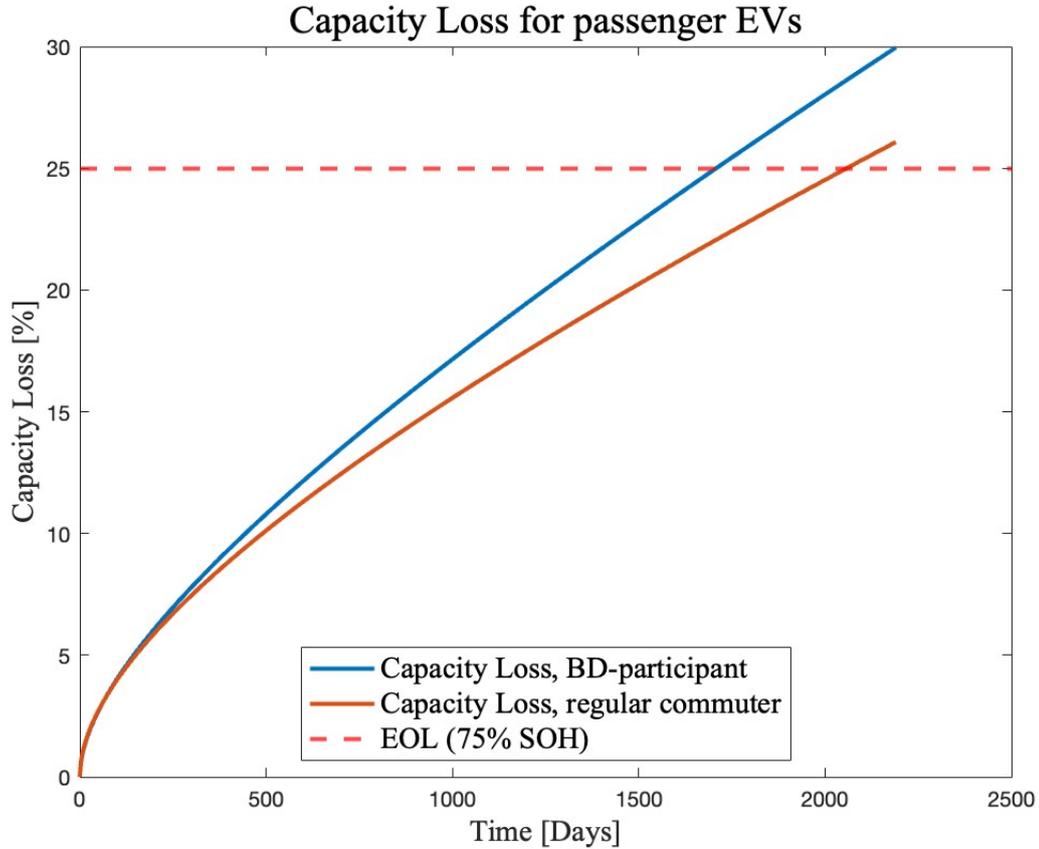


Figure 57: Capacity Loss for the two different cycles until EOL.

In figure 57, the x-axis represents the degradation over a defined number of cycling days for a new battery, while the y-axis indicates the percentage of capacity loss. The findings indicate that the cycle incorporating BD-charging reaches its EOL at 1708 days, and the cycle that does not reaches its EOL at 2057 days, which means that the vehicle which is not participating will last approximately 20% longer according to the model. At their EOL they have reached 854 and 679 full equivalent cycles respectively, which means that the cycle 1 battery will experience significantly more charge throughput throughout its lifetime despite reaching EOL almost a year prior to cycle 2. The study also explored the effect of recharging up to 80% at work for both cycles, which did not yield any notable differences. It is relevant to mention the fact that this driving cycle implies connecting to the system every day both trips, which is an extreme case.

If a car participates every day during the 1708 days of its lifetime, with a net profit of 2 [SEK/kWh] as in scenario 1 and 2, it will correspond to a profit which can be calculated as

$$\dot{i}_{lifetime} = n_{lifetime} \cdot n_{cross,day} \cdot P_{car} \cdot t_{cross} \cdot c_{profit} = 1708 \cdot 2 \cdot 20 \cdot 0.33 \cdot 2 = 45\,091 \text{ [SEK/kWh]} \quad (47)$$

were  $n_{lifetime}$  is the number of days the cars will be used,  $n_{cross,day}$  the number of crossings the car participates in per day,  $P_{car}$  the Power output from the car,  $t_{cross}$  the crossing time of the ferry in hours, and  $c_{profit}$  the net profit for the passenger in [kWh], and  $\dot{i}_{lifetime}$  the total income during the cars lifetime from participation in the BD-system, in [SEK].

#### 5.4.7 Yearly Business Model of Scenario 1 and 2

A business model is provided for the combined scenarios in the following section.

### Profits for Ferry Operators

Combining the two scenarios throughout one year of operation provides an outline of an estimated Return of Investment (ROI). As stated by the operators, quarterly service is performed on each charging robot for two consecutive days. This equals 8 days in total every year with earnings of 7 634 [SEK/day]. This means that most of the time the ferry will operate within scenario 2. Using different constellations of participating cars, a best and worst case income statement can be created. The best case assumes  $n_{cars,day} = 30$ ,  $n_{cars,night} = 10$ , whereas the worst case assumes  $n_{cars,day} = 10$  and  $n_{cars,night} = 0$ . The profits for the best case is presented in Table 43 and for the worst case in Table 44.

Table 43: Best case profits of Scenario 1 and 2.

Scenario	Days in operation	Daily profits	Total profits
Scenario 1	8	7 634	61 072 [SEK]
Scenario 2	357	11 264	4 021 248 [SEK]
<b>Annual profit:</b>			<b>4 082 320 [SEK]</b>

Table 44: Worst case profits of Scenario 1 and 2.

Scenario	Days in operation	Daily profits	Total profits
Scenario 1	8	7 634 [SEK]	61 072 [SEK]
Scenario 2	357	2 816 [SEK]	1 005 312 [SEK]
<b>Annual profit:</b>			<b>1 066 384 [SEK]</b>

Calculating the costs of installation comes with limited accuracy, as the process is more complex on a ferry than in an industry, due to all existing electrical and mechanical systems [92]. The costs of the Bi-Directional chargers are also complex to calculate due to their limited availability. The 11.5 [kW] DC BD-charger Quasar 2 is said to cost approximately \$4 000 according to news channel Electrec [45]. This is estimated to 50 000 [SEK] to leave margins for import fees and other additional costs for the extra complexity for installation on a ferry. For 61 chargers this will equal 3 050 000 [SEK]. Cost of copper cables is taken from cable retailer electric-house.com and estimated to be 180 [SEK/m] [97]. From previous calculations it is estimated to be required 384 meters of copper cable, which means the costs of cables and chargers in total will reach 3 119 300 [SEK]. Which means that without labor costs during installations and cost of the DC-DC converter taken into consideration, the payback time would be between 0.76 to 2.9 years.

### Profits for Passenger Cars

As stated in 5.4.6, the battery life is reduced by 17% compared with a car that does not participate. For this the passengers are paid approximately 45 000 [SEK]. It is however important to strengthen the fact that the model is based on individual cells and exaggerates the degradation based on how many cycles can usually be expected from these vehicles.

However, using the net profit, we can estimate yearly earnings for a commuter based on different driving patterns. Based on the fact that the passenger sells 6.67 [kWh] during each crossing (20 [kW] during 20 minutes), and makes 2 [SEK/kWh], the annual earnings presented in 45 are reasonable.

Table 45: Passenger Earnings for different types of commuters.

Annual no. of weeks commuting	Commutes per week	Annual Profit [SEK]
46	5	6 136 [SEK]
10	5	1 334 [SEK]
52	7	9 711 [SEK]
46	3	3 682 [SEK]

In table 45, daily work commuters with 6 weeks of vacations are taken into consideration, as well as workers who work 2 out of 3 days of the week from home.

#### 5.4.8 An Overview of Suitable Ferry Routes for Bi-Directional Electrification in the US

Given that scenarios 1 and 2 do not specify technologies or utilizations unique to Sweden, it is pertinent to examine other markets and appropriate routes for electrification. Initially, the US EV market will differ, as it is not expected to achieve a 50% EV share until 2035, unlike Sweden, which is anticipated to reach this milestone by 2029 [94]. Consequently, the US is relatively less advanced in terms of electrification.

##### **Galveston - Bolivar Ferry, Peninsula (TX)**

The Galveston Bolivar Ferry covers a distance of 2.7 miles (about 4.3 km), closely matching the Helsingborg - Helsingör ferry's route [98]. It has a capacity of 100 vehicles, compared to 250 for the latter. This ferry service is free for all passengers. It includes 12-minute stops and operates on a schedule where it departs every 30 minutes, with each trip lasting roughly 18 minutes. Similar to the Helsingborg - Helsingör ferry in terms of travel distance and time, this ferry primarily serves as a link for vehicular traffic and minimizes its focus on providing additional amenities, evident from the small indoor space.

##### **Cape May - Lewes Ferry (NJ)**

The Cape May-Lewes Ferry covers a distance of 17 miles (about 27 km) in 85 minutes [99]. It can accommodate around 100 vehicles. Compared to Öresundslinjen, its schedule is less frequent, with 5 daily journeys or 32 over the course of a week. Despite the greater distance, the ferry's design is quite similar to M/S Aurora.

#### 5.4.9 Summary of Case 4: Electric Ferries

Case 4 findings indicate that installing a BD-charging system involving 61 vehicles, which represents 25% of all onboard vehicles, can effectively prevent the diesel generators from operating during significant disruptions to the ferry charger, while gaining further profitability. In regular operations, the system remains functional and yields considerable economic benefits through a V2L trading system among the vehicles present. Additionally, the data suggest that while passenger involvement may slightly hasten the wear and tear of vehicle batteries over time, the batteries' utilization at the EOL is greatly optimized, showing a marked increase in full equivalent cycles.

## 6 Discussion

The discussion is sectioned into a general discussion of the impacts of BD-technologies, which discusses the foundational outcomes common to all cases, and discussion regarding the cases and their respective results.

### 6.1 General Discussion of the Impacts of Bi-Directional Technologies

In this section, a general discussion is presented covering all cases and the general result as well.

#### 6.1.1 General Return for Ancillary Services

In Sweden, the income generated from ancillary services is currently substantial. Data indicate that the financial returns from the ancillary service market for a single stationary battery are exceptionally high, despite the limited energy capacity that such a battery contributes to the grid with. The trend for this price development can not go on forever; from the demand and supply perspective, the return for the ancillary services will decrease with the increase of the V2G system. With increasing electrification in society and in the transport sector, the number of suppliers to the ancillary markets will increase with the use of the V2G system. The market of ancillary services and other energy balancing markets will possibly generate less return according to recent market theory.

What the return from the ancillary service markets can be in the future cannot be predicted. The conclusion of the discussion is that there is a profitable market, further studies and other projects must be implemented to know the influence that the V2G technology will have on energy markets in the future.

#### 6.1.2 Accuracy of the Battery Degradation Model

As batteries exhibit varying behavior over their lifetimes, it is important to note that the aging models discussed were based on individual cells being discharged and recharged independently, rather than as part of a battery pack, as is typical in mobility applications. Considering this, along with the existing Root Mean Square error associated with the model, discrepancies are to be expected when applied in real-world scenarios.

The calendar aging model utilizes an NMC-cell, which reflects the reality of EVs. However, the cyclic model uses LFP cells, which are less common in EVs. Despite this difference, LFP cells exhibit similar degradation characteristics. Since cycling contributes to a smaller proportion of degradation compared to calendar aging, this difference in cell chemistry is more likely to accentuate variations rather than introduce significant errors.

Initially, a constant C-rate was chosen as a simplification. This choice proved relevant due to the driving data available, which indicated a consistent power output during both discharge and charging. For instance, a 20 [kW] discharge observed during a drive at 110 [km/h] matched the assumed power during charging for certain cases. Similarly, a discharge power of 45 [kW] was chosen for another case based on similar considerations. However, if comprehensive datasets of driving patterns, including discharge rates, had been available, a battery model incorporating variable C-rates would likely be more accurate. Such a model could result in less degradation and longer life cycles in terms of both cycles and time, as it would reduce overall battery stress.

Lastly, it's worth noting that the model's accuracy, based on individual lithium-ion cells, the basis of the empirical models, is very good, as they typically exhibit a lifetime of approximately 800 cycles. However, in mobility applications, this number is expected to be in the thousands rather than the hundreds.

### 6.1.3 Market Comparison with USA

The different cases all provide one common result, that not all markets are mature enough for BD-charging applications as of now. The US, which has been used as an example throughout the report, is yet to introduce large scale, and widely available ancillary services, which withdraws many of the sources of profitability in terms of V2G. Electrification is progressing slowly, with projections indicating a 50% EV share by post-2035, lagging over six years behind Sweden's target of 2029. This delay not only impacts the growth of the market for aggregators but also slows down the advancement of BD charger deployment in their country, thereby extending the timeline for the shift to renewable energy.

Secondly, the slower electrification rate in combination with a generally smaller vehicle capacity decreases the potential of efficiently implementing BD-systems on electric ferries as of now. The US could realistically also find profitability within this business area, although it will require either larger ferries, a larger portion of contributing EVs or higher power output per car. This could also be the case throughout other markets, as ferry routes are rarely the same, and it is challenging based on varying geography to categorize different ferry routes.

### 6.1.4 Benefits of the Energy Transformation in Society

The different case studies show that the BD-charging technology has many different applications in the whole society. A common finding across all cases was that BD-charging improves the utilization rate of batteries. This implies that the energy retained in the batteries is employed more efficiently, leading to a more sustainable consumption of energy for each EV and vessel. The technology enables more local energy storage solutions that can support the grid in various locations, including more remote areas that may not be accessible by other energy infrastructure. Additionally, the technology allows for an increase in the charge throughput for batteries, which means that the battery undergoes more cycles before reaching its EOL. This is also a result of more sustainable energy usage in batteries. This adaptable energy consumption is crucial for managing the substantial shift in energy dynamics within society.

The energy storage capability is greatly enhanced throughout society with BD-technology. Through flexible storage that is not tied to a specific location, there is great potential to handle energy consumption more easily. As the number of EVs is expected to increase significantly, it becomes important to have flexible energy usage to reduce the strain on the energy system. This flexibility is also necessary to store energy from renewable sources which do not have constant production.

### 6.1.5 Social Impacts of Bi-Directional Technologies

There are some social aspects that needs to be taken into consideration when evaluating applications of BD-charging. In terms of cybersecurity, communication protocols between the charger and the vehicle could create windows for data leaks and monitoring of specific individuals. Providing grid companies or aggregators with data at which time during the day you will be at home can cause serious risk of crimes and break-ins if given into the wrong hands. It could also allow police states or illicit governments to further monitor its population, which is problematic.

The aspect of ones personal property and integrity must likewise be regarded. With many of the BD-charging applications investigated, ones EV will be a part of a larger, wider image, such as the local grid or the energy storage of a ferry. Letting go of one's property in this manner could be considered going against the norms the members of society are used to, which means a great change in mindset among EV owners. A transition which can not be expected to happen smoothly, as the owners will likely experience their personal property as being misused. It is also crucial to take into account the perspective of peoples attitude to this technology, since convincing EV owners to allow their vehicles to contribute energy to the electricity grid is essential. The acceptance and outlook of individuals towards this technology will significantly influence its global implementation.

One crucial consideration lies within the economical benefits offered by BD-charging. Should electric vehicles remain financially out of reach for segments of society, the potential for increased earnings

among EV owners could increase existing inequalities in society. This could widen the gap between the members of society that can afford to participate in these services, and those who cannot.

As many of the results show, the batteries comes to more use during their lifetime in terms of cycles, which is a substantially large advantage in terms of making the best use of the environments resource, but also the time spent manufacturing the batteries. However, with a wide expansion of new energy storage technologies, its important that BD-technologies does not prevent more resource efficient energy storage solutions to reach the market.

Another important aspect is the affect the BD-charging application might have on the transition to green electricity. In USA for example, where large parts of the electricity comes from non-renewable and non-green sources, the ability to buy electricity when its cheap, to use when the grid prices are peaking, might prevent investments in solar power, both on a private but also on a industrial scale.

A core area of this project is the use of batteries, and one must consider the fact that batteries are made of highly rare metals, which there is not a large amount of. It is important that the BD technology does not drive inhuman mining of these metals as a consequence of driving down the battery prices. Financial and environmental benefits cannot justify the suffering of others.

## **6.2 Discussion Case 1: Vehicle to Grid**

A more specific discussion of the case Vehicle to Grid is provided in the following section.

### **6.2.1 User Pattern for Electric Vehicle drivers**

The concept of BD-charging of EV is dependent on the availability of the power in the battery. The usage of the EV is therefore crucial for make this concept work. The possibility to sell the battery power for other purposes have to take into account the usage scheme, purpose of using a EV, how the EV normally is used etc. To fully understand how a EV is used a deep analysis was made. The usage scheme analyze included number of hours parked by a charger, how many hours it was used for transport and how far in km it was used. It also gives examples of different user categories. The result of the usage scheme survey show that most cars are available during nighttime. The available time when the car is parked is over 90 %. Most of the time at home. The potential of using a V2G charger is therefore high. However, this is not always the case, that is, there are variations in usage of EV. To use a EV compared to a stationary battery as a source for the ancillary service to the grid has a challenge as the availability cannot be guaranteed using an EV. The current bidding process is based on that the availability must be guaranteed for a specific time period. Which make the bidding process more difficult for aggregators when they do not have the same capacity around when bidding.

The analyze of user patter was made by a survey with 256 respondents and 5 interview people. It needs to be emphasized that these individuals do not represent all EV drivers and therefore do not reflect the entire truth. However, it provides a clear picture of the framework within which the usage patterns of EV actually lie. However, a more comprehensive investigation of driving patterns, linked to where in the country one is located, is required, as it could vary quite a lot. In order to fully formulate a business model for V2G, the location of its implementation must therefore be given great consideration in order to maximize the benefits of a V2G system.

### **6.2.2 Return for Ancillary Services for Vehicle to grid**

To analyze if the V2G could be financially profitable an assumption was made that the availability factor could be controlled, like a stationary battery. It was assumed that only the availability gave different revenue streams for different EV user. It gave a positive result, including the cost of energy when driving and the revenue of ancillary services when parked. Using the profit for the V2G charging investment gives a payback of less than 2 years. It shows that V2G concept is profitable, however, the challenge with the analysis of profitable is that it is based on current prices and costs. The chapter 2.5 describes how a market develop when the supply and demand changes and innovative solutions enter the market. In this case the number of EV will drastically increase

as well as the BD-charging technique is in a very early phase. The willingness to pay for the energy source that is not guaranteed is not included either, that is, how much the availability will effect the business model. The conclusion is that the profitability will change and could not be set.

### **6.2.3 Battery Degradation**

Another factor that might have an impact of the cost of a V2G solution is the battery degradation. The profitability analyzes only included the cost for a V2G charger, not anything related to the battery of an EV. The degradation model assumes that the car is driven 110km/h in 23 degrees and this is not the case for V2G. The collected data from the interviews indicates lower speed since the change of SOC is significantly lower then in the degradation model. This gives a result of the worst case scenario and since it still does not give a noticeable difference in the degradation, it can be neglected. Demonstrating that using V2G chargers for ancillary services does not significantly impact the battery could be an intriguing point for developing V2G business models in the future.

In this case only the use of ancillary service was considered in the battery degradation model. An intriguing aspect to examine would be the impact of various energy markets such as energy price arbitrage, peak shaving, and local flex markets, among others, to determine if their involvement would exacerbate battery degradation. Due to data constraints, the model only investigated frequency ancillary services.

### **6.2.4 Market and Business Model for Vehicle to Grid**

In Sweden, the income generated from ancillary services is currently substantial. Data indicate that the financial returns from the ancillary service market for a single stationary battery are exceptionally high, despite the limited energy capacity such a battery contributes to the grid. The trend for this price development can not go on forever; from the demand and supply perspective, the return for the ancillary services will decrease with the increase of the V2G system. The reports shows that the number of EVs will increase rapidly in the coming years and with new V2G charges the number of suppliers of ancillary services will be more and the market will possibly be saturated with the increase of energy suppliers. Similar conclusions in the ARENA study were also made about possible saturated ancillary service markets in the future. The market factors indicate that the supply and demand for ancillary services will change in the amount. To use a V2G solution will differ in the fundamental of being available for a set period, as current solutions are. The main purpose for having an EV is transportation according to the collected data. The question is how to combine the normal use of an EV for transport with the demand for being part of the ancillary services. How high is the willingness of a EV user to connect to a ancillary service? An interesting sales point could be that EV drivers do not use the full capacity of the car battery and to use the energy more effectively they could invest in V2G chargers to have an other stream of revenue.

The business model for V2G need to change and can not be the same as for a stationary battery solution. The main change is that key partners will be EV users that need to have another communication platform for its key activities, than stationary battery owners. The value proposition, customer and channels will most likely remain, but additional channels with availability information need to be added in line with the new key activities in the supply chain.

In order to solve the question of availability of EVs for aggregators to bid the excess energy on ancillary services markets, information about EV usage is essential. As stated above, a communication platform is required between EV users and aggregators, and other stakeholders in the value chain. The scheduling problem could be solved with a parking garage. The EV users will park their car at a certain time which can be notified in an app application. This knowledge of availability is helpful for aggregators to bid the energy in the EVs, because they can get exact information on how many EVs are parked and the available power in the garage ready for bid. That could remove the uncertainty factor from the equation, resulting in a higher return form ancillary services.

An other interesting aspect of connecting multiple chargers together is that the minimum bidding requirement for the ancillary services FCR and FFR is 0.1 [MW]. That entails a company or similar

entity only needs 5 units of 20 [kW] V2G chargers and 5 connected cars to be able to bid on the frequency market. Furthermore, with V2G chargers there is a potential revenue stream for big and small players in the frequency regulation market, and as CheckWatt business developer [36] pointed out, there will be new revenue streams for V2G in future markets.

### 6.2.5 US and other perspectives on Vehicle to Grid

In US the V2G concept has been studied for a longer period. It was kicked off as a part of the state of California zero emission initiative. They regard this concept as important for the environmental initiative. Besides the environmental effect, it also shows that the concept is profitable, even though the revenue varies between the states. It backs up the calculation made that it is profitable, but how much is to be analyzed further.

### 6.2.6 Avenues for Further Research

The environmental benefit of using batteries in EVs in more ways than just for transport is crucial. The solution of V2G supports environmental change. However, to make it viable and reliable, it must be further developed. In this study, two areas have been identified as the most interesting. The human behavior of EV owners and their priorities for participating in ancillary services and integrating with V2G solutions. This was not included in the user service study and need further research. How to develop the BD-chargers in line with the request of the EV owner, the supplier, to ensure the available capacity in these EVs. The communication is a new channel in the business model that needs to be developed and regulated. The development of standards and protocol has been defined, but how does it impact the business model? How to exact develop the business model for V2G will be a core area that need further research.

Another core area of future reach is where the inverter will be placed, that is, in the EV or in the charging station. The industry is not united on where the inverter should be, and this will impact the usage of V2G. Therefore, the aspect of where the inverter should be placed is an important avenue of future research. What the industry decides in the matter will impact further development of BD-charging solutions.

## 6.3 Discussion Case 2: Vehicle to Home

The following section will discuss the result shown in the previous section, the limitations investigation and future possibilities with V2H.

### 6.3.1 Interpretation of Results during Summer

The positive profitability in both scenarios is primarily attributed to the seasonal variations. In the summer, solar energy production is maximized while household electricity consumption is minimized. This season, facilitated by dynamic load balancing, results in surplus electricity for extended periods. Consequently, this surplus allows for the charging of the EV during available times such as weekends or before and after work hours using V2H. During nighttime and early morning, when solar power is not available, the EV's battery is utilized to meet the household's power needs. This solar inactivity causes the SOC to vary between 50-80%. The findings suggest that adopting V2H enables a household equipped with solar panels to potentially operate off-grid. The first scenario concludes with a profit of 5 835 [SEK], primarily driven by ancillary service profits amounting to 4 911 [SEK].

In contrast, the second scenario achieves a profit of 688 [SEK], which is 5 147 [SEK] lower than the first. The absence of V2H means that electricity must be sourced from the grid at night, and the battery cannot be used for ancillary services, explaining the profitability disparity between the two scenarios. Ultimately, the use of V2H during the summer months proves to be more economically and energy-efficient than not using it.

### 6.3.2 Interpretation of Results during Winter

The reason for the negative profitability for both scenarios is mainly because of the solar production being at its low-point and household consumption at its peak electricity consumption. With dynamic load balancing, many hours are in a deficit of electricity, leading to the depletion of the battery's capacity. As the battery is completely depleted within three days in the first scenarios, the rest of the simulation acts as if there is no battery available. As the main purpose of an EV is to transport the owner, V2H is not optimal from an energy-efficient perspective. Consequently, the difference of the final profit between the two scenarios concludes to 472.5 [SEK]. But as the second scenario recharges when the SOC is below 20%, which adds up to the overall profit and the first scenario does not recharge considering the lower limit, the difference in profitability is a bit unfair. When excluding the recharges in the second scenario, the difference in profits concludes to 7.5 [SEK].

In conclusion, as the profitability between both scenarios is minimal and the battery is depleted in an instance, using V2H during winter is not optimal from an economical and energy-efficient perspective.

### 6.3.3 Limitations with the Investigation

The main limitation is that a battery degradation model was not possible to simulate in this case, because of the complexity of the data. As the result in summer is positive for V2H, a negative perspective might be the increase of battery degradation, therefore a limitation that is not considered.

A significant constraint in the study was the transaction prices, which were calculated based on monthly averages, despite actual prices fluctuating with immediate demand. The primary reason for relying on average prices was the lack of specific data for the household in question. If variable electricity costs were taken into account, the outcomes might have varied. It is well-known that electricity costs tend to rise during early mornings and late evenings due to increased demand. Given this, the results from V2H could vary seasonally. During summer, when electricity rates are highest in the mornings and evenings and as the SOC with V2H ranged from 50-80%, avoiding peak rates could potentially increase overall profits as presented in the result section. In contrast, during winter, no variance between scenarios would be observed, as V2H is less effective in that season.

In the simulation, for wintertime there are a few conditions not taken in considerations as they vary depending on many factors. During winter the cold temperature tend to be around 0[°C] in Sweden, whereas the optimal temperature for an EV battery is around 15[°C]-35[°C] [100]. Consequently this leads to a demand of heating up the battery, leading to the battery depleting a bit before departure but also during the commute. Another consequence is slower charging pace, reason being that the lithium ions slow down in cold temperatures. The driving conditions during winter also has an affect and can have a energy increase of approximately 10% [101]. With the consideration of these facts, the result for V2H during winter might have been even worse, further motivating why V2H is not optimal for cold weather.

### 6.3.4 Possibilities with Vehicle to Home

With V2H, further possibilities and investigation could be:

1. V2H into condominiums, as it is common in big cities. Could potentially decrease the monthly bill for the accommodators, as V2H is profitable during summer.
2. V2H in warmer climates, for example southern Europe and America. Could potentially totally be disconnected from the grid year-round, but also have a negative impact on the battery degradation.
3. Commercial buildings, where employees can supply electricity and in return potentially get higher salary or benefits.

4. Public infrastructure as in airports, hospitals, train stations and so on. Here the V2H system could act as a backup in case of emergencies for example.

## 6.4 Discussion Case 3: Vessel to Grid

This subsection aims to underscore various inquiries that surfaced during the analysis of the results, to further investigate the assumptions used, and to investigate possible scenarios for the application of the Vessel to Marina and its potential configurations.

### 6.4.1 Survey Results

The survey consisted of nine specific multiple-choice questions aimed at investigating different boat types and their usage trends. This approach allowed respondents to choose the answer that most closely aligned with their views. To ensure that the responses were from knowledgeable participants, the survey was distributed through several online boating forums. It should be noted, however, that not all members of these forums are reliable respondents, which might lead to some fraudulent responses. Yet, upon reviewing the survey, these instances appeared to be in the minority.

The purpose of the survey was to gather comprehensive data, and employing a multiple-choice format aimed to ease the interpretation and analysis of the gathered data. Should the available answer choices not reflect the respondents' opinions, an 'other' option was provided to allow for customized responses. This approach was found to be effective and appropriate. Observing the frequent selection of the 'other' option facilitated the modification of the question or the addition of a complementary question when the existing questions were considered inadequate. While this can have both positive and negative implications, as it might inadvertently bias the survey towards favorable results, it is crucial to avoid such adjustments unless it is evident that a question has been misunderstood.

The survey collected a total of 176 responses, and as all questions were compulsory, each question received 176 responses. This quantity of responses was considered sufficient as it was supported by the Transportstyrelsen study [63]. Nonetheless, a greater sample size might lead to a broader variation in responses, which would be preferable.

### 6.4.2 Example User

The standard archetype for boats and users does not encompass all survey samples and makes significant assumptions. Thus, it is inaccurate to assert this as the definitive scenario. This archetype was crafted to provide a clear and comprehensible representation of user behaviors and BD-charging gains. Although the choices were data-driven, the data only indicated about 50% reliability in some cases. For instance, the selected user model asserts that every boat owner operates their boat for 8 hours, yet the data reveals that 68% of individuals operate their boats for 8 hours or fewer, which could skew the results. To develop a more accurate example user and archetype boats, this report recommends a broader data collection effort.

### 6.4.3 Battery Degradation

It should be highlighted that the battery degradation model employed is prone to substantial inaccuracies, partly due to the intricate nature of battery chemistry and also because of the core data it depends on, as shown in Section 6.4.2. Additionally, the model presumes a constant power output of 45 [kW] when operating the boat, which diverges significantly from actual conditions influenced by factors such as weather, the boat's hull, and varying regulations in harbors, all of which affect the feasible speed and power output. This issue is recommended to be addressed by collecting more detailed data on boat usage patterns. The precision of the simulation model is also important to note and is further analyzed in Section 6.1.2.

### 6.4.4 Results of Potential Revenue Streams

Ancillary services historically exhibit unpredictable profitability, making assumptions of linear cost progression problematic. Notably, the activation duration is crucial. Contrary to the model's

assumption of a continuous 20-minute activation per day, in practice, the grid requires support only for brief intervals scattered throughout the day. For instance, if a boat is away on an 8-hour journey, it may miss the opportunity for ancillary services entirely on that day, suggesting that our model might be overly optimistic. Nonetheless, as Cenex reports [80], the potential for increased returns exists, driven by the evolving market and diversity of ancillary services. A business developer at CheckWatt, notes that future ancillary services, which could be more lucrative, are anticipated to enhance profitability further [36]. This advancement might also spark new applications, such as custom services tailored for marinas or other battery storage facilities with high power output, a concept also endorsed by [36]. Detailed insights into the returns from ancillary services are discussed in Section 6.1.1.

#### 6.4.5 Vessel to Marina Results

The outcomes from the Vessel to Marina implementation provide insights into the costs of electrifying a marina and the benefits of ancillary services when BD-chargers are used. It is crucial to recognize that the model excludes the costs of installation, labor, and taxes related to the electrification subscription. Additionally, the model overlooks the grid connection fee for new installations, which depends on the distance in meters from the facility to the voltage/connection point. For distances between 1 200 and 1 800 meters, the fee is specified as 662,800 [SEK] plus 475 [SEK]/m for a standard subscription, which could be substantially higher for a high-voltage subscription. Furthermore, the harbor layout is quite compact, which implies that assumptions about cable costs might not be realistic. The model overlooks the management of chargers, including payment systems and user interfaces, which can lead to additional management expenses. These additional elements could add to the expected payback time.

The model presupposes that no boat users simultaneously fast charge at the maximum capacity of 75 [kW], which could lead to a fuse failure and possible power outage.

The primary goal of the model is to demonstrate the integration of electric boats and charging infrastructure within the maritime sector, thus this model does not extensively address safety or other regulations related to the construction.

The findings indicate that the investment's payback period is roughly 5 years, assuming that all ancillary services benefit the harbor, while only taking into account the expenses listed in Table 37 and disregarding the possible maintenance costs in the harbor. Considering that the average lifespan of harbors in Sweden is about 40 years, this result is reasonably acceptable. However, this scenario hinges on the assumption that boat owners are prepared to allow their batteries to be used for BD-charging at the marina at no cost while they are not using their boats. This assumption may not hold due to the significant wear and tear on the batteries, suggesting a need for further research and data gathering on the willingness of boat owners to engage in BD-charging despite its impact on battery life. Volvo Penta engineers also indicate that electrification will eventually include various other electric watercraft not currently considered, such as larger boats, yachts, and sailboats, which would require larger battery capacities, potentially leading to a higher total maximum energy output.

#### 6.4.6 Evaluation of Possible Business Models

Elaborating on the discussions in 6.4.5, it is possible to develop theoretical business frameworks. Taking into account the points discussed regarding the payback period and the usage of the boat's batteries, it might be feasible to set up various subscription or payment options with the boat owners, example solutions follows:

- Cheaper berth prices for BD-usage
- Reduced charging costs BD-providers
- Compensation for battery tear
- Implementation of boat sharing systems

Each of these implementations would naturally extend the payback period of the investment, yet they might encourage boat owners to more significantly allow the marina to use their BD-charging

facilities.

In addition to this, the Vessel to Marina model does not take into account the possible electricity arbitrage, generating further revenues for the marina. Conversations with Peter Berg from go:Leif also suggested potential earnings, stating that after covering the electricity fees for charging, the marina could potentially earn 208 [SEK] per full charging cycle. The depth of the cycle and the size of the battery were not specified, he also highlighted significant revenue opportunities for bigger marinas.

When considering the significant initial investments involved in setting up the BD-charging sections, it becomes apparent that the primary cost driver is the expense of the chargers, which were primarily derived from the interview with Peter. Given the less mature state of the electric boat market compared to the electric vehicle market, it is expected that the chargers would be more expensive, but just how more expensive is hard to say. Additionally, the company currently providing these chargers do not disclose specific pricing information for their chargers. Since they offer a free payment model in which they supply the charging infrastructure at no cost but handle the electricity arbitrage, which could lead to additional inaccuracies in pricing estimation. Furthermore, in accordance with Moore's law, the cost of electrical components generally decreases as technological advancements continue.

Taking all aspects into consideration, the Vessel to Marina business model seems feasible, even though it demands significant upfront investments and anticipates a return on investment over 20 years. This strategy could mark notable progress in the maritime sector. Additionally, it could greatly benefit the electric grid as the modeled marina showed potential to add 310 MWh for downward regulation and another 310 MWh for upward regulation, thus enhancing the integration of renewable energy sources. Economic incentives for boat owners should also be considered, with projections indicating that the cost of electric boats will follow Moore's Law, resulting in more affordable prices for the general public. Furthermore, payment schemes in marinas that support BD-charging compatible boats could encourage a substantial shift among boat owners towards electric propulsion systems, which would decrease emissions from combustion engines and be more beneficial for the marine environment.

## 6.5 Discussion Case 4: Electric Ferries

Despite the potential for significant initial costs for Ferry Operators, the return of investment is anticipated to be achieved within a remarkably short period, with substantial profits expected for both operators and passengers. The primary challenge lies in maintaining the system's profitability to consistently draw a sufficient number of passenger vehicles. Given that the energy output per trip and car is nearly 7 [kWh], the revenue per trip will remain modest, even with competitive pricing per [kWh]. An alternative to monetary compensation might be to offer free breakfast to commuting passengers. This could incur similar costs for the operators but could offer greater value to commuters by saving them time compared to a minor monetary return.

The return on investment for operators remains uncertain, influenced not only by the unpredictable rate of passenger participation but also by the costs of installation. Chargers are considered at a significantly high price, with an added markup reflecting the sophisticated ferry setup and the need for greater power output than what Quasar 2 provides. Neither bulk purchase discounts nor environmental subsidies are factored in. Moreover, labor costs will escalate the overall expense, potentially negating any profit margin considered for the chargers.

Even though the degradation is thoroughly exaggerated, the participating car is paid fairly well for the accelerated aging the car goes through considering that the aging model assumes everyday participation and aggressive driving patterns at a constant driving speed of 110 km/h in 23°C. In reality, it is realistic to assume the additional aging is very small or negligible. A more common use case, a 4-days a week commuter using their electric car leased through it's employer, could be provided free breakfast in return for selling electricity, and return the car when the 3 year leasing

agreement ends, which will then barely have aged excessively more than one's co-worker which has not participated. A great deal for employer, ferry operator and commuter. It is also realistic to see a green government subsidy, as the efficient use of the battery is increased through its lifetime.

Delving deeper into the finding that vehicles which participated had higher equivalent full cycles at end of life (EOL), raises significant social dilemmas. For car owners who own rather than lease or rent their vehicles, it's beneficial to maximize the vehicle's lifespan, which suggests avoiding participation in BD-system services if they indeed accelerate degradation. Conversely, it benefits society and the environment for these cars to participate, as this maximizes resource utilization over the vehicle's life and could enhance local environmental quality by reducing emissions of nitrogen oxides and carbon dioxide from ferries. Consequently, the system may be predominantly utilized by those who lease their vehicles, unless the financial incentives are sufficient to offset the potential loss in battery capacity. It is also advisable to conduct a more thorough investigation into how these emerging usage patterns might impact battery longevity, especially since it is possible that the effects are much less significant than the results suggest, or might even be negligible.

Using chargers with even higher output power would make the system further profitable. The difficulties are that the chargers will have to be installed upon the ferry walls to avoid losing parking spaces, which makes fast chargers inappropriate. C-rate is also one of the biggest stress factors for battery degradation, which is an additional reason to not increase the output power of the chargers further than necessary.

Another intriguing aspect that was mentioned but not explored in depth is the potential for incorporating trucks into the system. As shown in figure 54, the top section of the train deck lacks charging stations because it is designated for commercial vehicles like trucks. With the ongoing advancement and market maturation of truck electrification technologies, including hydrogen and battery electric systems, a significant amount of power could be exchanged between the trucks and the ferry, assuming installation space is available. The potential for specific energy contracts between shipping firms and ferry operators could lead to innovative business models. Such agreements, if formalized into business-to-business contracts, could enhance the system's reliability.

Although a copper cable was chosen, it could be more realistic to use aluminum for the BD system, as its more widely available and cheaper. However, the geometric constraints may prevent a large enough cable to be installed as the higher resistivity would entail a larger cross-section of the cable. It should however be considered and investigated closer ahead of a potential installation.

The results provided from an installation of a BD-system onboard M/S Aurora can be concluded to be very positive. The system can offer new flows of income, and reduce the already small climate impact of the ferries. Using a similar system onboard other electric ferries, can further decrease the payback time of electrification and hence accelerate the green transition. The system could also offer further interesting applications, such as grid support through ancillary service to grid operators, and extended range on the ferries, as electric ferries could potentially do longer crossings if allowed to buy electricity from their passengers.

## 7 Conclusion

The aim of these project was to explore the advantages with BD-charges in general, though different aspects and in various scenarios.

Four separate scenarios were examined to assess the potential of BD-charging. From a financial perspective, BD-charging tends to be profitable in various contexts, although profitability differs among scenarios. The financial reliability of BD-charging hinges on the particular market and application where it is used. An important factor to consider is the significant investment needed for BD-chargers. Returns from ancillary services in the energy sector have been profitable recently, yet future outcomes are uncertain as they rely on market supply and demand.

In every scenario, the revenue from ancillary services is compromised when the battery is absent, and extensive planning of trips is necessary to optimize profits.

For V2G, Vessel to Grid and the Electric Ferries, the extended use of the battery does not contribute significantly to the degradation. The amount of full equivalent cycles before EOL is higher using BD-charging then when it is not used.

Regarding operating off-grid, the V2H case concludes that disconnecting from the grid is possible depending on various factors. The factors include geographical location, time of the year (season) and the climate. Warmer and sunnier location tend to have more potential to operate off-grid for a longer time of period, whereas colder locations do not have the possibility.

By employing BD-charging alongside the untapped potential of battery storage in electric vehicles and boats, energy storage capabilities will be increased, and energy on demand will be more accessible. The increased storage will serve as a complementary solution to existing energy sources during times of variations in the grid frequency.

## 8 Recommendation

This study takes into account four different cases that implement BD-technology. This technology could cause great impact within markets at a certain point of energy transition progress. However, it is important to manage the applications as suitability will vary across different markets, due to factors as stability of the grid, geography, infrastructure etc.

The main recommendation is that further studies on the subject, especially real-world projects, are needed to actually see the potential of financial inclusion and general benefits of BD-technology.

It is also crucial to educate the public on the significance of this technology beyond just economic aspects. Transitioning to renewable energy necessitates the use of BD-technology to enhance the flexibility of the energy system and facilitate mobile energy storage. BD-technology will be integral to the future energy infrastructure, playing an essential role in the energy transition. Educating the public about its advantages is vital since the societal response to technology significantly influences its impact.

Nonetheless, numerous other applications exist where its implementation could be advantageous. For instance, it could be utilized for emergency power during outages caused by natural disasters. Additionally, it could serve as a temporary power solution in situations where establishing electrical infrastructure is challenging and expensive, such as at festivals, remote construction sites, and similar locations.

Sammanfattningsvis har dubbelriktad laddning bidragit till lönsamhet och energireserver i alla fyra fallen vi har undersökt.

Det har också bidragit till kortare total livslängd för batterierna. Värt att notera är att det totala fulla ekvivalenta cyklerna, i ALLA fallen, var fler med dubbelriktad laddning. Vilket indikerar effektivare användning trots kortare livslängd.

Trots den uppenbara ekonomiska lönsamhet och stödet till elnätet, återstår det att undersöka villigheten från användarna att dela sina batterier. Samt om de ekonomiska incitamenten är tillräckliga för att kompensera för minskad livslängd på batterierna. Därför rekommenderar vi ytterligare studier och datainsamling för att besvara dessa frågor.

Då dessa modeller är baserade på historisk data och antaganden, kan det leda till en dold osäkerhetsfaktor. För att kunna ta steget från teori till praktisk implementation är det därför viktigt att genomföra verklighetsankrade projekt och få tillgång till mer exakta mätvärden.

Elektrifieringen av samhället fortskrider, samtidigt som klimatmålen blir allt strängare och fler länder investerar i grön energi. Tillgången till flexibla, snabba och pålitliga energireserver är därmed viktigare än någonsin. Dubbelriktad laddning i kombination med stödtjänster erbjuder precis det här. Och kan visa sig vara en del i att nå målet.

## References

- [1] European Commission, “2050 long-term strategy”, 2024, (accessed 2024-05-06). [Online]. Available: [https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy\\_en](https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en)
- [2] P. A. Owusu and S. Asumadu-Sarkodie, “A review of renewable energy sources, sustainability issues and climate change mitigation,” *Cogent Engineering*, vol. 3, p. 1167990, 12 2016, (Accessed 2024-04-10 ).
- [3] Svenska Kraftnät, “Om olika energikällor— svenska kraftnät,” 2024, (Accessed: 2024-05-06). [Online]. Available: <https://www.svk.se/om-kraftsystemet/om-olika-energikallor/>
- [4] S. Ould Amrouche, D. Rekioua, T. Rekioua, and S. Bacha, “Overview of energy storage in renewable energy systems,” *International Journal of Hydrogen Energy*, vol. 41, no. 45, pp. 20 914–20 927, 2016. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0360319916309478>
- [5] D. Avery, “Bidirectional charging and evs: How does it work and which cars have it?” *CNET*, 2023, (Accessed 2024-04-10). [Online]. Available: <https://www.cnet.com/roadshow/news/bidirectional-charging-and-evs-how-does-it-work-and-which-cars-have-it/>
- [6] J. Werneskog and A. Wolf, “forskning och utveckling av v2x i sverige”, 2023, (accessed: 2024-04-25). [Online]. Available: <https://powercircle.org/syntes.v2x.pdf>
- [7] Power Circle, “What is v2g - vehicle to grid?” Power Circle, Tech. Rep., 2024, (accessed: 2024-04-25). [Online]. Available: <https://powercircle.org/wp-content/uploads/2024/03/240311-V2G-faktablad-uppdatering-jan-2024-Engelsk-version-1.pdf>
- [8] L. Olsson, S. Fallahi, M. Schnurr, D. Diener, and P. van Loon, “Circular business models for extended ev battery life,” *Batteries*, vol. 4, 12 2018.
- [9] J. S. Edge, S. O’kane, R. Prosser, N. D. Kirkaldy, A. N. Patel, A. Hales, A. Ghosh, W. Ai, J. Chen, J. Yang, S. Li, M.-C. Pang, L. B. Diaz, A. Tomaszewska, M. W. Marzook, K. N. Radhakrishnan, H. Wang, Y. Patel, B. Wu, and G. J. Offer, “Lithium ion battery degradation: what you need to know,” *Phys. Chem. Chem. Phys.*, vol. 23, p. 8200, 2021.
- [10] A. Roy, H. Movahedi, J. B. Siegel, and A. G. Stefanopoulou, “Empirical modeling of degradation in lithium-ion batteries and validation in complex scenarios,” *IFAC-PapersOnLine*, vol. 56, pp. 457–462, 1 2023.
- [11] J. Jiang, W. Shi, J. Zheng, P. Zuo, J. Xiao, X. Chen, W. Xu, and J.-G. Zhang, “Optimized operating range for large-format lifepo4/graphite batteries,” *Journal of The Electrochemical Society*, vol. 161, pp. A336–A341, 12 2013.
- [12] F. D. Castro, L. Cutaia, and M. Vaccari, “End-of-life automotive lithium-ion batteries (libs) in brazil: Prediction of flows and revenues by 2030,” *Resources, Conservation and Recycling*, vol. 169, p. 105522, 6 2021.
- [13] S. K. Rechkemmer, X. Zang, W. Zhang, and O. Sawodny, “Empirical li-ion aging model derived from single particle model,” *Journal of Energy Storage*, vol. 21, pp. 773–786, 2 2019.
- [14] K. Qian, C. Zhou, Y. Yuan, and M. Allan, “Temperature effect on electric vehicle battery cycle life in vehicle-to-grid applications,” pp. 1–6, Sep. 2010.
- [15] Svenska Kraftnät, “vårt uppdrag”, 2023, (Accessed: 2024-04-09). [Online]. Available: <https://www.svk.se/om-oss/verksamhet/>
- [16] —, “om systemansvaret”, 2023, (Accessed: 2024-05-02). [Online]. Available: <https://www.svk.se/om-kraftsystemet/om-systemansvaret/>
- [17] —, “frekvensstabilitet”, 2024, (Accessed: 2024-05-08). [Online]. Available: <https://www.svk.se/om-kraftsystemet/om-systemansvaret/kraftsystemstabilitet/frekvensstabilitet/>

- [18] —, “”stødtjänster och avhjälpande åtgärder”,” 2023, (Accessed: 2024-04-09). [Online]. Available: <https://www.svk.se/om-kraftsystemet/om-systemansvaret/verktyg-for-systemdrift/stodtjanster-och-avhjalpande-atgarder/>
- [19] —, “”stødtjänster och avhjälpande åtgärder i ett energisystem under förändring”,” 2021, (Accessed: 2024-04-25). [Online]. Available: [https://www.svk.se/siteassets/om-oss/rapporter/2021/rapport-regeringsuppdrag-avseende-stodtjanster\\_211018\\_.pdf](https://www.svk.se/siteassets/om-oss/rapporter/2021/rapport-regeringsuppdrag-avseende-stodtjanster_211018_.pdf)
- [20] —, “”införande av aktörsrollerna bsp och brp”,” 2024, (Accessed 2024-05-02). [Online]. Available: <https://www.svk.se/utveckling-av-kraftsystemet/systemansvar--elmarknad/inforande-av-aktorsrollerna-bsp-och-brp/>
- [21] —, “”guidance on the provision of reserves”,” 2023, (Accessed: 2024-04-14). [Online]. Available: <https://www.svk.se/siteassets/english/stakeholder-portal/provision-of-ancillary-services/prequalification/guidance-on-the-provision-of-reserves.pdf>
- [22] —, “”om olika reserver”,” 2024, (Accessed: 2024-04-09). [Online]. Available: <https://www.svk.se/aktorsportalen/bidra-med-reserver/om-olika-reserver/>
- [23] —, “”så kan du som privatperson bidra med stødtjänster”,” 2024, (Accessed: 2024-05-07). [Online]. Available: <https://www.svk.se/om-kraftsystemet/om-systemansvaret/verktyg-for-systemdrift/stodtjanster-och-avhjalpande-atgarder/sa-kan-du-som-privatperson-bidra-med-stodtjanster/>
- [24] —, “”handel och prissättning”,” 2024, (Accessed: 2024-05-03). [Online]. Available: <https://www.svk.se/aktorsportalen/bidra-med-reserver/handel-prissattning/>
- [25] Mer, “”vad är skillnaden på 1-fas och 3-fas installation, och hur påverkar det laddeffekten?”,” 2024, (Accessed: 2024-05-06). [Online]. Available: <https://se.mer.eco/mer/faq/skillnaden-pa-1-fas-och-3-fas-installation/>
- [26] HemSol, “”så väljer du huvudsäkring”,” 2024, (Accessed: 2024-05-06). [Online]. Available: <https://hemsol.se/solceller/huvudsakring-a/>
- [27] Laddboxbolaget, “”Lastbalansering – så funkar det!” 2021, (Accessed: 2024-05-06). [Online]. Available: <https://laddboxbolaget.se/lastbalansering-sa-funkar-det/>
- [28] J. Fernando, “”Law of supply and demand in economics: How it works,” *Investopedia*, 2023, (Accessed: 2024-03-25). [Online]. Available: <https://www.investopedia.com/terms/l/law-of-supply-demand.asp>
- [29] Energimyndigheten, “”Resan till ett mer elektrifierat samhälle,” 2023, (Accessed 2024-05-02). [Online]. Available: <https://www.energimyndigheten.se/klimat--miljo/sveriges-elektrifiering/>
- [30] TWI, “”what is a product life cycle? (definition, stages and examples)”,” 2024, (accessed: 2024-05-05-05). [Online]. Available: <https://www.twi-global.com/technical-knowledge/faqs/what-is-a-product-life-cycle>
- [31] C. K. Udokporo, *Understanding the Stages of the Product Life Cycle*. IntechOpen, 12 2021.
- [32] Volvo Penta, “”bi-directional charging”,” 2024, (Aaccessed:2024-01-30). [Online]. Available: [https://chalmers.instructure.com/courses/30070/files/3125388?module\\_item\\_id=435598](https://chalmers.instructure.com/courses/30070/files/3125388?module_item_id=435598)
- [33] M. Nyström, “”Tredubbling av elbilar på två år,” 2023, (Accessed: 2024-03-25). [Online]. Available: <https://www.scb.se/hitta-statistik/redaktionellt/tredubbling-av-elbilar-pa-tva-ar2/>
- [34] ForSea Helsingborg AB, “”Hållbarhet - med batteridrift för miljön,” 2024, (Accessed: 2024-05-08). [Online]. Available: <https://www.forsea.se/om-forsea/hallbarhet/>
- [35] News Øresund, “”Elbilsförsäljningen ökar i både danmark och sverige – samtidigt minskade den totala bilförsäljningen,” 2023, (Accessed: 2024-05-08). [Online]. Available: <https://www.newsøresund.se/elbilsforsaljningen-okar-i-bade-danmark-och-sverige-samtidigt-minskade-den-totala-bilforsaljningen/>
- [36] O. Mattsson, “”Personal communication, april 5, 2024.”

- [37] Svenska Kraftnät, “Fcr,” 2024, (Accessed: 2024-03-19). [Online]. Available: <https://mimer.svk.se/Primaryregulation/HistoryIndex2023>
- [38] —, “Utbud på marknaderna för reserver,” 2024, (Accessed: 2024-04-20). [Online]. Available: <https://www.svk.se/aktorsportalen/bidra-med-reserver/behov-av-reserver-nu-och-i-framtiden/utbud-pa-marknaderna-for-reserver/>
- [39] S. Kraftnät, “Fcr,” 2024, (Accessed: 2024-04-25). [Online]. Available: <https://mimer.svk.se/Primaryregulation/HistoryIndex2023>
- [40] P. Nyman, “Sexdubblad miljardnota för att balansera elsystemet – du får betala — tidningen näringslivet,” *Tidningen Näringslivet*, 1 2024, (Accessed: 2024-04-15). [Online]. Available: <https://www.tn.se/naringsliv/34915/sexdubblad-miljardnota-for-att-balansera-elsystemet-du-far-betala/>
- [41] Varberg Energi AB, “Flex batteri,” 2024, (Accessed: 2024-04-09). [Online]. Available: <https://www.varbergenergi.se/privat/tjanster/energilosningar/flex-batteri/>
- [42] CheckWatt AB, “Smarta tjänster för hållbar energianvändning,” (Accessed: 2024-04-09). [Online]. Available: <https://www.checkwatt.se/batteri-intresse>
- [43] EV-Database, “Energy consumption of full electric vehicles,” 2024, (Accessed: 2024-04-25). [Online]. Available: <https://ev-database.org/cheatsheet/energy-consumption-electric-car>
- [44] Konsumenternas elmarknadsbyrå, “Normal elförbrukning och elkostnad för villa,” 2024, (Accessed: 2024-05-03). [Online]. Available: <https://www.energimarknadsbyran.se/el/dina-avtal-och-kostnader/elkostnader/elforbrukning/normal-elforbrukning-och-elkostnad-for-villa/>
- [45] S. Weintraub, “Wallbox quasar 2 bidirectional v2h ccs-combo dc charger announced, turns evs into huge powerwall,” *Electec*, 1 2022, (Accessed:2024-04-19). [Online]. Available: <https://electrek.co/2022/01/03/wallbox-quasar-2-bidirectional-v2h-ccs-combo-dc-charger-announced-turns-evs-into-huge-powerwall/>
- [46] J. Kristensson, “Svenska bolaget siktar på dubbelriktad dc-laddare för v2g – till halva priset,” *Ny Teknik*, 2 2024, (Accessed 2024-04-26). [Online]. Available: <https://www.nyteknik.se/elbilar/svenska-bolaget-siktar-pa-dubbelriktad-dc-laddare-for-v2g-till-halva-priset/4237774>
- [47] Ellvio, “Hur lång livstid har en laddstation?” 2022, (Accessed: 2024-05-08). [Online]. Available: <https://www.ellevio.se/privat/kundservice/faq/ovrigt/ellevio-elmarknaden/elbilsladdning/hur-lang-livstid-har-en-laddstation/>
- [48] T. Signer, F. Unger, M. Ruppert, and W. Fichtner, “Economic potential of v2g in electricity markets – a systematic literature review,” pp. 1–6, 2023.
- [49] Fermata Energy, “End-to-end bidirectional charging platform for your evs,” 2024, (Accessed: 2024-05-02). [Online]. Available: <https://fermataenergy.com/solutions>
- [50] —, “Residential v2x revenue potential in texas wholesale markets -part 2,” 2024, (Accessed: 2024-05-02). [Online]. Available: <https://fermataenergy.com/resources/residential-v2x-revenue-potential-in-texas-wholesale-markets-part-ii>
- [51] “Insights from the realising electric vehicle-to-grid services project – final repor,” Febraury 2024, (Accessed 2024-05-04). [Online]. Available: <https://arena.gov.au/knowledge-bank/arena-vehicle-to-grid-insights-final-report/>
- [52] Svenska Kraftnät, “Räkneexempel – leverans av fcr-d ned och mfr ned,” 2 2024, (Accessed: 2024-04-25). [Online]. Available: <https://www.svk.se/siteassets/aktorsportalen/bidra-med-reserver/fcr-d-ned-och-mfr-ned-rakneexempel.pdf>
- [53] Fingrid, “Frequency quality analysis 2022 fingrid,” 2023, (Accessed 2024-04-29). [Online]. Available: [https://www.fingrid.fi/globalassets/dokumentit/fi/kantaverkko/suomen-sahkojarjestelma/frequency\\_quality\\_analysis\\_2022\\_public.pdf](https://www.fingrid.fi/globalassets/dokumentit/fi/kantaverkko/suomen-sahkojarjestelma/frequency_quality_analysis_2022_public.pdf)

- [54] Svenska Kraftnät, “Frekvenshållningsreserv störning nedreglering (fcr-d ned),” 2023, (Accessed: 2024-05-07). [Online]. Available: <https://www.svk.se/aktorsportalen/bidra-med-reserver/om-olika-reserver/fcr-d-ned/>
- [55] —, “Frekvenshållningsreserv störning uppreglering (fcr-d upp),” 2023, (Accessed: 2024-05-07). [Online]. Available: <https://www.svk.se/aktorsportalen/bidra-med-reserver/om-olika-reserver/fcr-d-upp/>
- [56] EV Database, “Volkswagen id.4 pro,” 2024, (Accessed: 2024-04-29). [Online]. Available: <https://ev-database.org/car/2028/Volkswagen-ID4-Pro>
- [57] A. Gullberg, “Här finns den lediga kapaciteten i storstadstrafiken,” 2015, (Accessed: 2024-04-10). [Online]. Available: <https://www.cesc.kth.se/se/news/news-archive/har-finns-den-lediga-kapaciteten-i-storstadstrafiken-1.559966>
- [58] Power Circle, “Elis – elbilsstatistik,” 2024, (Accessed 2024-04-30). [Online]. Available: <https://powercircle.org/elis-elbilsstatistik/>
- [59] Energimarknadsinspektionen, “Främjande av ett mer flexibelt elsystem,” Energimarknadsinspektionen, Tech. Rep., 2023.
- [60] V. Distribution, “Välj rätt huvudsäkring,” (Accessed 2024-05-03). [Online]. Available: <https://www.vattenfalleldistribution.se/kund-i-elnatet/anslutning/valj-ratt-huvudsakring/>
- [61] E. V. Database”, 2024, (Accessed 2024-05-04). [Online]. Available: <https://ev-database.org/#sort:path~type~order=.rank~number~desc|rs-price:prev~next=10000~100000|rs-range:prev~next=0~1000|rs-fastcharge:prev~next=0~1500|rs-acceleration:prev~next=2~23|rs-top-speed:prev~next=110~350|rs-battery:prev~next=10~200|rs-towweight:prev~next=0~2500|rs-eff:prev~next=100~350|rs-safety:prev~next=-1~5|paging:currentPage=0|paging:number=10>
- [62] Eways, “”laddbox”,” 2024, (Accessed: 2024-05-07). [Online]. Available: <https://www.eways.se/produktkategori/laddstationer/>
- [63] P. A. Markus Lagerqvist, “Båtlivsundersökningen 2020,” *Electec*, 3 2021, (Accessed 2024-05-01). [Online]. Available: <https://www.transportstyrelsen.se/globalassets/global/sjofart/dokument/fritidsbatar1/transportstyrelsen-batlivsundersokningen-2020.pdf>
- [64] Candela, “Charging an Electric Boat; (The Ultimate Guide 2024,” 2024, (Accessed: 2024-05-07). [Online]. Available: <https://candela.com/charging-an-electric-boat-the-ultimate-guide-2024/>
- [65] Xshore, “8 tips on how to charge an electric boat,” 2022, (Accessed: 2024-05-07). [Online]. Available: <https://xshore.com/us/news/8-tips-on-how-to-charge-an-electric-boat>
- [66] Yachting-pages, “Electric charging points in norway and sweden,” 2023, (Accessed: 2024-05-07). [Online]. Available: <https://www.yachting-pages.com/articles/eu-to-finance-400-electric-charging-points-in-sweden-and-norway-news.html>
- [67] P. Berg, “Personal communication, april 5, 2024.”
- [68] www.praktisktbatagande.se, “Pressmeddelande,” 2021, (Accessed 2024-05-05). [Online]. Available: <https://www.praktisktbatagande.se/artiklar/ny-laddstationer-i-stockholms-skargard#:~:text=Pressmeddelande%3A,till%20fossilfria%20b%C3%A5tar%20p%C3%A5%20sj%C3%B6n.>
- [69] J. S. och Louise Eriander, “Eko marina iii – inventering, kartläggning och miljömärkning av sveriges fritidsbåtshamnar,” *Havsmiljöinstitutet*, 6 2021, (Accessed 2024-05-06). [Online]. Available: <https://www.havsmiljoinstitutet.se/publikationer/havsmiljoinstitutets-rapportserie/eko-marina-iii-inventering-kartlaggning-och-miljomarkning-av-sveriges-fritidsbatshamnar>
- [70] Yachting-pages, “First charging network for boats launches in stockholm!” 2021, (Accessed: 2024-05-01). [Online]. Avail-

- able: [https://www.linkedin.com/posts/candela-speed-boat\\_str%C3%B6mma-saltsj%C3%B6baden-sandhamn-activity-6727948438471811072-edkc/?trk=public\\_profile\\_like\\_view](https://www.linkedin.com/posts/candela-speed-boat_str%C3%B6mma-saltsj%C3%B6baden-sandhamn-activity-6727948438471811072-edkc/?trk=public_profile_like_view)
- [71] V. TT, “Market study 2023 europe becomes the most important electric boat market,” 2024, (Accessed: 2024-05-05). [Online]. Available: <https://via.tt.se/pressmeddelande/3358720/boatscom-presents-the-electric-boat-market-study-2023---europe-becomes-the-most-important-electric-boat-mar-publisherId=259167>
- [72] Market and markets, “Electric boat market by end use,” 2023, (Accessed: 05.05.2024). [Online]. Available: <https://www.marketsandmarkets.com/Market-Reports/electric-boat-market-260762373.html>
- [73] Future markets insight, “Electric boats market outlook (2023 to 2033),” 2023, (Accessed: 2024-05-05). [Online]. Available: <https://www.futuremarketinsights.com/reports/electric-boats-market#>
- [74] Statzon, “Electroc boat market,” 2023, (Accessed: 2024-05-05). [Online]. Available: <https://statzon.com/insights/electric-boat-market>
- [75] Candela, “Candela,” *Candela web page*, 4 2024, (Accessed: 2024-05-01). [Online]. Available: <https://candela.com/electric-vs-combustion-engine-boats-all-you-need-to-know/>
- [76] Xshore, “Eelex 8000,” 2024, (Accessed: 2024-05-05). [Online]. Available: <https://xshore.com/us/eelex-8000>
- [77] Y.-J. S. Seon Hyeog Kim, “Optimize the operating range for improving the cycle life of battery energy storage systems under uncertainty by managing the depth of discharge,” *Journal of Energy Storage*, 12 2023. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2352152X23025422>
- [78] Candela, “Candela c-8,” 2024, (Accessed 2024-05-05). [Online]. Available: <https://candela.com/candela-c-8/>
- [79] N. Lundin, “Volvo penta interview, april 2, 2024.”
- [80] CENEX, “An analysis of revenue streams and vessel archetypes for bi-directional charging of electric vessels,” *Maritime Journal*, 8 2023. [Online]. Available: <https://www.cenex.co.uk/app/uploads/2023/11/Vessel-to-Grid-Revenue-Streams-Report-Cenex.pdf>
- [81] Svenska Kraftnät, “”frekvenshållningsreserv störning nedreglering (fcr-d ned)”,” 2024, (Accessed: 2024-05-05). [Online]. Available: <https://www.svk.se/aktorsportalen/bidra-med-reserver/om-olika-reserver/fcr-d-ned/>
- [82] S. Kraftnät, “”frekvenshållningsreserv störning nedreglering (fcr-d upp)”,” 2024, (Accessed: 2024-05-05). [Online]. Available: <https://www.svk.se/aktorsportalen/bidra-med-reserver/om-olika-reserver/fcr-d-upp/>
- [83] J. Svarc, “Bidirectional ev chargers review,” 2024, (Accessed: 2024-05-05). [Online]. Available: <https://www.cleanenergyreviews.info/blog/bidirectional-ev-chargers-review>
- [84] Kempower, “Kempower dc fast charging solutions for electric boats brought to yacht club de monaco by aqua superpower,” 2024, (Accessed 2024-05-05). [Online]. Available: <https://kempower.com/news/yacht-club-monaco-aqua-superpower/>
- [85] —, “Kempower dc fast charging solutions for electric boats brought to yacht club de monaco by aqua superpower,” 2024, (Accessed 2024-05-05). [Online]. Available: <https://kempower.com/news/yacht-club-monaco-aqua-superpower/>
- [86] AquaSuperPower, “Aqua-75-datasheet,” 2024, (Accessed: 05.05.2024). [Online]. Available: <https://villageofnorthport.net/wp-content/uploads/2022/03/Aqua-75-datasheet.pdf>
- [87] C. Andersson, “Personal communication, february 14, 2024.”
- [88] EBR, *EBR kostnadskatalog 2020 Lokalnät 0,4-24 kV samt optonät*. Energiföretagen Sverige - Swedenenergy - AB, 3 2020.

- [89] MadeInChina, "11kv transformer," 2024, (Accessed: 2024-05-07). [Online]. Available: <https://hfy-substation.en.made-in-china.com/product/edlTryFVSBpq/China-Price-Sell-10-5kv-11kv-Three-Phase-S11-630kVA-800kVA-1000kVA-Dyn11distribution-Transformer.html>
- [90] Alibaba, "'10.5 kv transformer'," 2024, (Accessed: 2024-05-07). [Online]. Available: <https://www.alibaba.com/showroom/10.5-kv-transformer.html>
- [91] A. Navgren, "Personal communication, april 25, 2024."
- [92] C. Andersson, "Personal communication, april 16, 2024."
- [93] J. Wieckowska, "Personal communication, april 16, 2024."
- [94] N. Rietmann, B. Hügler, and T. Lieven, "Forecasting the trajectory of electric vehicle sales and the consequences for worldwide co2 emissions," *Journal of Cleaner Production*, vol. 261, p. 121038, 7 2020.
- [95] Ferroamp AB, "Ferroamps likströmsnät: Effektiv och framtidssäker energilösning," 2023, (Accessed: 2024-05-02). [Online]. Available: <https://ferroamp.com/produkter/ferroamp-systemet/likstromsnatet/>
- [96] A. J. Inge Karlsson, "Beräkningsmodell för bensin respektive diesel förbrukning per kommun," 2009, (Accessed: 2024-03-25). [Online]. Available: [https://miljobarometern.stockholm.se/content/docs/tema/trafik/Berakningsmodell\\_SCB.pdf](https://miljobarometern.stockholm.se/content/docs/tema/trafik/Berakningsmodell_SCB.pdf)
- [97] Varberg Energi AB, "Bahra cables - power cable low voltage, bare copper, 120mm," 2024, (Accessed: 2024-05-02). [Online]. Available: <https://electric-house.com/en/copper-conductor-120-mm2.html>
- [98] Coastal Outdoors Group, "Galveston - bolivar ferry," 2024, accessed: 2024-05-06. [Online]. Available: <https://www.bolivarpeninsulatexas.com/About/Galveston-Bolivar-Ferry>
- [99] The Cape May-Lewes Ferry, "Cape may-lewes ferry history," 2024, (Accessed: 2024-05-06). [Online]. Available: <https://www.cmlf.com/cape-may-lewes-ferry-history>
- [100] W. Team, "All you need to know about driving your ev in the cold," (Accessed: 05.05.2024). [Online]. Available: <https://blog.wallbox.com/ev-maintenance-in-cold-weather/>
- [101] MER, "How does the cold weather affect ev car battery performance?" 2024, (Accessed: 05.05.2024). [Online]. Available: <https://uk.mer.eco/news/how-does-cold-weather-affect-ev-car-battery-performance/>
- [102] Car Info, 2024, (Accessed 2024-05-05). [Online]. Available: <https://www.car.info/sv-se/stats?from=2023-06&to=2024-05&vd=4&et0=3&tcb=registered&tcs=registered&tcf=registered>

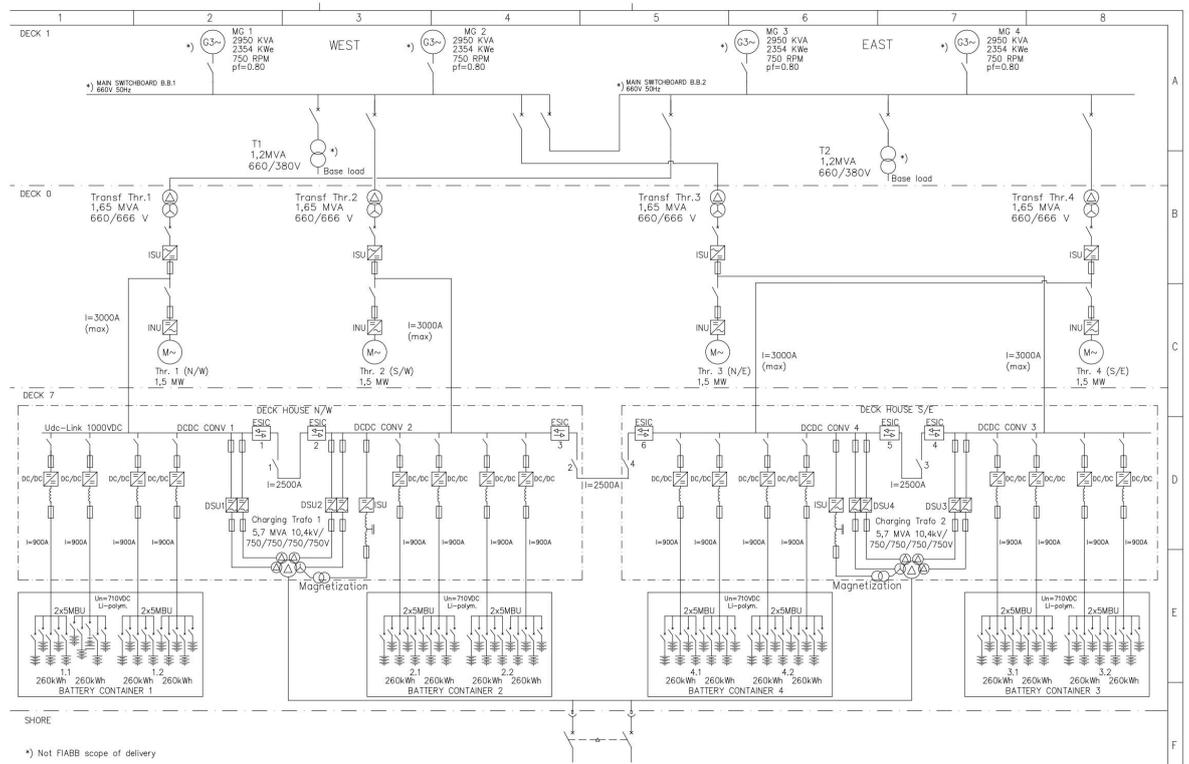
## A Appendix

### A.1 Data on the Most Common EVs in Sweden

Most Common EVs in Sweden	Car Model	Quantity [102]	Usable Battery Capacity [kWh] [61]
1	TESLA MODEL Y	30 774	57.5-75
2	VW ID.4	27 130	52-77
3	VOLVO XC40	20 255	67-79
4	KIA E-NIRO	19 208	64.8
5	TESLA MODEL 3	18 950	57.5-75
6	NISSAN LEAF	14 300	39-59
7	POLESTAR 2	13 258	67-79
8	SKODA ENYAQ iV	13 216	58-77
9	VW ID.3	11 616	58-79
10	RENAULT ZOE	9 657	52
	<b>Total</b>	<b>178 364 (52.8% of all EVs in Sweden)</b>	<b>Mean: 57.5-72.8</b>

Table 46: Most common EVs in Sweden

## A.2 Single Line Diagram of M/S Aurora, Öresundslinjen



### A.3 Vehicle Distribution Statistics, Öresundslinjen

Analysenavn  
 Periodetype  
 Periode  
 Analysevej

Bilstatistik, Månedsfordelt  
 Dag  
 01/03/2023 - 29/02/2024  
 Mols-Linien A/S : Opdelt på hovedruter, Alle :

Nøgle	Beskrivelse	Bilstatistik - Total		
		Antal		
		reg.nr	billetter	m/reg.nr
<b>ForSea</b>				
22	Helsingør - Helsingborg	144 124	609 452	385 426
<b>BS: BIL DRIVKRAFT:</b>				
		24 433	227 559	3 783
<b>AUTOMATTYPE:</b>				
Manuel	Mangler	3 430	83 491	3 308
A	Auto	21 312	144 061	475
B	Boarding	1	5	0
G	Gående	1	2	0
1	Benzin	47 721	143 502	143 324
11	Hybrid (HEV), benzin\el	3 054	10 129	10 129
12	Plugin-hybrid (PHEV), benzin\	10 335	30 230	30 230
13	Benzin (MHEV)	2 889	8 760	8 760
2	Diesel	39 989	140 250	140 199
21	Hybrid (HEV), diesel\el	21	36	36
22	Plugin-hybrid (PHEV), diesel\	553	1 637	1 637
23	Diesel (MHEV)	1 866	6 623	6 623
3	Gas	72	119	119
4	El (BEV)	12 147	37 342	37 321
51	Benzin FlexFuel	819	2 792	2 792
52	Benzin FlexFuel (MHEV)	33	54	54
8	Petroleum	2	2	2
99	Andet	190	417	417
<b>ForSea Total:</b>		--	<b>609 452</b>	<b>385 426</b>
<b>Kombardo</b>		--	<b>0</b>	<b>0</b>

% fordeling m/reg.nr	24-Feb			24-Jan			Antal billetter
	Antal		% fordeling	Antal		% fordeling	
	billetter	m/reg.nr	m/reg.nr	billetter	m/reg.nr	m/reg.nr	
15,1	65 363	45 411	25,1	52 193	34 307	23,2	57 127
<b>100,0</b>			<b>100,0</b>			<b>100,0</b>	
1,0	19 978	48	0,1	17 902	41	0,1	20 535
<b>100,0</b>			<b>100,0</b>			<b>100,0</b>	
87,4	10 167	6	12,5	8 675	3	7,3	10 896
12,6	9 811	42	87,5	9 226	38	92,7	9 637
0,0	0	0	0,0	1	0	0,0	2
0,0	0	0	0,0	0	0	0,0	0
37,2	16 136	16 123	35,5	11 780	11 766	34,3	13 152
2,6	1 014	1 014	2,2	841	841	2,5	999
7,8	3 962	3 962	8,7	2 946	2 946	8,6	3 000
2,3	1 066	1 066	2,3	741	741	2,2	806
36,4	15 883	15 877	35,0	12 854	12 847	37,4	13 543
0,0	2	2	0,0	2	2	0,0	7
0,4	248	248	0,5	199	199	0,6	191
1,7	825	825	1,8	682	682	2,0	713
0,0	1	1	0,0	8	8	0,0	20
9,7	5 964	5 961	13,1	3 904	3 900	11,4	3 821
0,7	222	222	0,5	290	290	0,8	286
0,0	8	8	0,0	6	6	0,0	1
0,0	0	0	0,0	0	0	0,0	0
0,1	54	54	0,1	38	38	0,1	53
<b>15,1</b>	<b>65 363</b>	<b>45 411</b>	<b>25,1</b>	<b>52 193</b>	<b>34 307</b>	<b>23,2</b>	<b>57 127</b>
<b>0,0</b>	<b>0</b>	<b>0</b>	<b>0,0</b>	<b>0</b>	<b>0</b>	<b>0,0</b>	<b>0</b>

23-Dec		23-Nov			Oct 23		
tal m/reg.nr	% fordeling m/reg.nr	Antal		% fordeling m/reg.nr	Antal		% fordeling m/reg.nr
		billetter	m/reg.nr		billetter	m/reg.nr	
36 632	19,3	52 055	35 106	19,1	63 030	41 997	19,2
	<b>100,0</b>			<b>100,0</b>			<b>100,0</b>
65	0,2	16 987	64	0,2	21 158	143	0,3
	<b>100,0</b>			<b>100,0</b>			<b>100,0</b>
4	6,2	7 730	16	25,0	7 386	85	59,4
61	93,8	9 255	48	75,0	13 772	58	40,6
0	0,0	2	0	0,0	0	0	0,0
0	0,0	0	0	0,0	0	0	0,0
13 133	35,9	12 330	12 311	35,1	15 983	15 969	38,0
999	2,7	1 034	1 034	2,9	1 070	1 070	2,5
3 000	8,2	2 743	2 743	7,8	3 202	3 202	7,6
806	2,2	814	814	2,3	987	987	2,4
13 539	37,0	13 601	13 595	38,7	15 199	15 197	36,2
7	0,0	6	6	0,0	0	0	0,0
191	0,5	166	166	0,5	162	162	0,4
713	1,9	721	721	2,1	712	712	1,7
20	0,1	8	8	0,0	11	11	0,0
3 819	10,4	3 325	3 324	9,5	4 261	4 259	10,1
286	0,8	290	290	0,8	261	261	0,6
1	0,0	6	6	0,0	3	3	0,0
0	0,0	0	0	0,0	0	0	0,0
53	0,1	24	24	0,1	21	21	0,1
<b>36 632</b>	<b>19,3</b>	<b>52 055</b>	<b>35 106</b>	<b>19,1</b>	<b>63 030</b>	<b>41 997</b>	<b>19,2</b>
<b>0</b>	<b>0,0</b>	<b>0</b>	<b>0</b>	<b>0,0</b>	<b>0</b>	<b>0</b>	<b>0,0</b>

Bilstatistik - Fordelt

23-Sep			23-Aug			23-Jul	
Antal		% fordeling	Antal		% fordeling	Antal	
billetter	m/reg.nr	m/reg.nr	billetter	m/reg.nr	m/reg.nr	billetter	m/reg.nr
62 172	38 782	16,7	79 086	46 955	18,0	110 518	65 936
		<b>100,0</b>			<b>100,0</b>		
23 591	215	0,6	33 118	1 027	2,2	45 672	1 136
		<b>100,0</b>			<b>100,0</b>		
8 428	184	85,6	9 624	964	93,9	12 147	1 036
15 163	31	14,4	23 494	63	6,1	33 523	100
0	0	0,0	0	0	0,0	0	0
0	0	0,0	0	0	0,0	2	0
14 788	14 779	38,1	17 803	17 772	37,8	26 361	26 328
1 012	1 012	2,6	1 292	1 292	2,8	1 754	1 754
2 966	2 966	7,6	3 472	3 472	7,4	5 058	5 058
886	886	2,3	1 092	1 092	2,3	1 462	1 462
14 192	14 191	36,6	17 164	17 157	36,5	23 004	22 992
0	0	0,0	9	9	0,0	7	7
140	140	0,4	165	165	0,4	219	219
653	653	1,7	800	800	1,7	834	834
8	8	0,0	13	13	0,0	31	31
3 624	3 620	9,3	3 732	3 730	7,9	5 532	5 531
268	268	0,7	364	364	0,8	492	492
9	9	0,0	2	2	0,0	13	13
0	0	0,0	0	0	0,0	1	1
35	35	0,1	60	60	0,1	78	78
<b>62 172</b>	<b>38 782</b>	<b>16,7</b>	<b>79 086</b>	<b>46 955</b>	<b>18,0</b>	<b>110 518</b>	<b>65 936</b>
<b>0</b>	<b>0</b>	<b>0,0</b>	<b>0</b>	<b>0</b>	<b>0,0</b>	<b>0</b>	<b>0</b>

% fordeling m/reg.nr	23-Jun			May 23			Antal billetter
	Antal		% fordeling	Antal		% fordeling	
	billetter	m/reg.nr	m/reg.nr	billetter	m/reg.nr	m/reg.nr	
19,3	67 908	40 300	15,5	0	0	0,0	0
<b>100,0</b>			<b>100,0</b>			<b>100,0</b>	
1,7	28 618	1 044	2,6	0	0	--	0
<b>100,0</b>			<b>100,0</b>			<b>100,0</b>	
91,2	8 438	1 010	96,7	0	0	--	0
8,8	20 180	34	3,3	0	0	--	0
0,0	0	0	0,0	0	0	--	0
0,0	0	0	0,0	0	0	--	0
39,9	15 169	15 143	37,6	0	0	--	0
2,7	1 113	1 113	2,8	0	0	--	0
7,7	2 881	2 881	7,1	0	0	--	0
2,2	906	906	2,2	0	0	--	0
34,9	14 810	14 804	36,7	0	0	--	0
0,0	3	3	0,0	0	0	--	0
0,3	147	147	0,4	0	0	--	0
1,3	683	683	1,7	0	0	--	0
0,0	19	19	0,0	0	0	--	0
8,4	3 179	3 177	7,9	0	0	--	0
0,7	319	319	0,8	0	0	--	0
0,0	6	6	0,0	0	0	--	0
0,0	1	1	0,0	0	0	--	0
0,1	54	54	0,1	0	0	--	0
<b>19,3</b>	<b>67 908</b>	<b>40 300</b>	<b>15,5</b>	<b>0</b>	<b>0</b>	<b>0,0</b>	<b>0</b>
<b>0,0</b>	<b>0</b>	<b>0</b>	<b>0,0</b>	<b>0</b>	<b>0</b>	<b>0,0</b>	<b>0</b>







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