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Energy and Revenue Optimization of Marinas with Electric Leisure Boats by Utilizing B2G

An Optimization Model for Marinas Located in Gothenburg

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Abstract

This thesis explores the potential for revenue generation through the use of batteries integrated into a marina's energy system. The studied batteries include a stationary battery energy storage system and the batteries of electric leisure boats. These boats are connected to the energy system with bidirectional chargers, enabling both charging and discharging via the same charger—a technology commonly referred to as Vehicle-to-Grid, but here adapted as Boat-to-Grid.

The methodology involved modeling the marina's energy system based on its electricity consumption profile. This model was expanded to include solar and wind power generation, as well as the usage patterns and energy demands of electric leisure boats. An optimization model was developed to evaluate various revenue streams: peak shaving, electricity sales on the Nord Pool market, participation in the local flexibility market, and engagement in the Frequency Containment Reserve for Disturbances market.

Simulations were conducted across scenarios with varying numbers of electric boats and combinations of revenue-generating activities. The results indicate that integrating a battery energy storage system and Boat-to-Grid technologies can reduce electricity costs through peak shaving, Nord Pool trading generate limited revenue, while participation in the local flexibility market and the Frequency Containment Reserve for Disturbances market offer higher revenue opportunities. These findings suggest that marinas can benefit both economically and environmentally from integrating electric leisure boats in the energy system.

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Populärvetenskaplig sammanfattning

Sverige har som mål att bli klimatneutralt till år 2045 ett mål som innebär stora utmaningar. För att målet ska nås krävs omfattande förändringar, inte minst inom transportsektorn, som står för ungefär en tredjedel av landets totala växthusgasutsläpp. Ett avgörande steg är att minska vårt beroende av fossila bränslen, bland annat genom att ersätta traditionella förbränningsmotorer med eldrivna alternativ.

Elbilar har redan etablerat sig på marknaden, men intresset för elektrifiering av fordon sträcker sig långt bortom vägtrafiken. Idag diskuteras allt från eldrivna lastbilar till elflygplan – men ett område som fortfarande är relativt outforskat är eldrivna fritidsbåtar. Sverige är ett av de länder i världen med flest fritidsbåtar per invånare, och många av dessa drivs av förbränningsmotorer som saknar avgasrening. Detta leder till stora utsläpp av både giftiga ämnen och växthusgaser. Utöver utsläppen orsakar båtmotorerna också undervattensbuller som påverkar marina djur och ekosystem, något som helt kan undvikas med eldrivna alternativ. Därför skulle bytet av förbränningsmotorer till eldrivna båtar innebära en del miljöinvesteringar.

I dag är eldrivna fritidsbåtar fortfarande betydligt dyrare än båtar med förbränningsmotorer, vilket bromsar utvecklingen. I denna uppsats undersöks om elbåtar skulle kunna användas även för andra syften än enbart fritid, för att därigenom göra investeringen mer ekonomiskt attraktiv. Tanken är att båtbatterierna kan lagra el när priserna är låga och sedan använda eller sälja elen när priserna är höga, eller användas för att delta i olika stödtjänstmarknader. För att detta ska vara möjligt krävs att båtarna är utrustade med så kallad Vehicle-to-Grid-teknik, som gör det möjligt att koppla upp dem mot elnätet. Just fritidsbåtarnas batterier har stor potential, eftersom båtarna ofta står oanvända från september till maj. Under denna tid skulle de i princip kunna fungera som ett stort, stationärt energilager.

I denna uppsats har tre olika hamnar i Göteborg undersökts utifrån ett scenario där de utrustas med eldrivna fritidsbåtar. I scenarierna är hamnarna försedda med ett batterilagersystem, solceller och vindkraftverk. Därefter har en optimeringsmodell i Python skapats för att optimera energianvändningen i hamnen med hjälp av batterilager och elbåtar. Optimeringsmodellens mål är att minska kostnaderna i form av elräkningen som hamnarna behöver betala. För att minska dessa kostnader kan olika metoder användas. En sådan metod är peak shaving, där batterilagret och elbåtarnas batterier används för att lagra solel och vindel. Den egenproducerade elen kan då utnyttjas under timmar med höga elpriser, vilket möjliggör en kapning av effekttoppar. Det är även möjligt att utnyttja el från elnätet genom att ladda batterierna när priset är lågt, för att senare använda den elen när priset är högt – en strategi som kallas energy arbitrage. Ett annat sätt att generera vinst är att sälja överskottet av den egenproducerade elen på elmarknaden. Slutligen är det även möjligt att lämna in bud med sitt batteri på en lokal flexibilitetsmarknad samt på Svenska kraftnäts stödtjänstmarknad, för att bidra till att stabilisera elnätet.

Optimeringsmodellen behöver indata såsom energiförbrukning, storlek på solceller, solinstrålning, antal vindkraftverk, vindhastighet, antal elbåtar, storlek på elbåtsbatteriet samt storlek på batterilagret. Utdatan blir den nya elräkningen för hamnen samt vilken inkomst hamnen kan generera med hjälp av de olika sätten att tjäna pengar på. Modellen räknar även ut hur mycket inkomst som genereras per båt samt den nya elförbrukningen. I uppsatsen har detta simulerats för olika antal elbåtar för respektive hamnen.

Resultaten visar att det är möjligt att tjäna pengar genom att använda de olika metoderna och delta på marknaderna. När endast peak shaving och försäljning av el på elmarknaden används i modellen minskar elanvändningen från nätet och elkostnaderna mest. När simulering av den lokala flexibilitetsmarknaden integreras i modellen ökar elanvändningen och elkostnaderna

något, men även vinsten som genereras ökar. Slutligen, när budgivning på två av Svenska kraftnäts stödtjänstmarknader läggs till i modellen, genereras en ännu högre vinst. Något som måste tas i beaktande är att investeringskostnader inte är inkluderade i denna uppsats – endast driftkostnader i form av elräkningar för hamnarna.

Executive summary

Electrification of the transportation sector is a key strategy for reducing greenhouse gas emissions. While the transition to electric vehicles in road transport is progressing rapidly, the electrification of marine vessels—particularly electric leisure boats—remains limited. In Sweden, where leisure boat ownership per capita is the worlds highest, these boats represent a significant emission source. Given Sweden's goal of achieving net-zero green house gas emissions by 2045, exploring the potential of electric leisure boats is of growing interest.

This thesis investigates whether electric leisure boats, equipped with Boat-to-Grid technology, can optimize electricity usage in marinas and generate revenue. By integrating solar panels, wind turbines, a battery energy storage system, and electric leisure boat batteries into a microgrid, renewable electricity can be stored and later used to supply the marina with electricity or be sold to the grid.

A Python-based optimization model was developed to simulate the operation of such a microgrid over a full year, accounting for the marina's electricity demand and self-produced electricity. The model was designed to optimize the usage of the battery enenrgy storage system and the electric leisure boats batteries, under various scenarios, including peak shaving, electricity sales on Nord Pool, and participation in local flexibility market and frequency regulation markets.

The results indicate that Boat-to -Grid participation has significant potential to reduce electricity costs and generate revenue. Annual revenue per electric leisure boat ranged from 20,000 SEK to 40,000 SEK, excluding investment costs, which aligns with estimates from external energy companies. Larger marinas benefit more from scaling up the number of participating boats, as they can better utilize the available battery capacity. While the model includes simplified assumptions and is sensitive to weather-dependent variables, the study suggest that electric leisure boats can contribute generating revenue and help maximize usage of renewable energy sources. In particular, they offer potential for supporting grid stability and may form the basis for a viable business case for electrifying leisure boats in Sweden.

Acknowledgment

This thesis has been made possible thanks to the support and contributions of many individuals.

We would like to express our gratitude to Volvo Penta for providing us with this project. A special thank you to Niklas Lundin, our supervisor, for his continuous guidance, support, and insightful feedback throughout the project. This thesis would not have been possible without the help of Richard Stefansson, who provided us with valuable data. We are also grateful to Lars-Gösta Alsterberg at Björkö and Bessekroken marina, for the inspiring meetings, insightful field trips, and essential data he shared with us.

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Nomenclature

Abbreviations

aFRR	automatic Frequency Restoration Reserve
BESS	Battery Energy Storage System
B2G	Boat to Grid
EV	Electrical Vehicle
FCR-D	Frequency Containment Reserves Disturbance
FCR-N	Frequency Containment Reserve Normal
FRR	Frequency Restoration Reserve
GHG	Greenhouse Gas
LFM	Local Flexibility Marker
mFRR	manual Frequency Restoration Reserve
PS	Peak Shaving
PV	Photovoltaic
RES	Renewable Energy Sources
DSO	Distribution System Operators
Svk	Svenska Kraftnät
V2G	Vehicle to Grid
V2H	Vehicle to Home
V2L	Vehicle to Load
V2V	Vehicle to Vehicle
V2X	Vehicle to Anything
AC	Alternating Current
DC	Direct Current

Contents

1 Introduction

Today, the energy sector is responsible for three-quarters of global greenhouse gas (GHG) emissions [1, 2] and approximately 85% of global anthropogenic CO_2 emissions [2]. Consequently, reducing the carbon intensity of the sector is of critical importance. However, in the future it is unlikely that the energy usage will reduce globally [2]. In contrast, global energy demand will most likely increase due to a growing population in addition to a rapidly increasing energy consumption [3, 2]. Additionally, there is also a strong correlation between increased GHG emission and climate change [4]. To mitigate the problems mentioned above, the energy sector must transition toward sustainability where utilization of renewable energy is one solution [2].

To address these problems, Sweden has, according to the Paris agreement, set a goal to achieve net-zero GHG emission by 2045, which is only 20 years away [5]. A sub-sector in the energy sector is transportation and due to it being mostly fossil fuel based in Sweden, the domestic transport emits one third of Sweden's total GHG emissions [6]. A promising solution is the use of electric mobility [7]. With no pipeline emissions it contributes to the reduction of GHG emission as well as air pollution [8]. In recent years, there has been a rapid transition from combustion engines to batteries, especially in passengers cars [9]. However, it is important to address all parts of the transportation sector, and an underexplored area is the market for electric leisure boats. Sweden has approximately 700,000 registered leisure boats which is one of the highest numbers in relation to population size [10]. There is a large scale of leisure boat engines that lack gas treatment technology. This contributes to a high amount of emissions, and leisure boats in Sweden emit as much as domestic Swedish aviation [11].

Apart from GHG emission, leisure boats contribute negatively to the surrounding environment. For instance, boats with combustion engines release toxic substances and contribute to underwater noise, which disturbs the marina life [11]. Changing from a traditional combustion engine into an electric boat motor can mitigate the problems with underwater noise as well as hazardous emissions [12]. Unfortunately, the market for electric leisure boats is not a lucrative market today and traditional combustion engines are often a cheaper choice [13]. To respond to this challenge, it is of interest to investigate financial incentives.

In Sweden leisure boats are only serving a leisure purpose from May to September. During the rest of the year, the boats are stored in the winter [14], which means there is a great potential to use the battery capacity for other purposes. Batteries can be used for various services such as peak shaving, energy arbitrage, and participate in an ancillary service market, which can generate revenue [15, 16, 17]. To enable the battery to provide these services, Vehicle-to-Grid (V2G) technology is required. Many studies and pilot projects have been conducted using this technique with electric vehicles (EVs), showing positive outcomes [18, 19, 20]. Notably, electric vehicles are only operated for 4% of the year, resulting in a large potential for utilizing the capacity in the batteries [18]. This suggests an even greater potential for electric leisure boats, which are used less frequently. A few studies on utilizing the capacity in the batteries on electric boats have been conducted, using the V2G-technique, but for this case called Boat-to-Grid (B2G), showing a potential in optimizing electricity usage and generating revenue [21, 22].

In addition to generating revenues, batteries can also contribute positively to the grid stability. Due to the rapid expansion of renewable energy, the power system is reshaping into a less predictable and more decentralized system. This results in an increased need for more flexibility to support grid stability and to optimize the usage of renewable electricity [23]. This has generated a fluctuation in electricity prices as well as a cost for high peak usage [24]. For marinas located in remote places, the importance of both optimizing electricity usage and lowering costs of electricity is rising.

1.1 Purpose and Objectives

The purpose of this thesis is to investigate the possibility of revenue by optimizing the battery utilization of electrical leisure boats in small marinas including a battery energy storage system, (BESS), solar power and wind power. To fulfill this purpose, the following objective will be achieved.

- Create an energy model which simulates the optimal energy usage for a defined set of marinas
- Calculate the financial impact of the result from the energy model.

1.2 Problem Statements

In this thesis the following problem statements will be addressed.

- What is the optimal electricity usage for a defined marina with electrical leisure boats?
- Can electric leisure boats generate revenue by utilizing B2G technique?
- What is the optimal number of electrical leisure boats in a defined marina, with regard to optimal revenue?

1.3 Limitations

The thesis is limited to only investigate leisure boats and does not include other type of vessels. Additionally, in this thesis only lithium ion batteries are investigated. The marinas studied in this thesis are all located in Sweden and data on electricity usage have been collected from the respective marinas. All other data such as spot price, solar irradiance and wind speed have been found specifically for Sweden or Gothenburg, due to the marinas locations. If requested to simulate for a marina located somewhere else, the input data need to be changed. The data retrieved from Volvo was limited to year 2023 meaning the rest of the data in this thesis are also limited to the same year. When calculating and analysing the financial impacts, no investment cost of electric boats, (BESS), solar power or wind power have been taken into consideration.

1.4 Work Distribution

This masters thesis has been conducted by two students, Maria Dryagina and Maja Eneström. Table 1 presents how the work has been distributed between the students. Although, worth mentioning is that there has been continuous dialogue during the whole process, and both students have been involved in decision-making and knowledge-sharing.

Table 1: An overview of how the work has been distributed between Maria Dryagina and Maja Eneström.

Chapter	**Maria Dryagina**	**Maja Eneström**
1 Introduction	Written together	
2 Background	2.2 The Electricity Market 2.3 Revenue Streams	2.1 The Swedish power grid 2.4 Vehicle-to-X 2.5 Environment 2.6 Marinas
3 Theory	3.1 Load Profile 3.2 Self-produced electricity 3.5 Revenue Streams	3.3 Cost of electricity 3.4 B2G and BESS
4 Method	4.1 Literature review 4.2 Interviews 4.4 Data Collection in Python 4.6 Revenue Streams 4.7 Simulation	4.1 Literature review 4.4 Data Collection in Python 4.5 Optimization in Python
5 Results	5.1 Reference Case 5.2 Comparison of Simulated Cases 5.3 Sensitivity analysis	5.1 Reference Case 5.2 Comparison of Simulated Cases
6 Discussion	6.1 Methodology discussion 6.2 Simulation results 6.3 Ethical and sustainability aspects	6.1 Methodology discussion 6.2 Simulation results 6.4 Limitations and uncertainties 6.5 Future studies
7 Conclusion	Written together	

2 Background

In this chapter, relevant background and facts regarding this thesis will be presented. This chapter is based on literature reviews.

2.1 The Swedish Power Grid

The Swedish power grid is one of the oldest power grids in the world [25], with a history dating back more than 100 years [26]. The history began by connecting the local power grid in Trollhättan with the local power grid in Älvkarleby, with a voltage of 130 kV-a which was a record in the early 1920's. In 1936 a 220 kV transmission line connecting the north of Sweden with the south was installed, and about 15 years later the first 400 kV transmission line was installed. Since 1989 Sweden has twelve 400 kV transmission lines left, providing a basis for high voltage transmission and allowing electricity to transfer long distances [26].

Since 2011 the Swedish power grid has been divided into four price areas; SE1, SE2, SE3 and SE4, as illustrated in Figure 1. The price areas were established to handle limitations in electricity transmission to other countries, especially when the demand was higher than the Swedish electricity production [27]. The electricity price differs between the price areas and is based on supply and demand in the area as well as limitations in transmission capacity.

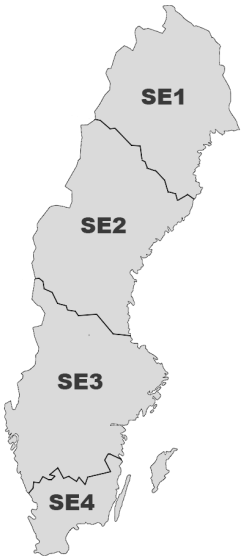


Figure 1: An illustration of Sweden's electricity price areas [28].

The Swedish electricity mix is primarily based on hydropower, nuclear power and wind power, where they represent 40%, 30% and 25% respectively [29]. The remaining 5% mainly comes from solar power and combined heat and power plants. Out of all the fuels used for electricity production, only 1.2% is fossil fuels, making the Swedish electricity mix one of the greenest in Europe. With the high rate of wind and solar power in the system, which are variable renewable energy sources, planned power production is crucial to maintain stability in the grid. Due to the rising share of intermittent power production, flexibility and storage services have become more important for grid stability [29].

2.1.1 Gothenburg's Power Grid

Gothenburg and its surrounding areas are supplied with 90% electricity imported from the transmission grid via the regional grid. The rest, 10%, is produced locally from combined heat

and power plants with mainly combustion of bio fuels and waste, but to some extent fossil fuels [30]. The regional grid has already reached its limit of how much electricity it can transmit to the local grid. However, since Gothenburg has locally produced electricity, problems with grid capacity congestion especially for certain hours during winters can easily be handled [31]. At the same time, the transmission grid is undergoing a reinforcement which will improve the transmitted capacity to the municipality [30]. Gothenburg's municipality is part of SE3, see Figure 1, meaning that their electricity bill reflects the price in SE3 [32].

2.2 The Electricity Market

In Sweden, the electricity market was deregulated in 1996, and since then, the electricity is traded in a free market, meaning the electricity price is based on the balance between supply and demand. Over time, neighboring countries have connected their power grid enabling electricity transmission between each other [33]. Nowadays, electricity is traded among 15 countries in Europe every hour [34]. The electricity market consists of four sub-markets including financial, day-ahead, intraday and balance market which are illustrated in Figure 2 [33].

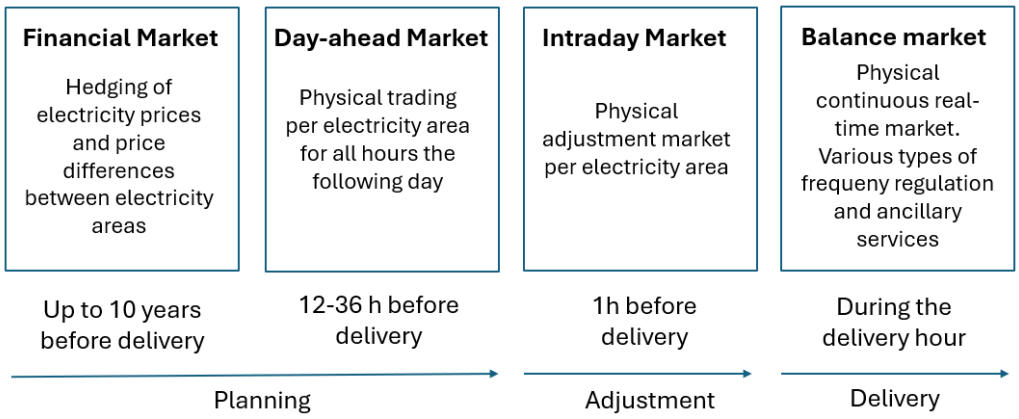


Figure 2: A schematic illustration of the electricity market and its sub-markets [33] [35].

Bids in the *Financial Market* are traded up to several years before delivery [33], which is beneficial for some market participants who are in need of hedging price risk. For example, producers need to secure earnings while suppliers do it to offer fixed price contracts to customers [36]. In the financial market participants can hedge price risks with so-called "futures" which are traded at the stock exchange Nasdaq Commodities [37].

The majority of all electricity is traded and purchased in the *Day-Ahead Market* [38]. As mentioned above, the electricity price is based on the balance between supply and demand [33]. All trades occur in a joint European market. The day before, buyers and sellers decide the amount of electricity they want to purchase and sell, including the price and electricity area, for the following day. When all bids have been submitted, an auction occurs at noon the day before the price is set, where all purchase and sell bids get matched. The price is set where the supply and demand curve is met, called the spot price, illustrated in Figure 3. The spot price is determined by the most expensive energy source used to meet the demand in that specific hour [38]. This is called marginal pricing [33]. The electricity suppliers with the lowest variable costs are used first and, if necessary, bids from electricity suppliers with higher bids are selected to meet the demand. The variable cost consists of fuel costs and taxes. Wind power has a relatively low variable cost while fossil fuels have high carbon taxes and fuel costs, which means that their variable cost is higher [33].

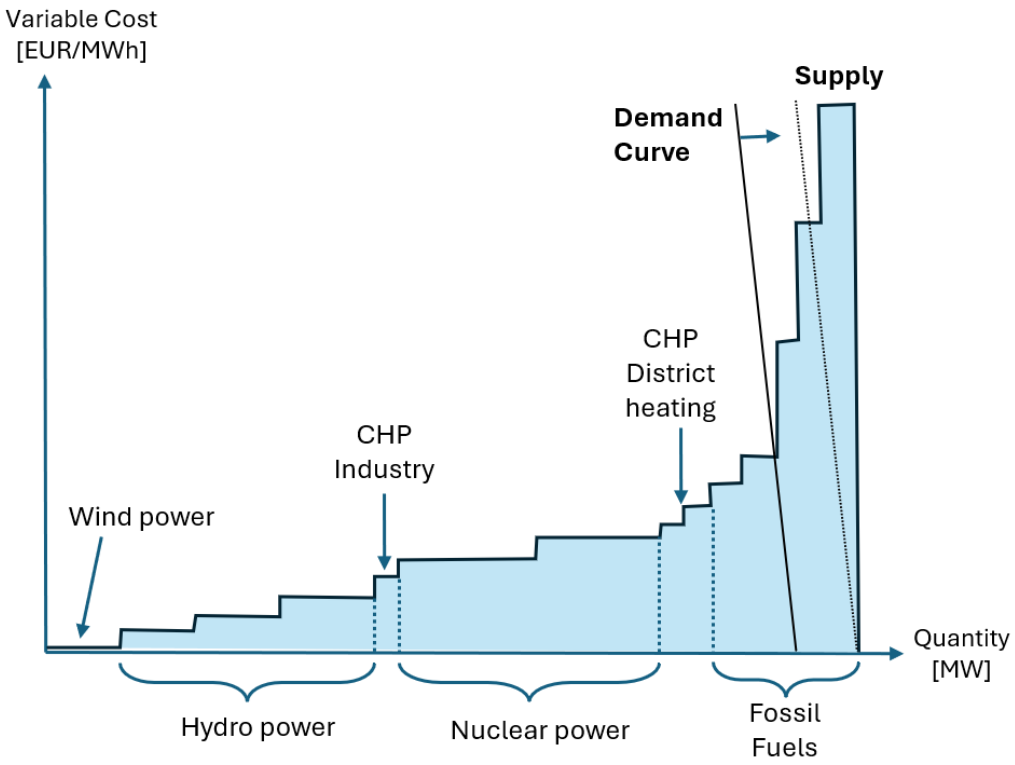


Figure 3: A schematic illustration of the supply and demand curve, which illustrates the price for electricity at a specific hour determined by the intersection of the demand and supply curves [33].

The *Intraday Market* is an adjustment market, meaning the bids that were procured in the day-ahead market can be adjusted [33]. For example, an electricity supplier of wind power always faces uncertainties in their bids due to weather conditions. There is a strong chance that the wind will blow less or more than predicted for the next day. However, this can be adjusted in the intraday market. It is possible to trade into balance up to one hour before delivery. Stakeholders responsible for balancing the power grid, which includes all electricity suppliers, are active in this market [39].

Lastly, there is the *balance market*. The balance market, similar to the intraday market, is aimed at balancing supply and demand. The difference is that the balance market is a real-time market that stabilizes the grid. In Sweden Svenska kraftnät (Svk) is responsible for maintaining the power grid, ensuring that the frequency of the power grid is always 50 Hz [40]. With the help of various types of ancillary services traded at the balance market this can be regulated. Svk purchases reserve capacities in this market from independent parties [41]. A further explanation of the different ancillary services that Svk offers will follow.

2.3 Revenue Streams

This section will discuss the potential for generating revenue by participating in the different markets such as the electricity market, balance market and a local flexibility market. Furthermore, different strategies and methods such as energy arbitrage and peak shaving will be presented.

To participate in the electricity market, certain conditions must be met, such as a minimum bid size. It is uncommon for individuals or small companies to meet these requirements, and then an aggregator is needed. Varberg Energi is an example of an aggregator, connecting multiple

batteries and production units enabling participation in the electricity market and balancing the power grid [42].

2.3.1 Frequency Regulation

Svk is responsible for ensuring grid stability with the help of various types of grid supporting services. There are three types of grid-supporting services that Svk offers: grid services for balancing, non-frequency related grid services and corrective actions which are illustrated in Figure 4 [43]. It is only grid services for balancing that is relevant for this project, the rest of the services are not within the scope of this study.

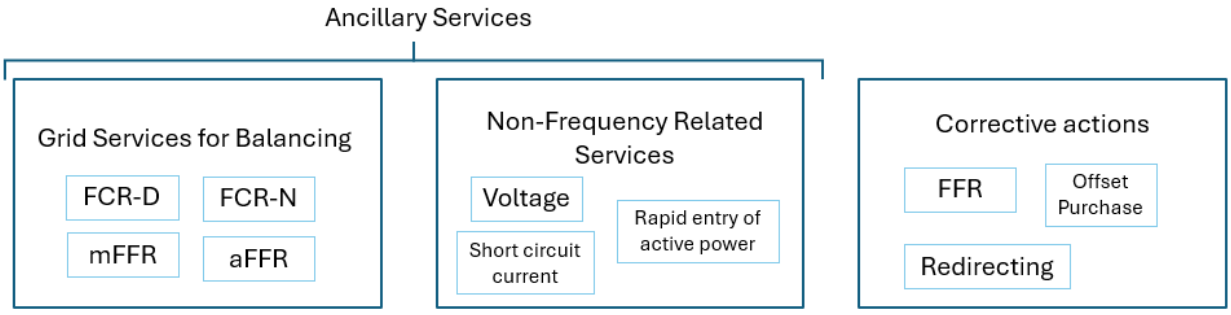
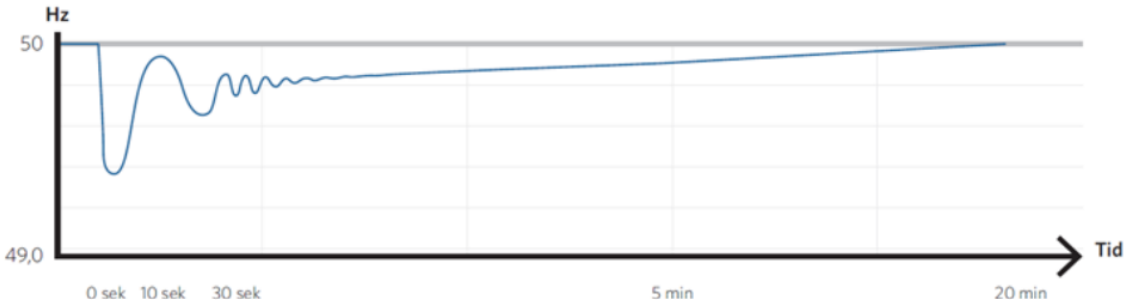


Figure 4: The various types of grid supporting services offered by SvK

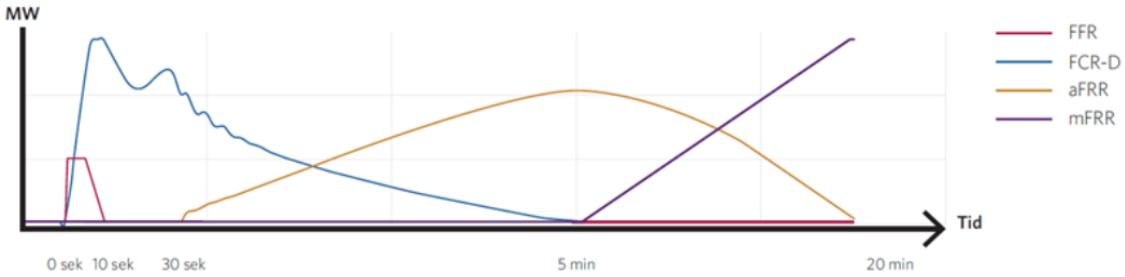
The balancing market consists of two types of balancing services: Frequency Containment Reserves (FCR) and Frequency Restoration Reserve (FRR) which can be divided into an automatic reserve (aFRR) and a manual reserve (mFRR). Furthermore, FCR can be divided into upward and downward Frequncy Containment Reserve Disturbance (FCR-D) and Frequency Containment Reserve Normal (FCR-N) [44].

If a disturbance occurs in the power grid, the following process would take place. FRR is the first reserve to start and is responsible for managing quick and deep frequency changes. The reserve has to deliver power quickly and within an interval of 0-10 seconds. FRR does not count as an ancillary service and is contracted on a yearly basis. After 10 seconds, the ancillary service FCR-D starts, relieves FRR, regulates the frequency further and is responsible for stabilizing the frequency [44].

FCR-D consist of various types of reserve capacities that can regulate their production, increasing it if the usage of power is high, and vice versa. If the deman of power is greater than what is produced the grid frequency will decrease. Therefore, reserve capacities would need to increase their production. When this happens the actions of FCR-D upward are needed. It is the opposite way around if the power usage is less than the production and then FCR-D downward is needed. FCR-N has the same function as FCR-D but is used when small changes occur in the power grid. When the frequency is stabilized aFRR steps in and has the responsible to restore the frequency. If needed mFRR can relive aFRR. This process is illusterated in Figure 5 [44].



(a) Frequency restored after disturbance.



(b) Time intervall for the diffrent types of frequency regulators.

Figure 5: The different ancillary services and when they are used to restore the frequency after a disturbance in the grid. Figures from [44].

All the ancillary services are contracted on an hourly basis. Svk purchases reserve capacities in an ancillary service market from different actors who trade their capacities, for example battery storage systems or wind power. Only qualified traders by Svk are able to participate in this market and there is a minimum bid size which can be found in Table 2 [44]. In the table one can also find the remuneration that is given for participating in the markets. For FCR-D up and down, only capacity remuneration is given, meaning even though a procured bid is not activated a remuneration is generated. For FCR-N market, both capacity and energy remuneration is given. If the procured bid is activated a remuneration of the activated energy volume is given [45].

Several recent studies have revealed that by participateing in multi-markets a maximum profit can be generated. In both [17] and [46] the maximum profit was achieved with electricity in a BESS purchased in both the FCR-D and FCR-N markets, which is also the reason why these markets will be further investigated in this project. In addition, a BESS is more suitable for these ancillary services due to its ability to charge and discharging quickly [47].

Table 2: The various types of ancillary services that Svk offers [48].

	Regulator	Minimum Bid Size	Activation	Endurance	Remuneration
FCR-D	Frequency Containment Reserve Upward	0.1 MW	49.90-49.50 Hz	20 minutes	Capacity remuneration
FCR-D	Frequency Containment Reserve Down	0.1 MW	50.10-50.50 Hz	20 minutes	Capacity remuneration
FCR-N	Frequency Containment Reserve Normal	0.1 MW	49.90-50.10 Hz	1 h	Capacity & Energy remuneration

2.3.2 Spot Price Arbitrage

Electricity arbitrage utilizes the volatility of electricity prices. It involves a form of energy storage, for example BESS, which is charged when electricity prices are low and discharges when electricity prices are higher, generating a profit [16]. These trades are made in the *Day-Ahead Market*. In Figure 6, a schematic drawing of the average spot price and electricity generation is illustrated. Instead of selling the electricity when it is produced, it can be stored in batteries and feed out to the power grid at the price peaks to generate the highest revenue.

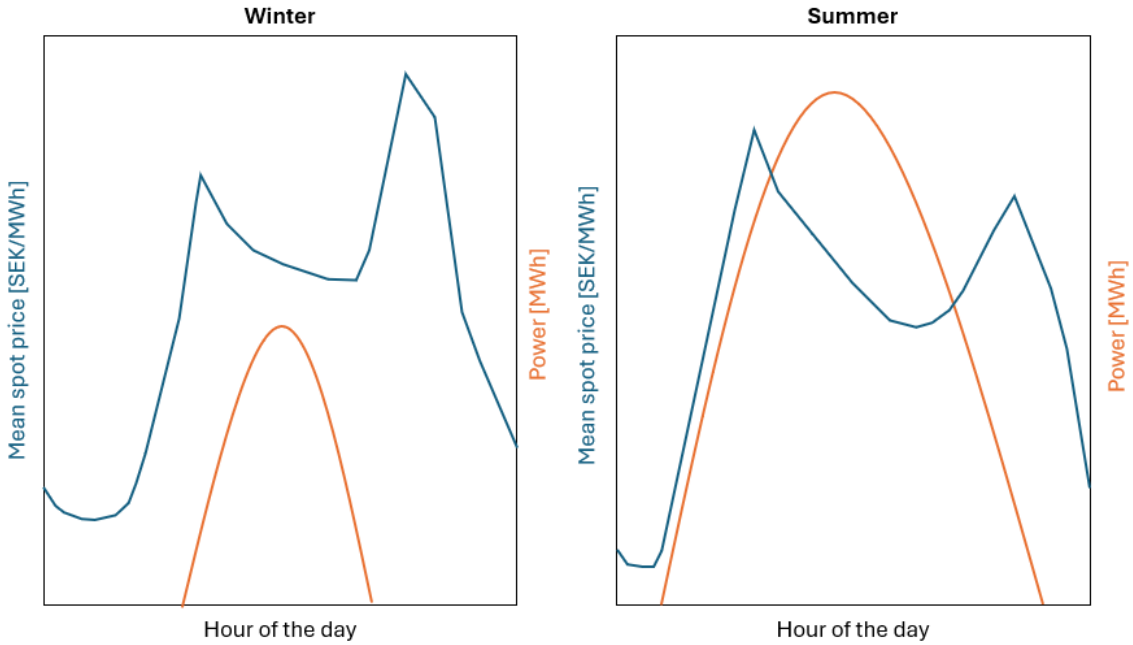


Figure 6: A simplified illustration of spot price arbitrage

Nowadays, when the share of renewable energy is increasing this is a promising business model and a potential for individuals and small companies generating revenues, especially energy storage with batteries [49].

2.3.3 Peak Shaving

The term 'peak shaving' (PS) refers to minimizing peak loads, thereby reducing the demand for power supplied by the grid. This is mainly a problem during certain hours of the day

and by utilizing for example locally produced electricity stored in batteries during peak hours, electricity users can help reduce grid capacity congestion as illustrated in Figure 7. This will also help consumers minimize their electricity bill if their electricity agreement is structured for peak loads [50]. However, starting from the first of January 2027 all electricity producers must change their price models, structured for peak loads [51]. In other words, the electricity bill will increase if the customer uses a large amount of electricity at the same time rather than spreading it out evenly during the day. If customer are not able to spread out their electricity consumption (i.e, load shifting) PS is a good alternative to decrease peak loads.

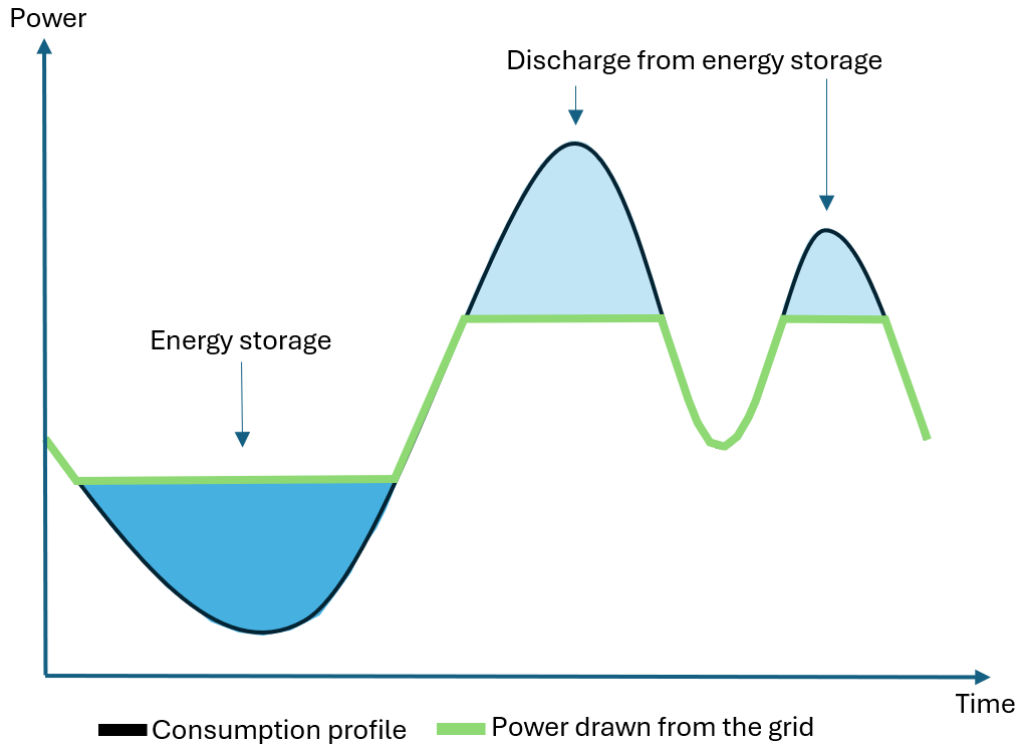


Figure 7: A simplified illustration of peak shaving [52].

Numerous studies have been conducted in this field, and one research group from Uppsala University studied PS for EVs in a parking garage in Uppsala [15]. PS was achieved with the help of locally produced electricity from solar energy, V2G and BESS. This case has shown that PS can help reduce load demands with 25.4-38.5%. However, there are other concerns with PS such as influencing surrounding peak loads negatively, which has also been investigated by the same research group [53].

2.3.4 Local Flexibility Market - Effekthandel Väst

The design of European electricity markets, such as Nord Pool, has historically been shaped around traditional centralized large-scaled and fuel-based generation units [23, 54]. Due to the rapid expansion of renewable energy the power system is now reshaping into characteristics such as variable, less predictable and more decentralized. This results in an increased need for more flexibility to support grid stability and efficiency. One way of achieving this is with the help of mechanisms such as local flexibility markets (LFM) [23]. In LFM, owners of flexibility resources are able to offer their capacity to distribution system operators (DSO) in exchange for payment, which can help manage peaks and congestion problems [54].

LFMs are relatively new market mechanisms and are still in a developmental and testing phase [54]. In Sweden, several LFM pilot projects have been demonstrated, including CoordiNet,

an EU-funded innovation project [55]. One location tested in this project was Uppsala where the goal was to reduce congestion in the grid during high-demand hours in the winter [56]. The result of the demo-LFM was analysed and supported their objectives, that LFM can alleviate congestion and reduce system costs [55]. The CoordiNet innovation project was only a demonstration and since then more LFMs have been created. One example is a LFM called Effekthandel Väst located in Gothenburg [57].

Owners of flexibility resources and operations with high electricity demand within the electricity area Gothenburg can participate in this market. The market is open from November to March and the demand for flexibility is largest during mornings between 7-9 and in the evening between 17-19. There is a minimum bid size of 0.05 MW and the bids are purchased on an hourly basis. The endurance of an activated bid is 1–2 hours. All procurement takes place on the market platform NODES [58]. Effekthandel Väst offers three different types of products: Shortflex, Longflex and Maxusage. The products are presented in Table 3 [57].

Table 3: The various types of products that are offered in Effekthandel Väst [59].

Shortflex	**Longflex**	**Max Usage**
This product is for customers who want to put bids on the market on hourly basis and keep track on the market themselves. If there is a demand customers can place a bid, and if their bid wins a remuneration is given for activated bid.	Customers decided, in discussion with Göteborgs Energi, which hours of the day their resources are available. A remuneration is given for being available but if their bid is activated an activation remuneration is given. This product is suitable for customers with battery storage.	Max Usage is for customer that have controllable operations. Customers decide together with Göteborgs Energi a lower power output during certain hours of a day. If this decided level is met a remuneration is given

2.3.5 Previous Studies on Multi-market Participation

Several studies with various outcomes have been conducted in this field with different setups of participation in markets. In [60], a Norwegian case study, a football stadium with 1.1 MW BESS and 800 kWp photovoltaic (PV) system installed was examined. The aim of the study was to investigate if a BESS that offers stacked values such as spot price arbitrage, peak shaving and self-consumption would be profitable. The model in the study was simulated over a 10-year period and the result revealed that the investment costs for a BESS were too high and repaying the BESS failed. In the simulations the BESS was replaced once in a 10-year period. The study also investigated the outcome if the BESS was not replaced, which supported their objectives. In this case study FCR was not included which is one of the most profitable applications and has been studied in [61].

In [61], a BESS connected to PVs was examined and the potential of maximum revenues in both the energy and frequency market. By participating in a multimarket the PV-BESS had a payback time of 1.8 years. The result also indicates that the yearly revenue slightly increased with combined spot price arbitrage and FCR compared to only participating in the FCR market. However, the generated revenue in the frequency market is marginally bigger, hence an interesting market to explore in this thesis. However, at the same time, forecasts predict that the FCR market will generate lower remunerations in the future due to increased

participation of BESS in this market. However, the forecasts are also predicting a higher demand of ancillary services especially FCR-D down [62].

Both of the studies mentioned above are conducted at a large-scale level. Ahmed et.al [46] investigates the potential of generating revenue in both the frequency market and electricity market for prosumers with batteries connected to PVs. The result supports the objectives, similar to [61], if the frequency market can be accessed. The highest revenues were gained by participating in multi-markets: FCR-D, FCR-N, spot price arbitrage, peak shaving and PV self-consumption. Additionally the payback time of the PV-system reduced from 14 to 11 years if the frequency market was added.

These studies indicates that there may be a potential for generating revenues if the BESS participates in multi-stacking markets such as spot price arbitrage, peak shaving and frequency regulation. However, the results from the studies mentioned above differ and there are some disagreements whether the revenues can repay the investment costs or not, but there is an agreement that revenues are generated. There is also an agreement that the highest revenues are generated from det frequency regulations market.

2.4 Vehicle-to-X

With the challenges that the power grid faces, the need for energy storage and frequency regulation is growing. A technology that utilizes the energy storage capacity in batteries in electric vehicles (EVs) has the potential to address some of these challenges. The term Vehicle-to-Anything (V2X) describes the general concept of the technology, but can be utilized within different areas. A few of the explored areas utilizing this technique are Vehicle-to-Grid (V2G), Vehicle-to-Home (V2H), Vehicle-to-Load (V2L) and Vehicle-to-Vehicle (V2V) [63]. The technology enables EVs to be both charged and discharged through the same charger, allowing the stored energy in the battery to supply other loads or supply the grid with electricity when the vehicle is connected to the charger. By utilizing V2G technology, electricity costs may be reduced by allowing users to supply stored energy while electricity prices are high or by charging when the price is low to then sell the electricity when the price is high [19].

The growing interest in V2G technology is a result of the potential that the unutilized battery storage capacity in EVs has, when they are not being used for transportation. A study conducted by Demuth et al. [18] shows that electric cars are only used for transportation 4% of their operational time, resulting in a significant time when EVs are possibly available for a secondary usage. Furthermore, Demuth et al. [18] states that V2G offers both financial and environmental benefits, with studies indicating potential for financial benefits when using V2G and supplying the grid with electricity [18, 20, 64]. Additionally, when supplying the grid with electricity from battery storage, the utilization can provide the grid with ancillary services [18, 20].

2.4.1 The V2G-technology

The V2X technology uses a bidirectional charger which is a two-way charger that converts AC (alternating current) to DC (direct current) when the EV is charging and, in contrast, converts DC back to AC when the electricity is sent back to the grid [18]. To utilize the energy stored in an EV, a few requirements is needed for the EV to be V2G-compatible. The EV needs to be equipped with hardware designed for bidirectional power flow along with software allowing monitoring and communication to control the power flow [63].

Although, V2G technology is possible, there are a few challenges to apply the technology in practice. This is due to the EV needing to be equipped with hardware designed for bidirectional

power flow. Additional challenges are software allowing monitoring and communication to control the power flow [63]. Lastly, regulatory framework is a key part in ensuring that the technology may be practiced [19].

2.4.1.1 Battery Health

Battery degradation is a frequently discussed challenge when adopting V2G technology. There are two different types of battery degradation, calendar degradation and cycle degradation. Calendar degradation is due to the battery age affecting the capacity of the battery, and cycle degradation is the result of the battery's minimized capacity due to charging and discharging repeatedly. A study conducted by Sagaria et al. [65] analyses the effect V2G-usage has on the battery degradation. The study concludes the battery degradation mainly depends on calendar degradation, causing between 85-90% of the total degradation [65]. When adding the V2G usage to the battery, the effects of calendar aging are reduced, and the cyclic degradation effects increases, resulting in a 14% higher degradation level after 10 years.

On the other hand, the study by Sagaria et al. [65] shows that different cycling scenarios affect the degradation at different levels. Further studies show that low and high SOC-levels result in a faster battery degradation rate compared to limiting the SOC to not reaching high or low levels [66]. Another study, by Uddin et al. [64], analyzing optimized charging shows that limiting cycling to specific levels of the battery SOC may result in a lower grade of battery degradation, reducing the effects the degradation has on both capacity and power. It is important to note that an optimized charging protocol is critical for reaching these results, rather than V2G usage itself.

2.4.2 Electric Leisure Boats

Recent shift towards EV has sparked a transformation in the transport industry, among these transformations, electric leisure boats have gained interest. Offering cleaner and sustainable solutions, as well as a more silent experience, the electric leisure boat is promoted as the best option according to the Swedish Naturskyddsföreningen [12]. The International Energy Agency [67] mentions electrification of smaller vessels as a solution towards lowering emissions. Transportstyrelsen mentions the growing popularity of leisure boats both with electric propulsion and hybrid propulsion [68].

A study by Caprara [69] analyses the effects of converting a leisure boat with a combustion engine to an electric leisure boat. In conclusion, the study shows the possibilities of conversion for the 5.3 meter long boat with a 27 hp motor. The conversion utilizes a 77 kWh battery energy storage system to obtain comparability with the traditional combustion engine with a range varying between 3 and 6 hours depending on power usage. The electric engine requires both a financial investment and an installation, but the study [69] emphasizes the lower fuel costs, presenting possible savings of up to 85%. This demonstrates the possibilities with conversions to electric leisure boats, but also the challenges with high investment costs as well as range.

2.4.3 Previous Studies on B2G

Utilizing the technology of Vehicle-to-Grid with electric leisure boats is called Boat-to-Grid (B2G). One study of this analysed the potential of utilizing the energy storage with B2G-technology around the largest lake in Hungary [21]. The conclusion suggests utilizing electric boats as energy storage in the marinas to maximize solar power production and usage. The conclusion highlights the win-win situation when utilizing B2G, where suppliers better can manage their energy resources at the same time as vehicle owners can generate income by

selling electricity. The study was carried out on a large area which differs from this thesis, but shows the potential of B2G. Conclusions presents that, with suitable incentives, B2G in the marinas may provide Hungary with cost-efficient and effective flexibility service [21].

The project POSEIDON analysed and found a strategy for port microgrids to optimize and manage electricity production from renewable energy sources (RES) and energy storage [22]. The study illustrated utilizing energy storage capacity in EVs and boats, resulting in a more efficient use of RES improving the port's microgrid. The conclusion of the study highlighted that the potential for integrating this sort of solution in multiple ports promotes sustainable developments and reduces emissions [22].

A study on electric ferries for recreational usage in Stockholm, Sweden, was conducted for nine different marinas. An optimization model was formulated to find the best number of slow and fast chargers for the specific marina to meet the demand for charging and at the same time lower the cost [70]. The study showed that all marinas reached financial viability within the first seven years of the investment.

2.5 Environment

The transport sector accounts for a large share of the CO_2-emissions since the majority of the fuel used is fossil fuel [18]. Replacing combustion engines with electric engines will reduce emissions not only from the transportation sector on land, but also off-shore. For EVs on land a study by Da Costa et al. [71] shows that in terms of GHG emissions EVs are superior to internal combustion engine vehicles, and the same conclusion has been presented for electric leisure boats [69].

On the other hand, electric engines and batteries in comparison to combustion engines perform worse in categories such as human toxicity and metal depletion, aspects linked to the use of batteries. These are all categories that will be favored with technology evolutions in the future [70]. Oyediran et. al. [70] shows that electric ferries has a huge impact on minimizing GHG emissions, compared to ferries with combustion engines running on diesel. It is important to note that this is based on the cleanliness of the electricity in Sweden [20], which is high.

More so, electric boats may allow for a higher level of RES supplying electricity to the grid. Utilizing idle EVs to supply the grid with electricity, is not only an opportunity to support the grid with stability but also a way of allowing more renewable energy sources to supply the grid with clean electricity [21]. The reason for this is that RES supplies the grid with intermittent electricity production, which increases the demand for grid stability. Stability can be provided with energy storage in batteries, such as batteries in electric leisure boats [21].

2.6 Marinas

In this master's thesis, the microgrid of three different marinas will be simulated, Krossholmen, Björkö and Bessekroken. All three marinas are located outside of Gothenburg on the west coast of Sweden. Two of the marinas, Björkö and Bessekroken are located on an island outside of Gothenburg. The marinas locations are illustrated in Figure 8.

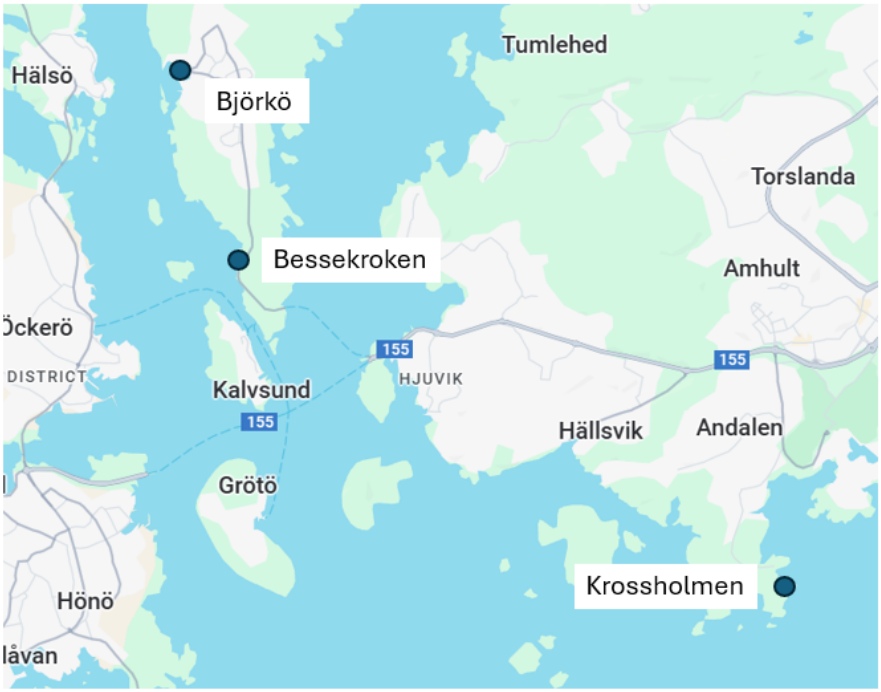


Figure 8: The locations of the three marinas simulated in this thesis.

These are all marinas with different purposes and activities, representing a wide variety of how the marinas are used as well as a difference in the electricity profile during a year. The marinas are characterized by different parameters presented in Table 4.

Table 4: System parameters for the marinas.

Category		**Krossholmen**	**Björkö**	**Bessekroken**
Grid limit	Input [kW]	1,680.0	242.2	13.8
	Output [kW]	840	121.1	6.9
Maximum self-production	PV [kW]	37	24	47
	Wind [kW]	6	0	6
BESS	Capacity [kWh]	533	533	533
	Power [kW]	352	352	352
Boat	Capacity [kWh/boat]	100	100	100
	Power [kW/boat]	60	60	60

2.6.1 Krossholmen

Krossholmen is the test facility of Volvo Penta, located in Torslanda. Here Volvo Penta builds, modifies and test different developed products. This results in the marina having a high electricity consumption during the year, with the highest usage during work hours. This gives the highest electricity consumption Monday to Friday between 8:00 and 17:00, with an especially low consumption during holidays and when the marina is closed in July. The marina has solar panels on some of the roofs, accompanied by a small wind turbine as well as a BESS installed. The maximal power that the grid may supply to Krossholmen is 1,680 kW.

2.6.2 Björkö

Björkö is a large marina located on the island of Björkö. The marina has docking spots for 500 boats and on-land outside storage for 250 boats. The main factors for the marinas electricity demand are two small facilities, fishing boats using electricity between fishing trips and charging the boat batteries in the marina especially during the summer. The boat batteries mentioned here are 12V batteries supplying electricity to the boat lights, fridges or electrical outputs, but the engines of the boats are combustion engines. The electricity consumption has some seasonable variations, with a steady consumption during the autumn, winter and spring and a slightly higher electricity consumption during the summer as well as in the beginning of the winter.

The maximal power that the grid may supply Björkö with is 242.2 kW. There is a possibility of installing solar panels on two of the facilities as well as an interest in additionally adding a BESS to the marinas microgrid.

2.6.3 Bessekroken

Bessekroken is a small marina also located on the island of Björkö. The marina has docking spots for 30 boats and an ability to store 100 small boats in a non-heated storage facility. The electricity consumption is quite low with small seasonal changes, where the summer has a slightly lower electricity demand. The possibility of installing solar panels, BESS and bidirectional chargers is high and next to the marina is a small wind turbine. Important to note for Bessekroken is that the maximum power that the grid may supply the marina with is 13.8 kW which limits this marina significantly.

3 Theory

3.1 Load Profile

The marinas load profile, or electricity demand, P_d $[W]$, can be described with Equation 1 and consists of two parts: P_{marina} $[W]$ which is the electricity usage in the marinas facilities such as lights, heating, ventilation, etc. and P_{boat} $[W]$ which includes the amount of electricity needed for charging the electric boats.

$$P_d(t) = P_{marina}(t) + P_{boat}(t) \tag{1}$$

To supply, P_s $[W]$, the marinas demand, various sources are used including the power grid P_{grid} $[W]$, solar power P_{PV} $[W]$, wind power P_{wind} $[W]$, a battery storage P_{BESS} $[W]$ and the electric leisure boats P_{boat} $[W]$. The boats may supply the marina with electricity since they are connected with V2G technology, the boats supply the marina with electricity when they discharge. This is illustrated in Equation 2.

$$P_s(t) = P_{grid}(t) + P_{PV}(t) + P_{wind}(t) + P_{BESS}(t) + P_{boat}(t) \tag{2}$$

The demand should always be equal to the supply in order for the microgrid to be in balance, shown in Equation 3.

$$P_d(t) = P_s(t) \tag{3}$$

The boats are only considered a demand when they are charged before trips, otherwise the boats acts as a supply together with BESS. However, if they act as a supply, they need to charge before being able to discharge.

3.2 Self-produced Electricity

In this thesis, weather data on solar irradiance and wind speed from the year 2023 were used, obtained from SMHI [72, 73] for the Gothenburg area. The self-produced electricity for solar power, P_{PV} $[kW]$, is calculated with Equation 4. η is the efficiency of the solar panels, A $[m^2]$ is the area and I $[W/m^2]$ is the incoming global solar irradiance.

$$P_{PV} = \frac{\eta \cdot A \cdot I}{1000} \tag{4}$$

Furthermore, the self-produced electricity from wind power P_{wind} $[kW]$ is calculated using the wind turbines power curve, illustrated in Figure 9. The correlation between wind speed and power output was extracted by using data from the technical specification of the wind turbine used in the system, see Apendix A. With a known wind speed v_{wind} $[m/s]$ linear interpolation was used to extract the power output P_{wind} $[kW]$.

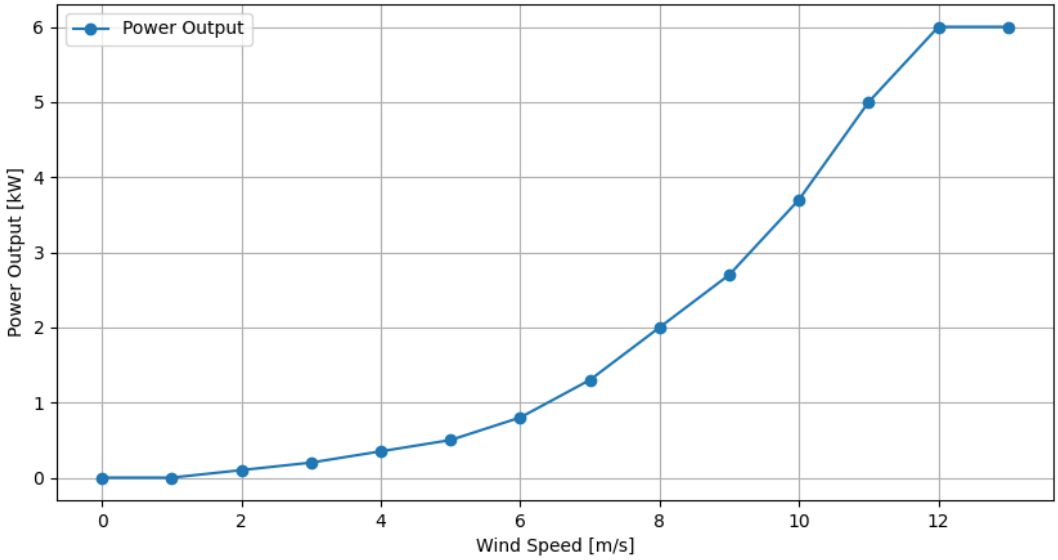


Figure 9: The wind turbine power curve obtained from Apendix A. For wind speeds greater than 12 $[m/s]$ the generated power output P_{wind} $[kW]$ is the same as for 12 $[m/s]$ which is called the nominal power output.

3.3 Cost of Electricity

When consuming electricity from the Swedish grid, the cost is correlated to the electricity spot price and a few other costs and tariffs. Some of these tariff or costs may differ depending on the electricity company [74]. These are energy tax, fixed charge, electricity transmission charge as well as VAT [74, 24]. Additionally, as mentioned earlier in Section 2.3.3, all Swedish electricity distribution companies by 2027, needs to charge a peak power tariff, based on the highest peak power drawn from the grid each month [51]. Based on this, an equation is created to calculate the cost of electricity, presented in Equation 5.

$$\begin{aligned} C_{electricity} = [&P_{grid} \cdot (C_{spot\ price} + C_{energy\ tax} + C_{transmission\ charge}) + \\ &P_{peak} \cdot C_{power\ tariff} + \\ &C_{fixed\ charge}] \cdot C_{VAT} \end{aligned} \tag{5}$$

The first part of the equation is dependent on the electricity supplied by the grid each hour, P_{grid} $[kWh]$. This depends on the spot price $C_{spot\ price}$ $[SEK/kWh]$, which varies each hour, the energy tax $C_{energy\ tax}$, which is 0.439 $[SEK/kWh]$ [75] and the transmission charge $C_{transmission\ charge}$ which is 0.113 $[SEK/kWh]$ [24]. The second part of the equation represents the tariff charged for the highest peak each month. The peak power tariff $C_{power\ tariff}$, charges 61.55 $[SEK/kWh]$ for the highest peak each month, P_{peak} [kWh] [24]. The third part of the equation is the fixed charge from the electricity company, $C_{fixed\ charge}$, which is 725 $[SEK/month]$ [24]. Lastly, VAT is added to the total cost, which is 25% in Sweden, defined in the equation by C_{VAT} [51]. The cost of electricity is based on prices in Gotenburg in 2025 with spot prices and load usage from 2023. The prices are also based on the marinas having a fuse of more than 63 A.

3.4 B2G and BESS

To analyse battery usage, the electricity throughput $E_{throughput}$ $[kW]$ is calculated for the BESS and the boat batteries, according to Equation 6. To compare the energy throughput for the batteries, the total energy throughput for Volvo's batteries are given as a measure of how much the batteries may charge and discharge to maintain a state of health of at least 70% for a full lifetime. This gives a maximum energy throughput at 325-375 MWh for the BESS and at 60-70 MWh for the boat, annually. For the batteries this is calculated as the sum of charge, P_{charge}, and discharge, $P_{discharge}$, per battery. This is then divided by 2, since the definition of energy throughput is how much energy passes through the battery, for example, if a battery is fully charged and then fully discharged, the energy throughput is the total capacity of the battery. When calculating the energy throughput for the boats, the total charge and discharge for all boats are added, to then be divided by the total number of boats, n. For the BESS n may be neglected, since there is only one BESS.

$$E_{throughput} = \frac{\sum_{t=0}^{T} P_{charge}(t) + P_{discharge}(t)}{2 \cdot n} \tag{6}$$

The cycling cost of a battery is presented in Equation 7, which is calculated separately for BESS and boat batteries. The electricity throughput used in this equation is the maximal throughput for Volvo's batteries, stated above. The investment costs for the BESS is based on 35% [76] of the cost of a full BESS, since this covers the cost of the battery pack. For the boats the investment cost differs, but according to [77] a commonly used number is 150 $US\$/kWh$. The residual value is defined as the second life value of a battery and is in percentage. For this master's thesis, the residual value was set to 30% [77, 78].

$$Cycling\ cost = \frac{Investment\ cost \cdot (1 - residaul\ value)}{Electricity\ throughput} \tag{7}$$

The battery's state of charge (SOC) is calculated according to Equation 8. SOC is defined as the available capacity in the battery for a given time in $[W]$ [79]. The SOC is calculated each hour with the SOC for the previous hour and then add the charge or subtract the discharge for that hour.

$$SOC(t) = SOC(t-1) + P_{charge}(t-1) - P_{discharge}(t-1) \tag{8}$$

3.5 Revenue Streams

3.5.1 Frequency Regulation

In the FCR-D market, remuneration is provided only for the procured capacity, not for the activated capacity, the generated revenue R_{FCR-D} $[SEK]$ can be calculated using Equation 9. R_{cap} $[SEK/kW]$ is defined as the given revenue for procured capacity.

$$R_{FCR-D} = P_{bid,FCR-D} \cdot R_{cap} \tag{9}$$

The size of the bid $P_{bid,FCR-D}$ $[kW]$ is defined in Equation 10 as the capacity of BESS, P_{BESS} $[kW]$, the battery capacity of the boat P_{boat} $[kW]$ multiplied with the number of electric boats n in the marina. 40 % of the capacity as bid size was chosen due to it meeting the requirement of the minimum bid size, stated in Section 2.3.1 in Table 2.

$$P_{bid,FCR-D} = (P_{BESS} + P_{boat} \cdot n) \cdot 0.4 \tag{10}$$

3.5.2 Local Flexibility Market

To calculate the remunerations R_{LFM} $[SEK]$ for participating in the local flexibility market, Effekthandel Väst, Equation 11 is used.

$$R_{LFM} = I_{bid} \cdot R_{cap,LFM} \cdot P_{bid,LFM} + I_{activated} \cdot R_{energy,LFM} \cdot P_{bid,LFM} \tag{11}$$

Similar to frequency regulation, remuneration is given for procured capacity but also activated energy. I_{bid} are the number of times a bid is placed, $R_{cap,LFM}$ $[SEK/kW]$ is the compensation for having the batteries available and P_{bid} $[kW]$ is the bidding volume. If the procured capacity is activated, energy remuneration is given which is represented at the right hand side of Equation 11. $I_{activated}$ are the number of times the procured bids are activated, $R_{energy,LFM}$ $[SEK/kW]$ is the compensation for activated energy and P_{bid} $[kW]$ is the bidding volume.

The size of the bid $P_{bid,LFM}$ $[kW]$ is defined in Equation 12 as the capacity of BESS P_{BESS} $[kW]$, the battery capacity of the boat P_{boat} $[kW]$ multiplied with the number of electrical boats n in the marina. When using 10 % of the capacity, the requirement of the minimum bid size for participating in the LFM is fulfilled, see Section 2.3.4.

$$P_{bid,LFM} = (P_{BESS} + P_{boat} \cdot n) \cdot 0.1 \tag{12}$$

3.5.3 Total Cost and Revenue Calculations

Calculations for the total cost and revenue are presented in this section. An overview of the types of costs, the revenue and the total savings are presented in Figure 10.

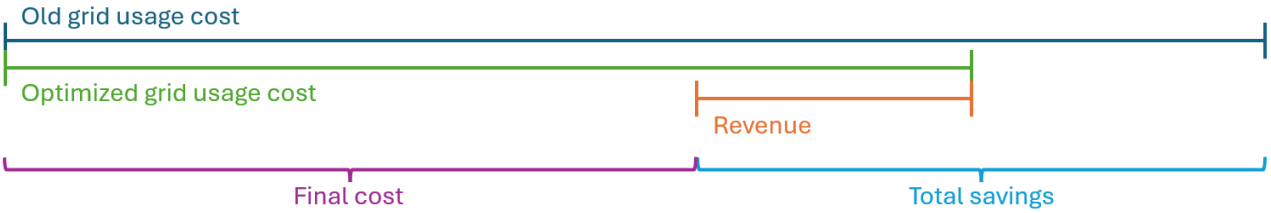


Figure 10: Representation of how the cost and revenue is related to each other.

The final cost $C_{final\ cost}$ $[SEK]$, is defined as the total cost one would pay for the electricity, after the revenue R $[SEK]$ pays off a part of the cost for the electricity used $C_{optimized\ grid\ cost}$ $[SEK]$. $C_{optimized\ grid\ cost}$ is defined as the cost of electricity after the optimization. This calculation is presented in Equation 13 and illustrated in Figure 10.

$$C_{final\ cost} = C_{optimized\ grid\ cost} - R \tag{13}$$

Another calculation made is the total saving S $[SEK]$ which consists of the old grid usage cost $C_{old\ grid\ usage\ cost}$ $[SEK]$ subtracted with the final cost $C_{final\ cost}$ [SEK]. This calculation is presented in Equation 14 and illustrated in Figure 10.

$$S = C_{old\ grid\ usage\ cost} - C_{final\ cost} \tag{14}$$

The cost savings and revenues are generated by utilizing the batteries in the BESS and the electric boats. To give an indication of how much the electric boats and the BESS separately contributes to reducing costs and generating revenue, Equation 15 was used. The boat participation factor, f, represents how much the electricity the electric boats have stored, compared to the BESS, by analysing the energy throughput.

$$f = \frac{E_{mean\ throughput,boat} \cdot n}{E_{mean\ throughput,boat} \cdot n + E_{mean\ throughput,BESS}} \tag{15}$$

Equation 15 shows how much all electric boats participate in storing and supplying electricity. The praticipation factor f is then used in Equation 16 to calculate the total savings per boat, S_{boat}, which represents how much savings each electric boat and its contribution to store and supply electricity has generated.

$$S_{boat} = S \cdot \frac{f}{n} \tag{16}$$

To compare different scenarios, a reference cost $C_{reference\ cost}$ $[SEK]$ is calculated for different numbers of boats, presented in Equation 17. The old grid usage cost, $C_{old\ grid\ usage\ cost}$ $[SEK]$, represents the cost of electricity for the marinas before any optimization. The power $P_{boat\ load}$ $[kW]$ used to charge the boats is based on slowly charging the boats during the night before the trip, to minimize the cost of electricity.

$$\begin{aligned} C_{reference\ cost} = {} & C_{old\ grid\ usage\ cost} + \\ & P_{boat\ load}(t) \cdot (C_{spot\ price} + C_{energy\ tax} + C_{transmission\ charge}) \cdot C_{VAT} \end{aligned} \tag{17}$$

4 Method

The methodology employed in this study involves a literature review to get a deeper understanding of the topics. Additionally, interviews were conducted with the marinas to gain insights into the physical limitations and accurately describe the system in accordance with real-world conditions. Furthermore, a model was developed to simulate the system's behavior with various scenarios. Historical data was used in the model from year 2023, due to limitations of data availability. An overview of the method is presented in Figure 11.

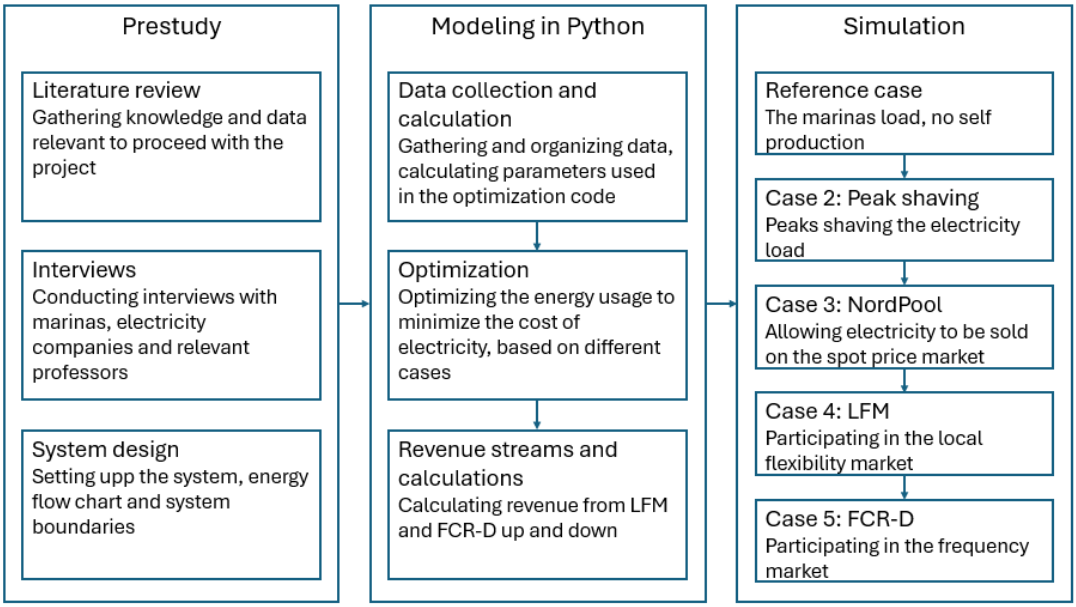


Figure 11: An overview of the different segments of the method.

4.1 Literature Review

The first step of the project was to conduct a literature review to gain a better understanding of relevant topics. Information was gathered such as different markets to participate for generating revenues, the functioning of B2G and information about the different marinas simulated in this thesis. Section 2 is based on the findings from the literature review.

4.2 Interviews

As a part of our study, contact and interviews were conducted with experts in the field to be able to make well-supported assumptions. In Tabel 5 all the interviews that were made are presented.

Table 5: Information about the interviewers and the purpose of the interviews.

Company organization	**Role**	**Purpose of Interview**	**Media**
Ringens Varv	Owner of the marina	Helped identify their priorities and inform the project's direction.	Teams video call In person
Björkö Hamn- och Fiskareförening	Owner of the marina	Helped identify their priorities and inform the project's direction.	Teams video call In person
Sjöstadens Varv	Owner of the marina	Helped identify their priorities and inform the project's direction.	In person
Göteborgs Energi	Planning Engineer	Discuss ideas and cost function	Teams video call
Göteborgs Energi	Responsible for flexibility	Get a better understanding of how the LFM works	Contact via email
Varberg Energi	Traders	Ancillary Service Market	Teams video call
Uppsala University	Expert in wind energy	Discussing wind power equation	Contact via email In person

During the first stage of this study, interviews were conducted with marinas interested in this project. These interviews helped to get a better understanding of what their priorities were and what they needed help with. Later, field trips were made to the respective marinas. The field trips gave a deeper understanding of what was physically possible, what the marinas needed help with and other relevant questions were answered. From these interviews, it was clear that reducing electricity costs is a key priority for all marinas. It was valuable to have contact with all three owners of the marinas, but in the end Björkö Hamn- och Fiskarförening, which owns both Björkö and Bessekorken marinas, were the only marinas chosen to conduct in this study due to lack of data from the other marinas.

Throughout the project, contact was established with Göteborg Energi and Varberg Energi to get a deeper understanding and to discuss various markets where it is possibe to participate and generate revenue. These interactions contributed to a deeper understanding of market mechanisms and to making well-supported assumptions. Varberg Energi provided input on the FCR-D market, while Göteborg Energi offered guidance on the local flexibility market Effekthandel Väst.

4.3 System Description

With the knowledge gained from the literature review and the interviews a description of the system was created. The system is based on the microgrid of a marina, illustrated in Figure 12. Solar panels and wind turbines are the two components that produces electricity to the microgrid. Another component is the load of the marina, illustrated by buildings in Figure 12, which consists of building heating, lighting, offices and other shipyard-loads. The system has two components with ability to both receive and deliver electricity, these are the electric boats (utilized with Boat-2-Grid) and a BESS. The last part of the system is the grid connection, which represents the system boundary.

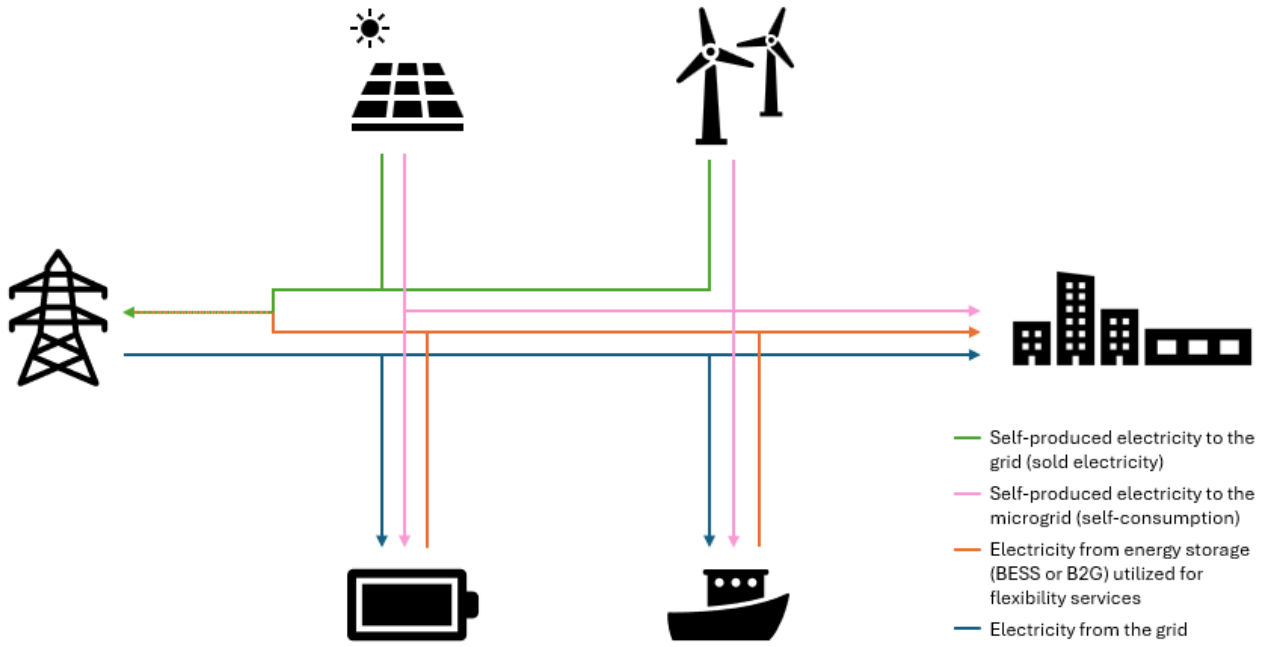


Figure 12: Illustration of the components in the micro grid and the flow of electricity between the components.

Electricity flows between the components in the system, represented by the different colored lines with arrows specifying the direction, shown in Figure 12. From the electricity producing components, solar panels and wind turbines, the electricity can be utilized in two ways, either as electricity sold to the grid, generating revenue, represented by the green line. The other way is by supporting the marinas load or charging either the BESS or the boat batteries, illustrated by the pink line. Another way of providing the system with electricity is from the grid, which can either supply the BESS, the electric boat batteries or the marinas load, represented by the blue line. The last electricity flow, illustrated by an orange line, is electricity either from the BESS or the boat batteries, discharging and supplying electricity to the marinas load, helping with self sufficiency, or to the grid, generating revenue.

4.4 Data Collection and Calculation in Python

To be able to create a microgrid model, relevant data was collected. This section describes the gathering and calculation of the data, as well as the assumptions needed.

4.4.1 Load Profile

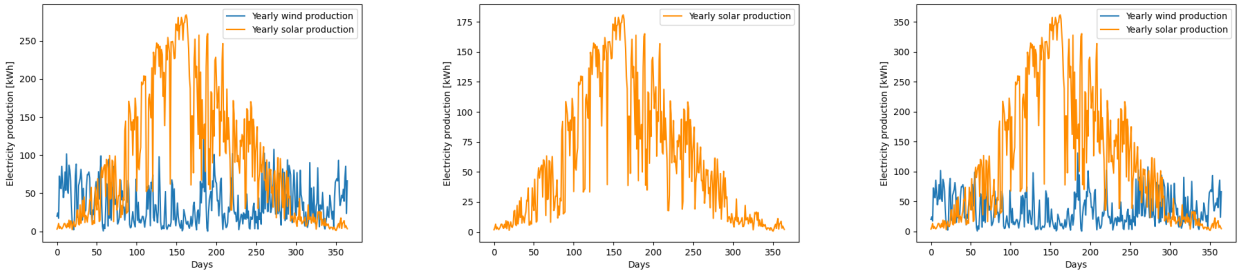
The electricity consumption is modeled in the script with data collected from each marina, presented in Section 2.6. The data show the marinas electricity load for each hour in a day over a full year. The marinas have different activities and slightly different target groups, which gives different load profiles. These are then presented in the first case which is the Reference case, in Section 5.1.

4.4.2 Self-produced Electricity

Apart from the marina's electricity consumption, there is also self-produced electricity such as solar power and wind power. In Figure 13 the annual self-produced power production at the marinas for 2023 is plotted. To calculate the produced solar power Equation 4 was used. The

result was later validated with the result from a photovoltic georapichal caluclator developed by European Comission. As mentioned in Section 3.2, weather data was extracted from SMHI from a monitoring station in central Gothenburg. For calculating solar power, solar irradiance data from 2023 was used. The efficiency of the solar power used in the simulations was 20% which is the highest efficiency of Svea Solar's solar panels [80] which are used at Krossholmen. For the other marinas, Björkö and Bessekroken, the assumption was made that the same solar panels would be installed with the same efficiency, but the area of the solar panels will vary.

Wind power production was calculated by using the wind power curve, illustrated in Figure 35, for the wind turbine installed in Krossholmen. By utilizing python's linear interpolation solver the power output for a defined wind speed was calculated. Similar to solar power production, weather data was extracted from SMHI but instead from a monitoring station located in the archipelagos. This monitoring station was selected due to two of the marinas investigated in this thesis are located in the archipelagos, providing a more realistic representation.



(a) Krosshomen (b) Björkö (c) Bessekroken

Figure 13: The yearly solar power and wind power production for all marinas in 2023.

4.4.3 Usage Pattern of Electric Leisure Boat

To understand the impact of electric leisure boats, a range between 0–50 boats was simulated. It was essential to analyse their usage patterns since this affected the possibility to utilize the boat batteries. In this thesis, the following assumptions was made regarding the usage pattern of an electric leisure boat.

During October to May leisure boats are not used in Sweden due to the weather and therefore they are fully available for B2G. In the first weekend in May the leisure boat is used for a daily trip, according to Appendix B [14], and then used every second weekend until the end of September. During these daily trips the boat is available in the morning and afternoon. For two weeks during the summer the boat is away for a longer trip and is not available at all. It was assumed that when the boat returns from its longer trip, the SOC of the battery is the same as that of daily trips, which is 20%. Hence, the charging of the boat battery is assumed to be the same.

For a full year, the boat is away for 10 daily trips and one longer trip that lasts for 14 days, illustrated in Figure 14. Since multiple boats was simulated, the usage pattern varies for three different boats. This is done by looping the pattern, if one boat is simulated the first usage pattern is applied and if two boats are simulated the first usage pattern is applied for the first boat and the second usage pattern is applied for the second boat. If more than three boats are simulated, the usage pattern applied follows a loop, meaning the fourth boat receives the first usage pattern, the fifth receives the second, and so on. The difference between these patterns is the starting day of the longer trip of 14 days, which occurs for the first boat pattern at 11th of June, the second boat pattern at 2nd of July and the third boat pattern 23rd of July.

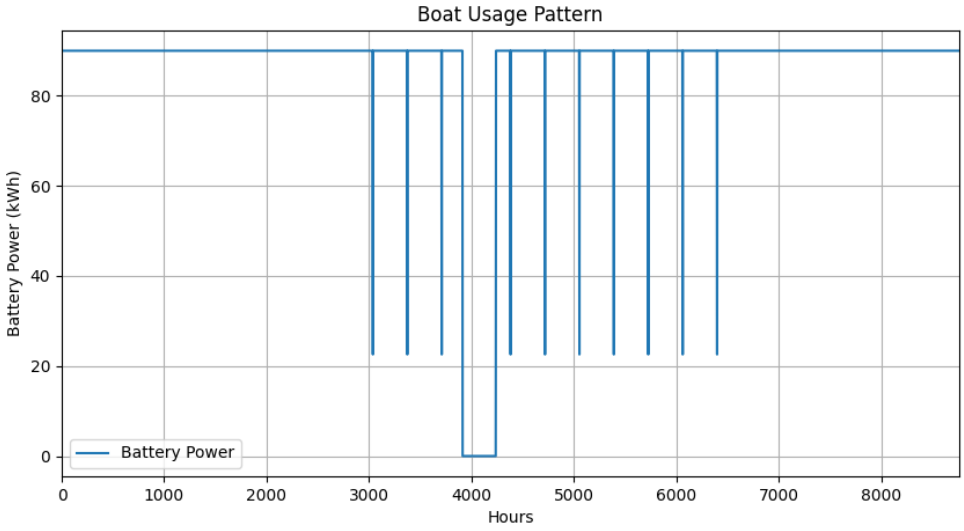


Figure 14: Electric leisure boat's usage pattern for a full year

4.5 Optimization in Python

The microgrids energy system is modeled in Python where an optimization model was utilized to find the best solution. A common way of optimizing energy systems is by formulating linear equations [81], which is used to build the model in this thesis. Another common method of optimizing energy systems is by using mixed integer-linear programming, according to [82], where integers are used for cost-saving controlled systems. For this thesis this was able to be controlled by regulating the input to the optimization model, hence the optimization model only consists of linear programming. Since the optimization only uses Linear Programming a solver called GLPK was used.

4.5.1 Objective Function

The optimization problem needs an objective function, which acts as a goal for the optimization problem. In this case the objective function was formulated as the total cost of electricity, with an objective to minimize the function. The objective function was set up as the total cost of electricity, presented in Equation 18.

$$Minimize: \sum_{t=0}^{T} \left(C_{electricity}(t) + C_{battery\ cycling}(t) - C_{sold\ electricity}(t)\right) + \sum_{m=0}^{M} C_{peak\ cost}(m) \quad (18)$$

The cost of electricity is represented by $C_{electricity}$ and $C_{peak\ cost}$ which is described in Section 3.3. The cost of electricity is calculated for each hour, depending on both the spot price and the electricity supplied from the grid that hour. The peak cost is calculated as the cost of the peak power supplied from the grid each month. The cost of battery cycling, $C_{battery\ cycling}$ represents a cost of cycling the battery to limit an over-use of the batteries and is calculated as a cost of charging or discharging. The last parameter is the cost of sold electricity, $C_{sold\ electricity}$, which is set to a negative since this represents the revenue from electricity sold to the grid. The revenue is calculated each hour since it depends on electricity sold each hour and the spot price.

4.5.2 Parameters and Variables

The next part for the optimization to run smoothly is to set limitations and constraints so that the energy system may be optimized in a correct way. The first part is to add the parameters and variables that the code may work with. Parameters are set values that are imported into the code while variables may be changed to find the best solution to fulfill the objective function. Following is a list of all the parameters in the code:

Parameter	**Explanation**
$P_{PV+wind}(t)$	All electricity production from solar panels and wind turbines combined.
$P_{marina}(t)$	The electricity demand for the marina.
P_{max}	The maximal allowed power that may be drawn from the grid.
$C_{spot\ price}(t)$	Electricity spot price.
$I_{boat\ usage}(t)$	Binary matrix showing when the boat is available or unavailable for the system.
$P_{boat}(t)$	Load used to simulate the load for when the boat leaves and arrives back.
$I_{LFM\text{-}bid}(t)$	Binary matrix for when bids are placed on the local flexibility market.
$I_{LFM\text{-}bid,\ activated}(t)$	Binary matrix for when the placed bids are activated on the local flexibility market.
$P_{LFM,\ bidsize}(t)$	Size of bid that will be placed on the flexibility market (different parameters for BESS and boats).
Q	Capacity of the battery (different parameters for BESS and boats).
Q_{upper}	The upper limit that the battery may be charged to, which is set to 90% for both BESS and boats.
Q_{lower}	The lower limit that the battery may be discharged to, which is set to 10% for both BESS and boats.
$Q_{initial}$	Sets the initial SOC of the battery to 50% (different parameters for BESS and boats).
$E_{charge,\ rate}$	The maximum rate the batteries may be charged with, limited by the size of the charger (different parameters for BESS and boats).
$E_{discharge,\ rate}$	The maximum rate the batteries may be discharged with, limited by the size of the charger (different parameters for BESS and boats).

The next part is to present all the variables in the code, as well as the limitations to these variables. The code may then test out different solutions with these variables with values allowed

within these limitations. Following is a list of all the variables as well as and explanation, their size and some limitations to them:

Variable	Limitations	Explanation
$P_{SS}(t)$	$\leq P_{PV+wind}(t)$	The electricity produced from solar panels and wind turbines that are directly applied to meet the electricity demand of the marina.
$P_{grid,\ load}(t)$	$\leq P_{max}$	The electricity drawn from the grid to meet the electricity demand of the marina.
$P_{grid,\ battery}(t)$	$\leq 10\% \cdot Q$	The electricity drawn from the grid to supply the batteries with electricity.
$P_{NP,\ sold}(t)$	$\leq 50\% \cdot P_{max}$	Electricity sales on Nord Pool.
$P_{peak}(m)$	$\leq 95\% \cdot P_{max,old}$	The highest power peak for each month.
$SOC(t)$	$Q_{lower} \leq SOC \leq Q_{upper}$	The state of charge of the batteries (different variables for BESS and boats).
$P_{charge}(t)$	$\leq E_{charge,rate}$	When the battery charges this variable will show how much the battery charges during that hour (different variables for BESS and boats).
$P_{discharge}(t)$	$\leq E_{discharge,rate}$	When the battery discharges this variable will show how much the battery discharges during that hour (different variables for BESS and boats).

4.5.3 Constraints

When all parameters and variables are set for the optimization code, some constraints must be defined. These are designed to make sure that the solutions found are working as the real system allows. The first part of the constraints are limiting how energy flows in the system. The base of this constraint is presented in Equation 19 and shows that the demand for electricity should match the supply for electricity, based on Equations 1 and 2.

$$P_{PV+wind}(t) + P_{discharge}(t) + P_{grid}(t) = P_{marina}(t) + P_{charge}(t) + P_{grid,sold} \tag{19}$$

The left side of the equation represents the supply of electricity to the system, first electricity from solar and wind production is delivered to the system, $P_{PV+wind}$. Electricity from the different batteries when they discharge acts like a supplier of electricity, $P_{discharge}$. The last part of the supply is electricity from the grid, P_{grid}, which delivers electricity both to match the load of the marina as well as to supply the batteries with electricity.

The right side of the equation represents the demand, which first is represented by the marinas load, marked as P_{marina}. The batteries then act as a demand when they charge, represented by P_{charge}. The last part of the constraint on the demand side is the electricity sold to the grid, P_{grid}. This is because in this constraint all electricity flow is presented in this equation, so for example when the electricity production from solar and wind is really high, the excess energy may be sold which is why sold electricity is a part of the demand in this equation.

The next constraint limits the flow of electricity to the load, shown in Equation 20.

$$P_{SS}(t) + P_{grid,\ load}(t) \leq P_{marina}(t) \leq P_{SS}(t) + P_{grid,\ load}(t) + P_{discharge}(t) \tag{20}$$

Where P_{SS} represents the electricity from solar and wind production that supplies electricity directly to the marina, instead of charging the batteries, i.e. the self production is used directly, self sufficiency. This constraint limits the supply of electricity to the load when batteries delivers electricity to the marina.

The electricity used to charge the batteries either comes from electricity produced by solar panels or wind turbines, but for cases when batteries are needed but the electricity production is to low, electricity from the grid may be utilized. Electricity from solar panels and wind turbines may also be used to supply the marina with electricity, defined as the self sufficieny, P_{SS}. Therefore, P_{SS} i subtracted from the electricity produced by solar and wind power. This constraint is applied by using Equation 21,

$$P_{charge}(t) = P_{PV+wind}(t) - P_{SS}(t) + P_{grid,battery}(t) \tag{21}$$

To limit the electricity supplied from the grid a constraint using Equation 22 is added,

$$P_{grid,load}(t) + P_{grid,battery}(t) \leq P_{peak} \tag{22}$$

which limits the total electricity supplied from the grid to the allowed maximum peak, P_{peak}. The next constraint regulates the electricity sold to the grid which is only sold by discharging the batteries, represented in Equation 23.

$$0 \leq P_{sold}(t) \leq P_{discharge}(t) \tag{23}$$

An exeption from this rule was made for Bessekroken. This was done due to the fact taht the solar and wind power production was higher than the actual load, which meant that at some points the marina and the batteries could not recieve more electricity. For this case self produced electricity was allowed to be sold directly to the grid, according to Equation 24. To limit this event, this was only allowed to happen when $P_{PV+solar} \geq 4 \cdot P_{marina}$ was fulfilled.

$$0 \leq P_{sold}(t) \leq P_{discharge}(t) + (P_{PV+wind}(t) - P_{SS}(t)) \tag{24}$$

The next part of the constraints regulate the update of the state of charge. The foundation of the rule is based on Equation 8. Added constraints regulates how the batteries behave when the boats are unavailable during the summer. The equations regulating this are presented in Table 6 and are presented how the SOC is updated due to when the boat is available or unavailable.

Table 6: Equations regulating the SOC when a boat becomes unavailable, showing how the constraints are limited to different stages for the boats unavailability.

$I_{boat\ usage}(t)$	1	0	0	0	1
Constraint: $SOC(t)$	$\geq Q_{upper\ limit}$	$\leq Q_{lower\ limit}$	unchanged	unchanged	20%
Constraint: $P_{charge}(t)$	$\leq E_{charge,rate} \cdot I_{boat\ usage}(t+1)$	$\leq E_{charge,rate} \cdot I_{boat\ usage}(t)$	$\leq E_{charge,rate} \cdot I_{boat\ usage}(t)$	$\leq E_{charge,rate} \cdot I_{boat\ usage}(t)$	$\leq E_{charge,rate} \cdot I_{boat\ usage}(t)$
Constraint: $P_{discharge}(t)$	$\leq E_{discharge,rate} \cdot I_{boat\ usage}(t+1)$	$\leq E_{discharge,rate} \cdot I_{boat\ usage}(t)$	$\leq E_{discharge,rate} \cdot I_{boat\ usage}(t)$	$\leq E_{discharge,rate} \cdot I_{boat\ usage}(t)$	$\leq E_{discharge,rate} \cdot I_{boat\ usage}(t)$

Furthermore, similar constraints are regulated for when bids are placed on the local flexibility market. How the local flexibility market is utilized will be explained in Section 2.3.4. Equations used to regulate this in the optimization model are presented in Table 7 and differs for times just before the bids are placed as well as when the bids are placed.

Table 7: Equations regulating the SOC when bids are placed on the local flexibility market, showing how the constraints are limited to different stages for when the bids are placed.

$I_{LFM-bid}(t)$	0	0	1	1
Constraint: $SOC(t)$	$\geq Q_{lower\ limit} + P_{LFM,\ bidsize}$	$\geq Q_{lower\ limit} + 2 \cdot P_{LFM,\ bidsize}$	$\geq Q_{lower\ limit} + 2 \cdot P_{LFM,\ bidsize}$	$\geq Q_{lower\ limit} + P_{LFM,\ bidsize}$

Some of the placed bids are activated, and at this point the SOC needs to be regulated. The bids are activated in pairs, and the equations used to regulate this is shown in Table 8.

Table 8: Equations regulating the SOC when bids are activated on the local flexibility market, showing how the constraints are limited to different stages for when the bids are activated.

$I_{LFM-bid,activated}(t)$	1	1	0
Constraint: $SOC(t)$	unchanged	$= SOC(t-1) - P_{LFM,\ bidsize}$	$= SOC(t-1) - P_{LFM,\ bidsize}$

4.6 Revenue Streams

Generating revenue is possible by participating in different electricity markets, as mentioned earlier. Following is an explanation of how participation is regulated and revenue is generated from the different markets.

4.6.1 Nord Pool

The electricity usage is optimized to primarily buy electricity when the spot price is low and sell electricity when the spot price is high, stated in Section 2.3.2, to reduce costs and also

generate revenue. This is added in the objective function, shown in Equation 18 as the cost of electricity, which is based on the spot price.

4.6.2 Local Flexibility Market - Effekthandel Väst

To model participation in the LFM, Effkethandel Väst, historical data of traded volumes and activated bids were analysed from the data platform NODES [83]. Based on this the following assumptions were made.

It is assumed that the BESS and B2G only participate in Longflex, see Section 2.3.4, meaning remunerations are given for both being available and when the energy is activated. The need for capacity is between 7-9 in the morning and 17-19 in the evening and therefore it is assumed that the battery will be available and bids are placed during those hours, so called block bids. Bids are only placed from November to March every second week. It is assumed that all bids that are placed will be accepted. The modeling of activated bids is based on data from 2024, where 13 % of all procured bids were activated. This activation rate is assumed and applied in this thesis. When bids are activated, the battery is discharging for 2 hours. It is therefore assumed that the entire block bid is activated.

4.6.3 Frequency Containment Reserve

The FCR market was modeled by starting to analyse frequency dataof the grid. Data wes retrieved from Fingrid [84] with a measured step of 3 minutes. The data was first sorted, and due to lack of a few data points, these were added with the assumption that the frequency for those specific time steps was 50 Hz. Furthermore, the frequency was sorted into the different intervals (50.1-50.0 Hz, 50.0-49.9 Hz , 49.9-49.5 Hz and 50.1-50.5 Hz) by adding all the data points within the intervals for each hour, one data point lasting three minutes. The intervals were then divided by 60 to get a fraction of the hourly duration. This made it possible to analyse how many hours of a year a deviation of the frequency occurs. In Table 9 the total number of hours in which a disturbance occurs is presented for the different frequency intervals.

Table 9: Total number of hours of 2023 when a frequency disturbance occurs in the different frequency intervals.

Interval	**Hours**
FCR-D up (49.5-49.9)	44.2
FCR-D down (50.1-50.5)	49.35
FCR-N low (49.0-50.0)	4528.4
FCR-N high (50.0-50.1)	3999.5

Presented in table 9, FCR-D up is only activated 44.2 h during 2023 and FCR-D down 49.35 h. This is a fraction of 0.5 % and 0.55 % for a full year. Similar to a study conducted by Lindgren [85], the frequency was only below 49.9 Hz 1 % 2018 and above 50.1 Hz 1 % of the year. Based on this and in dialogue with Varberg Energi it was assumed that the FCR-D bids will not be activated in this study, considering the low probability of activation. FCR-N on the other hand is activated for a significant part of the year. But, due to limitations of the optimization model, FCR-N market was not chosen to be modeled.

Figure 15 illustrates the bidding process of FCR-D. When a bid is accepted only capacity remuneration is given meaning no remuneration for activated energy is given. As stated in Section 2.3.1, FCR-D down is activated when the frequency is within the interval 50.1-50.5 Hz meaning the battery will be charged. FCR-D up is activated within interval 49.9-49.5 Hz meaning the battery will discharge.

Figure 15: Bidding process for FCR-D market participation. Only capacity remuneration is given.

It is assumed that all bids that are placed will be accepted and remuneration is given using Equation 9. The BESS and B2G is limited to only participate in this market between hours 20:00-06:00 due to the capacity used for Effekthandel väst and PS the rest of the day. Furthermore, the boats are only participating in this market from September to May, due to them being used for leisure purposes during summer. Data on capacity remuneration [86] were retrieved from Mimer.

There are some rules of how many bids in a row, so called chain bids, are allowed to be placed. There are two procurements where the first one closes D-1 at hour 00.30 and the second closes D-1 at 18.00 in the evening. Depending on which procurement is used the rules differ. For the first procurement it is allowed to place chain bids with a time span of 6 h. If bids are placed at the second procurement it is only allowed to place bids with a time span of 4h. It is also a requirement that the chain bids that are placed all have the same bid size [45]. In this thesis the assumption that all bids are placed at the first procurement wwas made. In the morning chain bids are placed with a time span of 6h and in the evening a time span of 4h.

4.7 Simulation

To model the system, a simulation-based approach was used, involving five different cases. A reference case was first simulated to serve as a baseline for comparison. The remaining cases were then incrementally simulated, each building on the previous one, as illustrated in Figure 16. All cases were simulated for a year using data from 2023, due to the limited availability of data. The cases were also simulated with different numbers of electric leisure boats starting from 0, 2, 4, 6, 8, 10, 20 and lastly 50 for each respective marina.

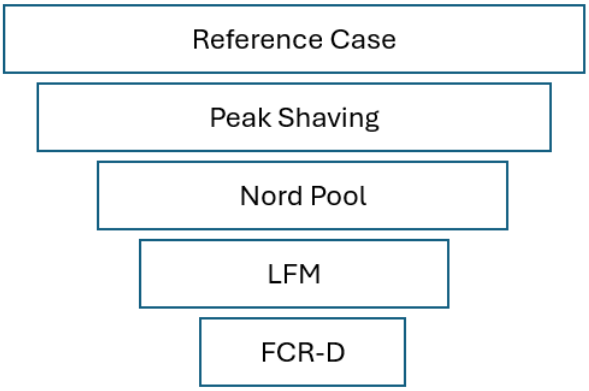


Figure 16: An illustration of how the model will be simulated. The cases will incrementally be simulated, each building onto the previous one.

4.7.1 Reference Case

In the reference case the load profile of the three different marinas were simulated without any self-produced electricity, BESS or revenues streams. To put it differently, the reference case illustrates the current appearance of the marinas. This reference case will serve as a baseline to compare the other cases with. The load profile was simulated with an hourly resolution. Furthermore, the optimized grid usage during the year was calculated as well as the cost of electricity consumption using Equation 5.

4.7.2 Case 1: Peak Shaving

The next simulated case implements self-produced electricity, BESS, B2G and an optimized approach for electricity utilization. However, there are no participations in markets for generating revenues. The only savings occurs due to PS. The yearly optimized electricity consumption was calculated, as well as the optimized cost of electricity using Equation 5.

4.7.3 Case 2: Nord Pool

This case adds the simulation of selling electricity to the power grid to generate a revenue. By utilizing the BESS and B2G the self-produced electricity is stored and sold during the spot price peaks to maximize profit. Similar to the other cases the optimized yearly electricity consumption was calculated likewise the optimized cost of electricity and potential revenues.

4.7.4 Case 3: Effekthandel Väst

The second to last case adds the simulation of the LFM Effekthandel Väst. The yearly optimized electricity consumption was calculated, the optimized cost electricity using Equation 5 and the annual generated revenue.

4.7.5 Case 4: FCR-D

For the last case the participation in the frequency regulation market FCR-D was investigated. In difference from the other cases, this case is not implemented in the optimization code. Instead it is simulated after the optimization where the SOC of the BESS and boats are investigated. In other words, the battery usage of BESS and boats is not optimized to participate in the FCR-D market but instead their availability for FCR-D market is examined. It is assumed that

the bid is placed D-1 at hour 00.30, when the first bidding closes [45]. This means that when the battery is participating in FCR-D up it should have SOC of 60% and FCR-D down a SOC of 40%. As stated in section 4.6.3 bids are placed between hours 20:00-06:00 when there is an availability in the batteries. The total annual revenue was calculated.

In this case all the methods mentioned above are implemented, meaning peak shaving, selling electricity to Nord Pool and participating in LFM is added. For this case the electricity througput for the BESS and the electric boats was calculated using Equation 6. To further analyse financial aspects, a reference cost, using Equation 17, and final cost, using Equation 13, have been calculated. Furthermore, total savings per boat is calculated in the simulations using Equation 14, 15 and 16. These calculations are only made for the last case.

4.7.6 Sensitivity Analysis

A sensistivity analysis is carried out by simulating different bid sizes placed on the local flexibility market. The selected bid sizes are 20%, 30% and 35% of the capacity, see Equation 12. The differences are simulated only on the marina of Krossholmen.

5 Results

5.1 Reference Case

The following sections, 5.1.1-5.1.3, will present the reference case for the three different marinas. The reference case is based on electricity supplied from the grid when there is no self-production and no types of batteries allowing PS. Thus, the electricity supplied from the grid directly shows the marinas load without any electric leisure boat used.

5.1.1 Krossholmen

The total load for year 2023 in Krossholmen is 906.8 MWh and the load profile for this year is presented in Figure 17. The load profile consists of the marina's electricity usage, including heating and electricity consumed by the facilities. The electricity cost of the marina is 1,608,118 $kSEK$. The high electricity cost is due to Krossholmen serving as Volvo's test center for boat engine development, which results in significantly higher electricity usage compared to typical marinas. The profile shows a lower electricity usage during the summer which is due to the marina being closed in July due to the summer holiday.

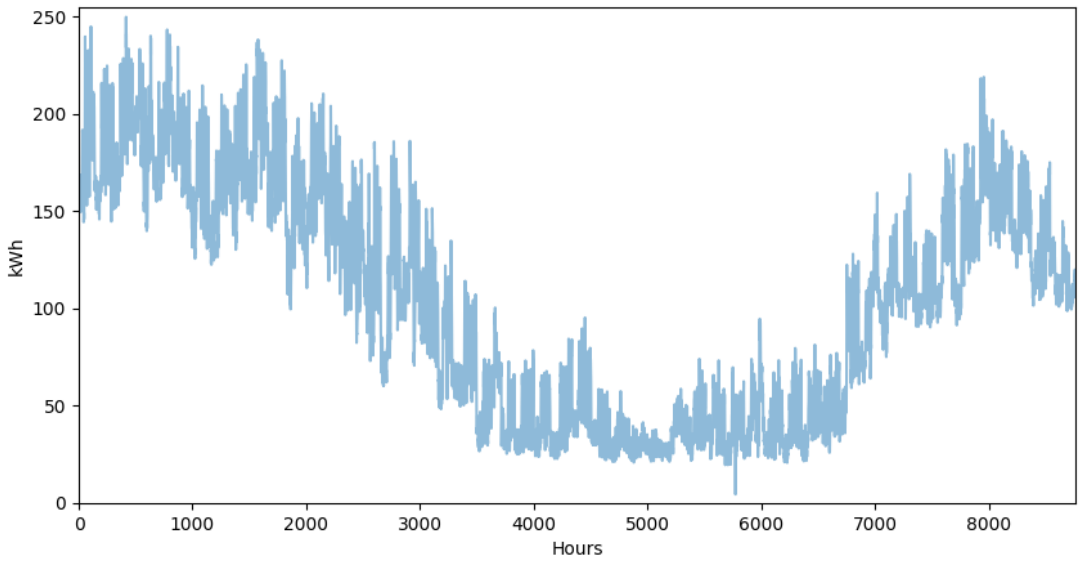


Figure 17: The yearly electricity load in Krossholmen.

5.1.2 Björkö

The total load for year 2023 in Björkö is 145.2 MWh and the load profile for this year is presented in Figure 18. The load profile consists of the marina's electricity usage, including heating and electricity consumed by boat owners and the facilities. This gives a total electricity cost of 264,804 $kSEK$. The profile shows higher peaks during the summer months which is due to the popularity of visiting the marina in the summer, resulting in a higher electricity consumption during that time.

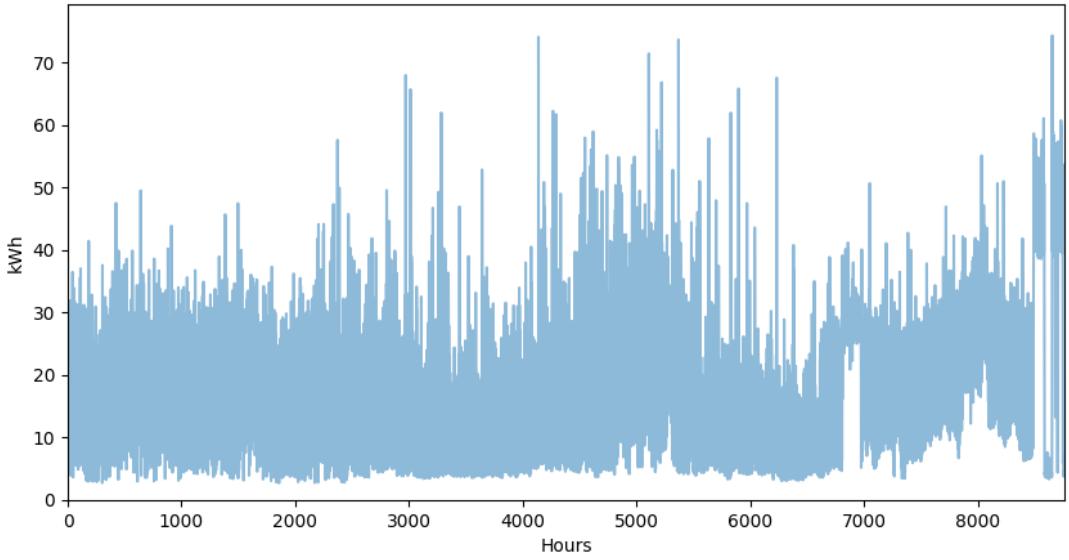


Figure 18: The yearly electricity load in Björkö.

5.1.3 Bessekroken

The total load for year 2023 in Bessekroken is 13.1 MWh and the load profile for this year is presented in Figure 19. The load profile consists of the marina's electricity usage, including heating and electricity consumed by the facilities. This gives a total electricity cost of 24,269 $kSEK$. The low electricity consumption is due to the marinas size, since it is small with a limited ability to dock and to distance to restaurants and cafes, the electricity consumption stays low all year.

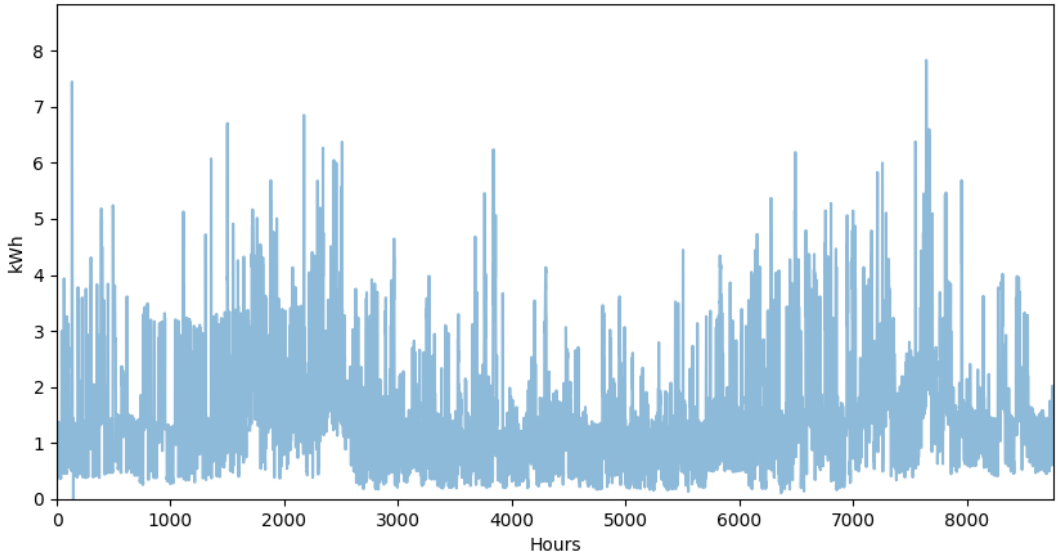


Figure 19: The yearly electricity load in Bessekroken.

5.2 Comparison of Simulated Cases

In this section the result is presented from first PS, then allowing for electricity sales on Nord Pool and lastly participating on the local flexibility market and FCR-D. When presenting the electricity supplied from the grid, these are presented as the result of simulating two electric leisure boats in the marinas. Results for all marinas are shown in the following sections.

5.2.1 Krossholmen

When optimizing the electricty usage by only PS, the electricity usage changes significantly, presented in Figure 20. The highest peaks during the year have been reduced and the electricity usage reaches low levels multiple times during a year. In contrast to the reference case, for these cases Krossholmen has a self-production from both solar power and wind power, with a yearly production of 33.7 MWh solar power and 13.27 MWh wind power.

Furthermore, the profile of electricity supplied from the grid has changed. Firstly, the new peaks are the same during a whole month. The second change is the lowest level the grid usage reaches, which is no electricity drawn from the grid, hence why the green graph reaches zero. This is made possible when the BESS and electric boat batteries have enough electricity stored to answer for the marinas full electricity demand. For the different cases, PS, allowing electricity sales on Nord Pool, and participating in the LFM, the electricity supplied from the grid is very similar. Figure 20 shows when all of these cases are applied.

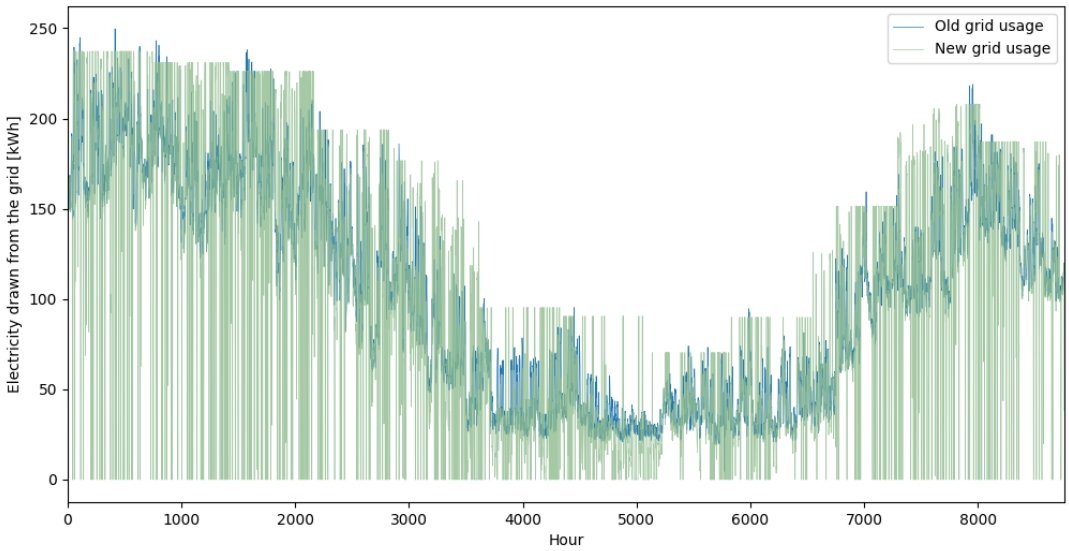
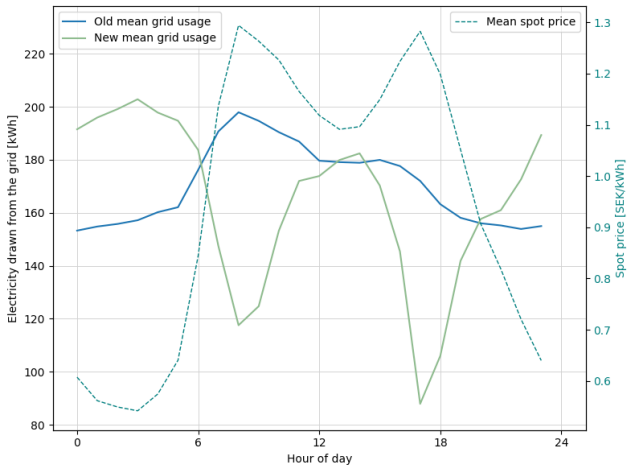
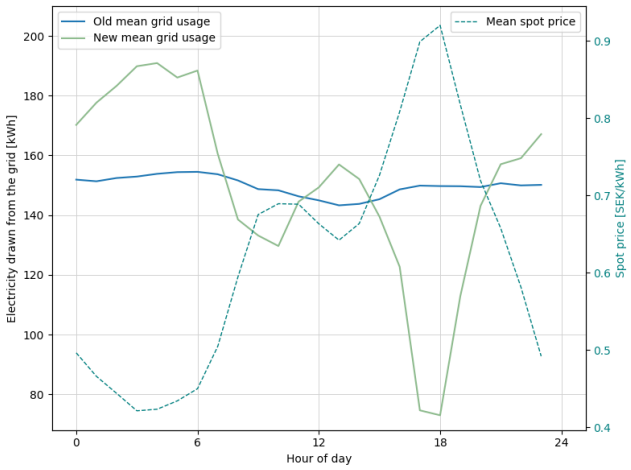


Figure 20: The yearly grid usage in Krossholmen, after applying the different cases. The new grid usage is shown by the green curve. Peaks have been reduced, and the grid usage reaches zero at several points, as indicated by the green line touching the x-axis.

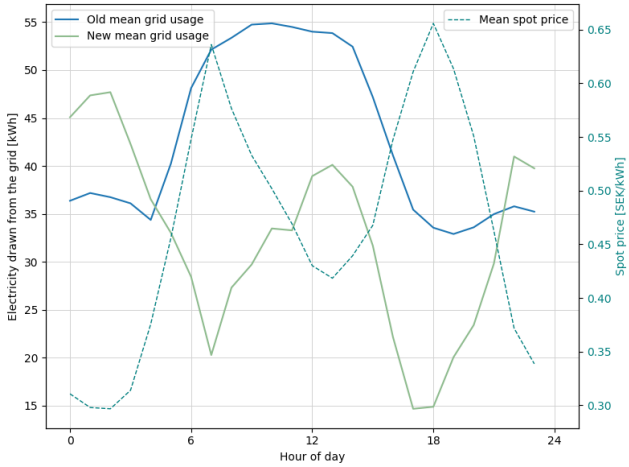
Analysing the electricity usage further, an average of electricity usage is presented in Figure 21. Figure 21a shows the average electricity profile for a weekday during the winter, and Figure 21b shows the average electricity profiles for the weekends. In a similar manner, Figure 21c and 21d shows the average electricity profiles for weekdays and weekends during the summer. For all cases the new grid usage correlates with the spot price. Hence, when the spot price is high, electricity supplied from the grid is low and when the spot price is low, electricity supplied from the grid is high. The electricity usage presented in the figures is based on simulating all cases.



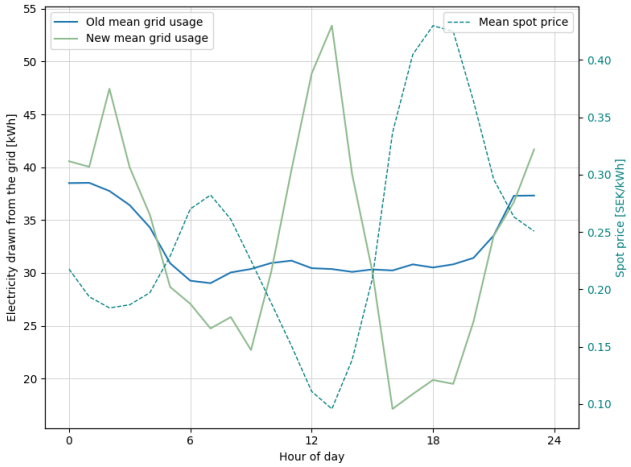
(a) Weekday during winter.



(b) Weekend during winter.



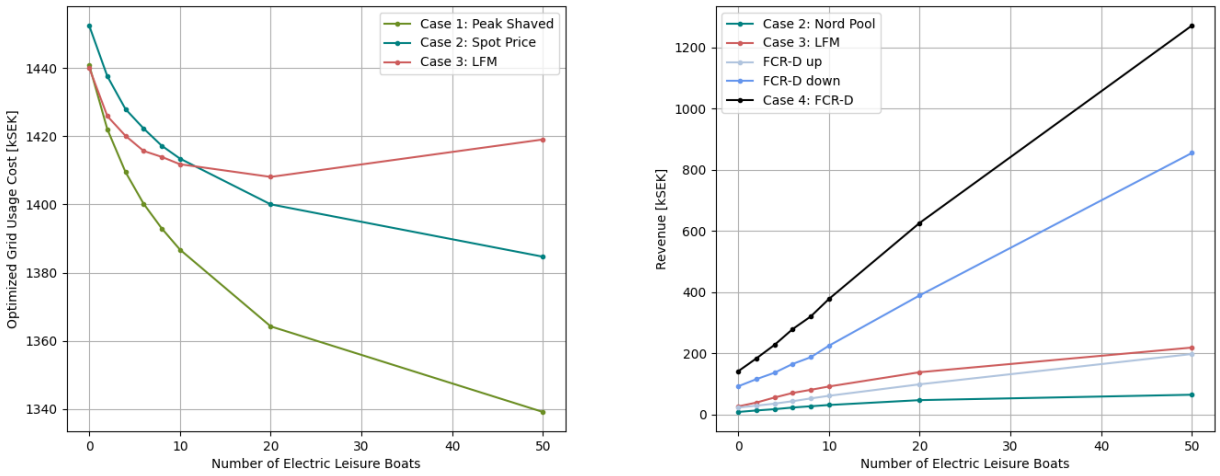
(c) Weekday during summer.



(d) Weekend during summer.

Figure 21: Electricity profile of an average day of the week and weekend for both the winter and summer in Krossholmen.

In Figure 22 the financial factors are presented, based on the simulation of different numbers of boats in the marina. Figure 22a shows how the new cost of electricity changes when applying the different methods, PS, participationg in Nord Pool and the LFM, optimizing the grid usage. Figure 22b shows the revenue generated by participating in different electricity markets.



(a) Optimized grid usage cost

(b) Revenue

Figure 22: The new estimated cost of electricity and revenue, for the different simulated cases in Krossholmen.

In Table 10 the electricity throughput for the BESS and boats is presented with all cases applied. The value of the electricity throughput for boats is an average value of the total electricity throughput. The electricity throughput for BESS decreases as the number of boats increases. This is due to the availability of more capacity as the number of electric boats is increasing. The electricity throughput does not trespass the maximum throughput which is between 325-375 MWh for BESS and 60-70 MWh for boats, see Section 3.4.

Table 10: Electricity throughput for BESS and average per boat, for different numbers of boats simulated in Krossholmen with all cases applied

Number of boats	**Electricity throughput BESS [MWh]**	**Electricity throughput boat mean value [MWh]**
0	114.1	0
2	106.1	16.5
4	96.5	14.5
6	87.0	13.6
8	83.1	12.2
10	77.8	11.4
20	63.5	7.9
50	40.6	4.5

The final cost, presented in Table 11, is calculated by subtracting the revenue from the electricity cost, as shown in Equation 13. The final cost can be compared to the reference cost, which is calculated from the reference case with an added cost of charging the electric leisure boats before trips, according to Equation 17. Moreover, a participation factor for the boats was fromulated, with Equation 15. The boat participation factor is used to calculate the total savings per boat,

presented in Equation 16, where total savings are defined as the difference between the reference cost and the final cost. The total savings per boat reflect the extent to which each boat battery contributes to cost reduction for the marina and revenue generation through electricity sales on Nord Pool, participation in the LFM, and remuneration for availability in the FCR-D up and down markets.

Table 11: Costs and savings per simulated number of boats in Krossholmen applying all the cases.

Number of of boats	**Reference cost [kSEK]**	**Final cost [kSEK]**	**Boat participation factor [%]**	**Total savings per boat [kSEK]**
0	1,608.1	1,298.9	0	0
2	1,609.5	1,242.7	23.7	43.5
4	1,610.9	1,192.8	37.5	39.2
6	1,612.2	1,136.7	48.3	38.3
8	1,613.6	1,093.4	54.0	35.1
10	1,615.0	1,034.3	59.4	34.5
20	1,621.8	781.9	71.4	30.0
50	1,642.4	148.0	84.6	25.3

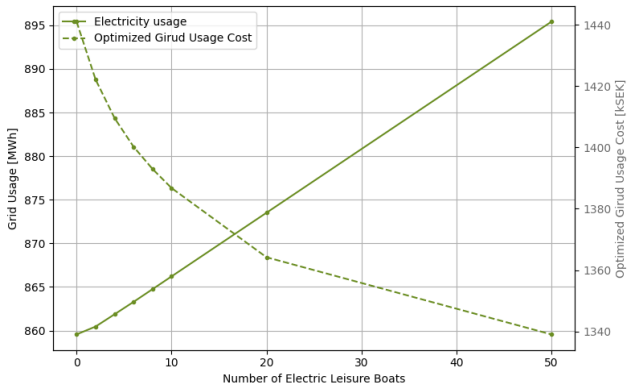
In Table 12 the total electricity drawn from the grid is presented for both the reference case and when all cases are applied, which is PS, selling electricity on Nord Pool and participating in the LFM. The grid usage presented as the reference grid usage is based on the electricity usage of the reference case as well as the added load for when charging electric leisure boats before trips.

Table 12: The total electricity drawn from the grid, for different numbers of boats simulated in Krossholmen.

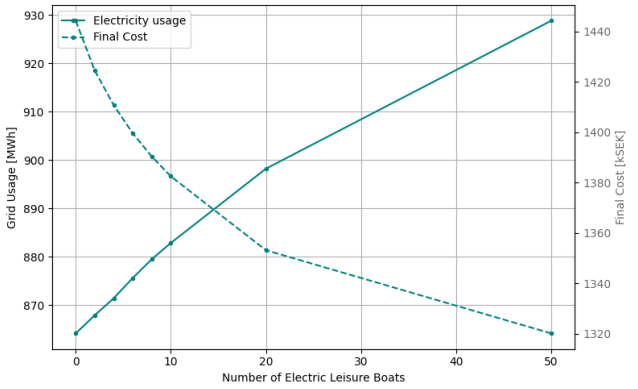
Number of boats	**Reference grid usage [MWh]**	**Optimized grid usage [MWh]**
0	906.8	860.6
2	908.3	864.9
4	909.9	870.7
6	911.4	875.5
8	913.0	880.8
10	914.5	885.7
20	922.2	905.5
50	945.3	947.8

In Figure 23 the electricity supplied from the grid for the different numbers of electric liesure

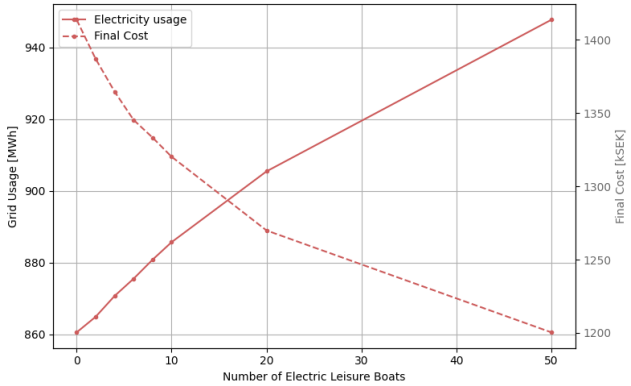
boats is compared to the final cost of electricity. The figures shows that for all cases the electricity supplied from the grid is rising with the numbers of boats, but the final cost minimized.



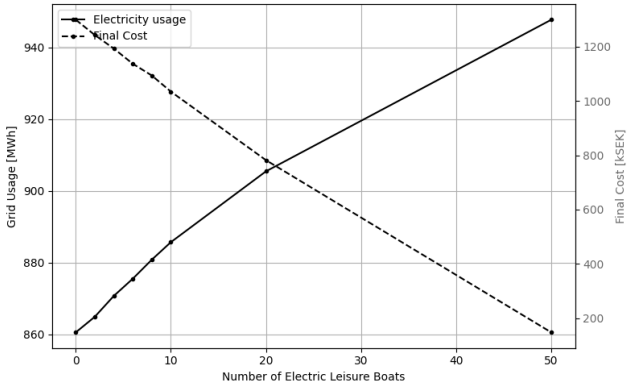
(a) Case 1: peak shaving



(b) Case 2: allowing electricity to be sold at Nord Pool



(c) Case 3: participating in the LFM



(d) Case 4: participating in FCR-D up and down

Figure 23: Comparison of the grid usage and the final cost for all cases in Krossholmen. All the cases are building upon each other, meaning case 2 consist of both peak shaving and selling electricity at Nord Pool etc.

5.2.2 Björkö

When peak shaving is applied, the electricity supplied from the grid can be both higher and lower than the load at different times. However, the maximum peaks are reduced, as illustrated in Figure 24. At some points the electricity supplied from the grid reaches zero, which means that no electricity is supplied from the grid. This is made possible with BESS and electric boats where the batteries may charge electricity when prices are low and then use that electricity to supply the marina when the electricity prices are high.

The diffference in electricity supplied from the grid between the different cases is small, hence why only the case of both PS, allowing electricity sales on Nord Pool and participation in the local flexibility market is illustrated in Figure 24. Additionally power production from solar panels are added, which is reflected in the slightly minimized grid usage during the summer. The total solar power production for a full year adds up to 21.44 MWh, with a peak during the summer, shown in Figure 13b.

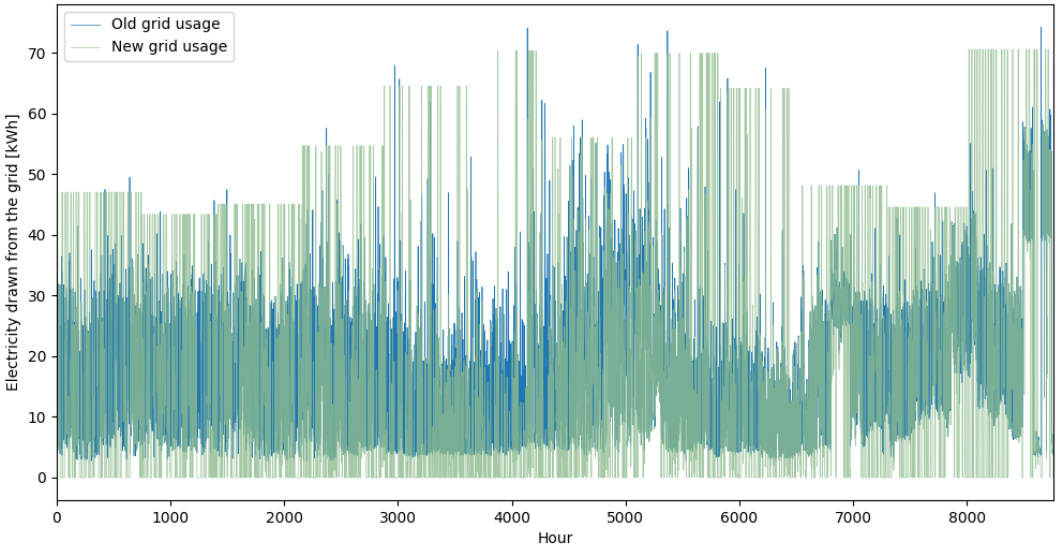
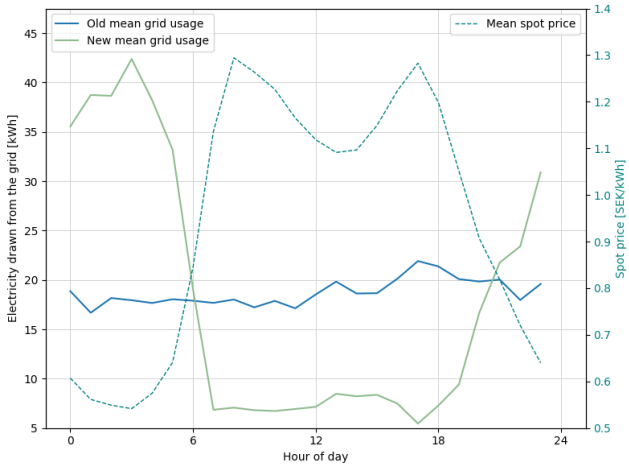
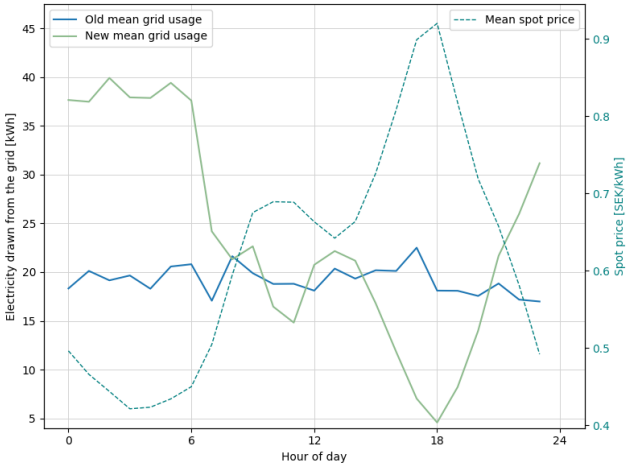


Figure 24: The yearly grid usage in Björkö, after applying the different cases. The new grid usage is shown by the green curve. Peaks have been reduced, and the grid usage reaches zero at several points, as indicated by the green line touching the x-axis.

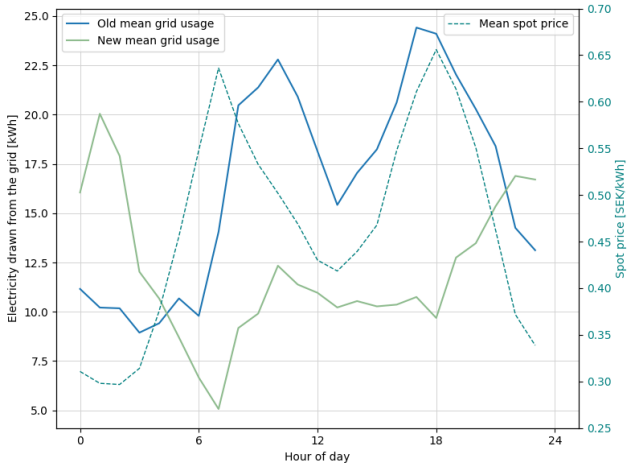
In Figure 25 the average grid usage for a day is presented, divided into average weekday and weekend electricity usage during the winter and summer. The electricity usage profile correlates with the spot price, where the electricity usage is high when the spot price is low and when the spot price is high the electricity usage is low.



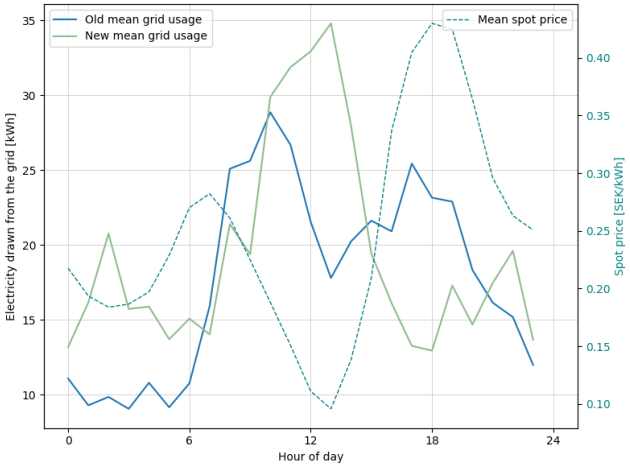
(a) Weekday during winter.



(b) Weekend during winter.



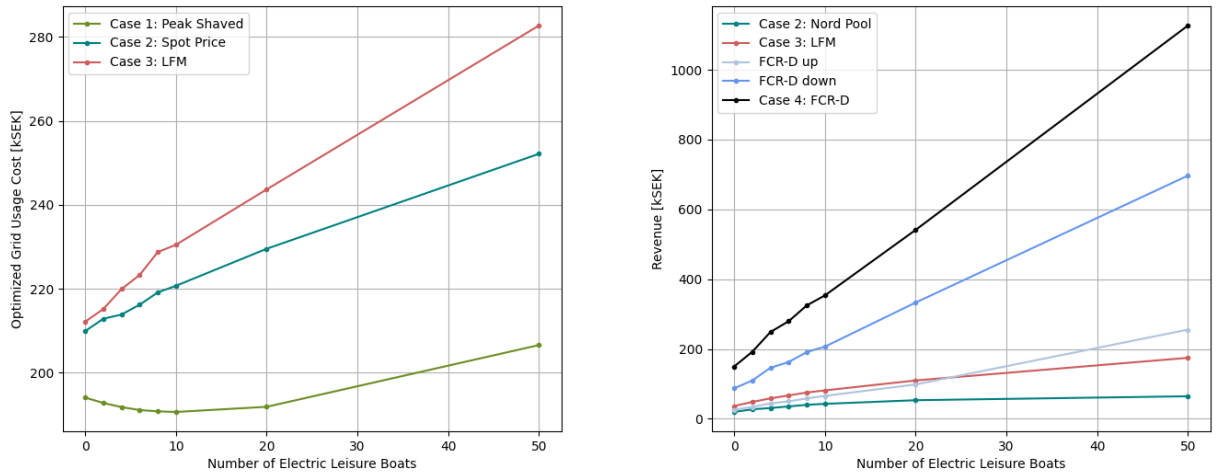
(c) Weekday during summer.



(d) Weekend during summer.

Figure 25: Electricity profile of an average day of the week and weekend for both the winter and summer in Björkö.

When analysing the financial aspects of the different cases, the cost of electricity for the new electricity usage is presented in Figure 26a. The revenue from participating in different electricity markets is presented in Figure 26b, where the revenue is purely the earnings of participation.



(a) Optimized grid usage cost

(b) Revenue

Figure 26: The new estimated cost of electricity and revenue, for the different simulated cases in Björkö.

The electricity throughput is presented in Table 13. In similarity to Krossholmen the electricity throughput is decreasing while the number of boats are increasing, as expected due to more capacity being available. The electricity throughput for boats is calculated as an average value, meaning the values in the table are per boat. No one of the values trespass the maximum electricity throughput for BESS which is between 325-375 MWh and for boats between 60-70 MWh.

Table 13: Electricity throughput forBESS and average per boat, for different numbers of boats simulated in Björkö with all cases applied.

Number of boats	**Electricity throughput BESS [MWh]**	**Electricity throughput boat mean value [MWh]**
0	56.0	0
2	44.6	9.0
4	35.0	8.2
6	32.8	6.5
8	29.4	5.8
10	26.9	5.1
20	20.0	3.5
50	14.0	1.8

Furthermore, the financial costs, savings and revenues may be compared to the reference cost, as presented in Table 14. The reference cost is the cost of the electricity for the reference case with the added cost of charging the electric leisure boats before the trips. The final cost represents the cost of electricity after optimizing the grid usage and subtracting the revenue from this value. When comparing the final cost to the reference cost the total savings after optimizing

the electricity usage is presented. To analyse the total savings per electric leisure boat, a factor of how much the boat batteries support the grid, compared to the BESS, is presented. This factor is then used to allocate the total savings each boat contribute with, in accordanc ewith Equation 14. As presented in Table 14 the total saving per boats minimizes with a large number of boats, even though the final cost minimizes and the boat participation factor rises. The total savings per boat reflect the extent to which each boat battery contributes to cost reduction for the marina and revenue generation through electricity sales on Nord Pool, participation in the LFM, and remuneration for availability in the FCR-D up and down markets.

Table 14: Costs and savings per simulated number of boats in Björkö applying all the cases.

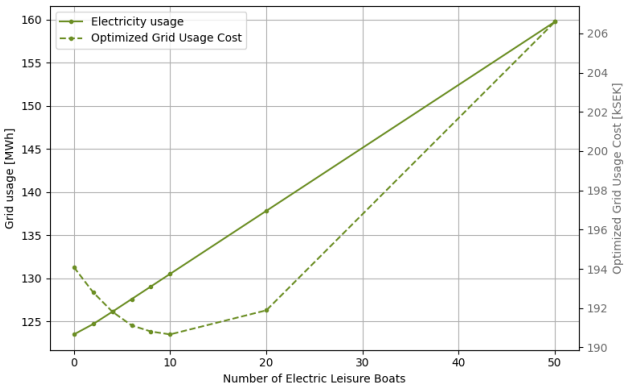
Number of of boats	**Reference cost [kSEK]**	**Final cost [kSEK]**	**Boat participation factor [%]**	**Total savings per boat [kSEK]**
0	264.8	62.3	0	0
2	266.2	23.0	28.7	34.8
4	267.5	-28.8	48.4	35.8
6	268.9	-56.2	54.2	29.3
8	270.3	-96.1	61.3	28.1
10	271.7	-123.1	65.6	25.9
20	278.5	-297.7	77.8	22.4
50	299.1	-844.2	86.6	19.8

In Table 15 the grid usage for the reference case is first presented, illustrating the grid usage for the marina load and the additional load for when electric leisure boats charges before trips. The other result presented in the table is the optimized grid usage, which is the electricity supplied from the grid after applying PS, allowing electricity sales on Nord Pool and participation on the local flexibility market.

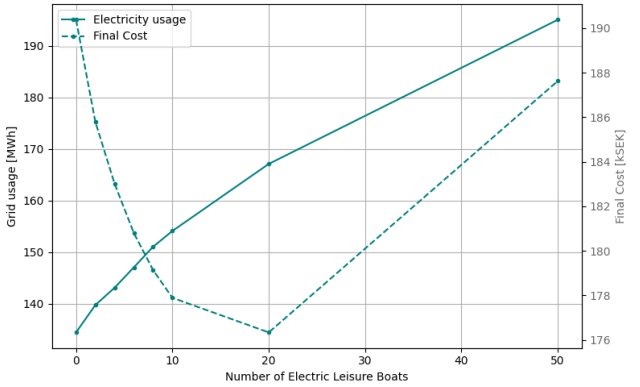
Table 15: The total electricity supplied from the grid, for different numbers of boats simulated in Björkö for case 4.

Number of boats	**Reference grid usage [MWh]**	**Optimized grid usage [MWh]**
0	145.2	138.0
2	146.7	143.4
4	148.3	149.4
6	149.8	153.7
8	151.3	159.1
10	152.9	162.0
20	160.6	178.5
50	183.7	214.4

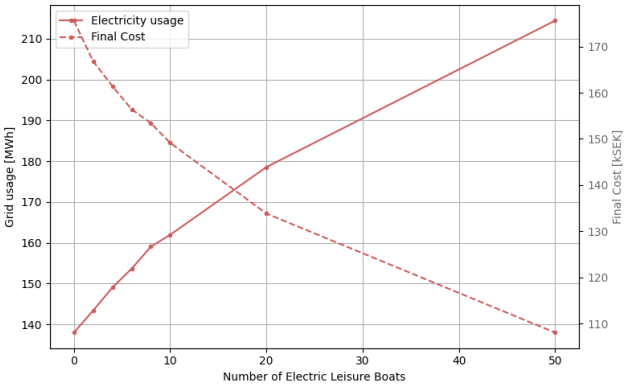
Additionally, the electricity usage is compared to the cost of electricity for all cases, presented in figure 27. For the first case when only PS is allowed, presented in Figure 27a and the second case when both PS and electricity sales on Nord Pool is allowed, shown in Figure 27b, the electricity usage rises with the numbers of electric boats. At the same time, the cost of this optimized grid usage for the first case, and the final cost for the second case is first decreased to then increase with a higher number of electric leisure boats. When analyzing the third and forth case, with simulated participation in the local flexibility market and in the frequency market, presented in Figure 27c and 27d, a difference is observed where the final cost is reduced even with the higher number of electric leisure boats.



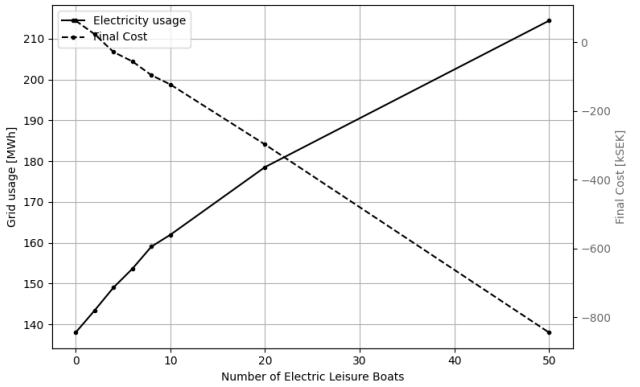
(a) Case 1: peak shaving



(b) Case 2: allowing electricity to be sold at Nord Pool



(c) Case 3: particiapting in the LFM



(d) Case 4: participating in FCR-D up and down

Figure 27: Comparison of the grid usage and the final cost for all cases in Björkö. All the cases are building upon each other, meaning case 2 consist of both peak shaving and selling electricity at Nord Pool etc.

5.2.3 Bessekroken

In contrast to the two other marinas, Bessekroken has a significantly smaller load profile and higher possibilities for PVs. Therefore, when optimizing the electricity usage using all methods in accordance to case 4, illustrated in Figure 28, there is a significant reduction of electricity supplied from the grid. This is due to the amount of self-produced electricity that covers the majority of the demand, especially during summer. The total amount of self-produced electricity is 43.88 MWh solar power and 13.27 MWh wind power and the total load for a full year is 13.1 MWh. For this case a special allowance was made: to allow electricity sales from solar and wind power directly on Nnord Pool when there was a surplus of self-produced electricity, reported in Tables 17 and 18.

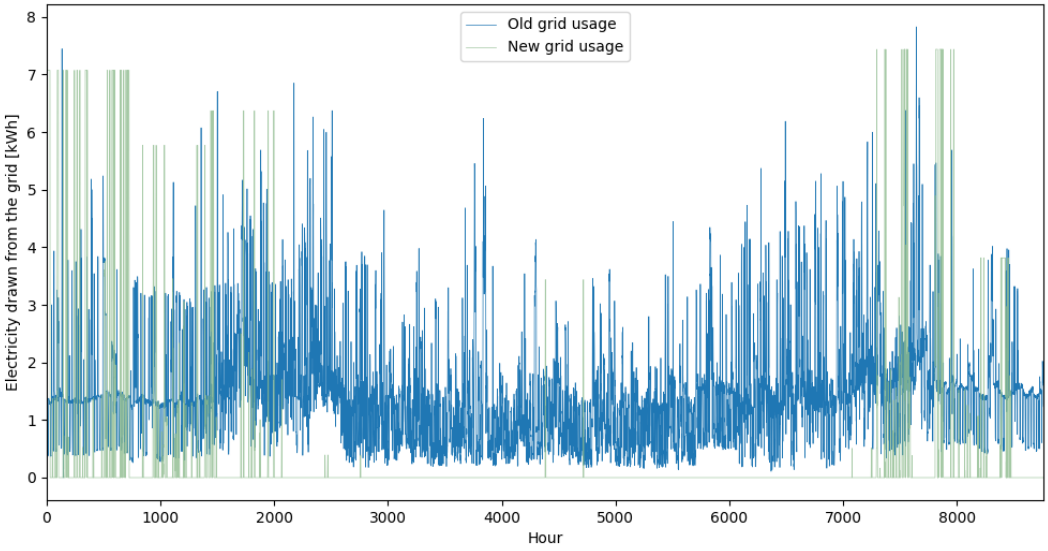
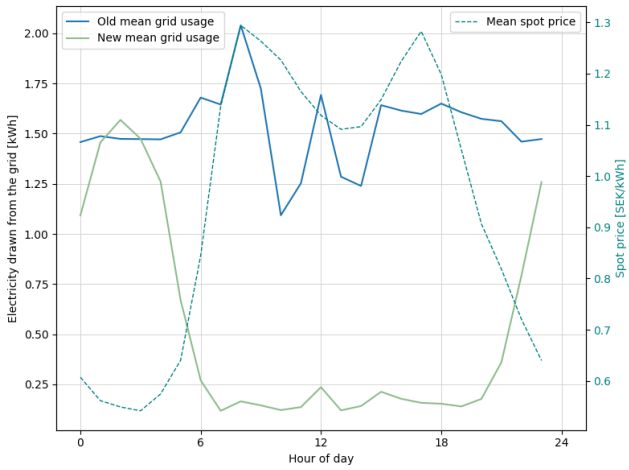
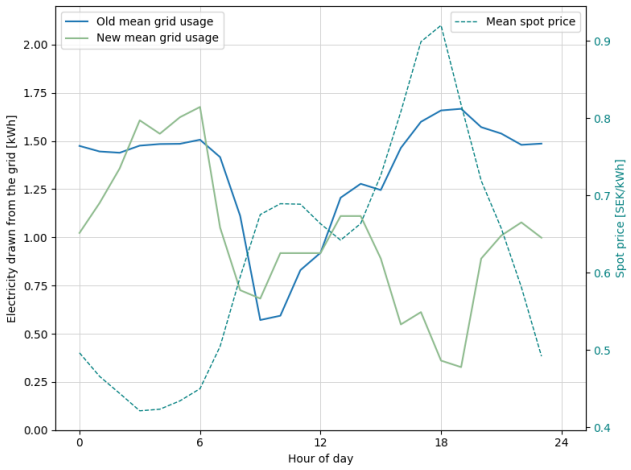


Figure 28: The yearly grid usage in Bessekroken, after applying the different cases. The new grid usage is shown by the green curve. The grid usage has been reduced significantly due to the high amount of self-produced electricity from solar and wind. The grid usage reaches zero at several points, as indicated by the green line touching the x-axis.

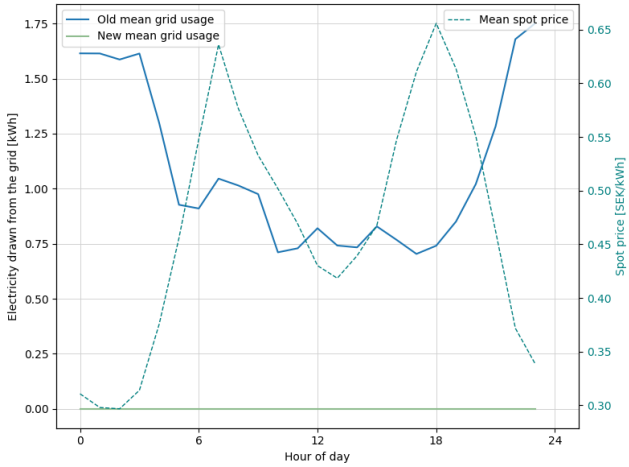
Furthermore, in Figure 29 the average seasonal load for Bessekroken is presented. In Figure 29a and Figure 29c average winter and summer weekday are presented. These graphs indicates the optimization of electricity usage. The new optimized grid usage has shifted and the highest peaks are now when the spot price is the lowest. In line with the other marinas, this is possible due to the utilization of BESS and boats. Similar results are presented in Figure 29b and 29d for an average winter and summer weekend.



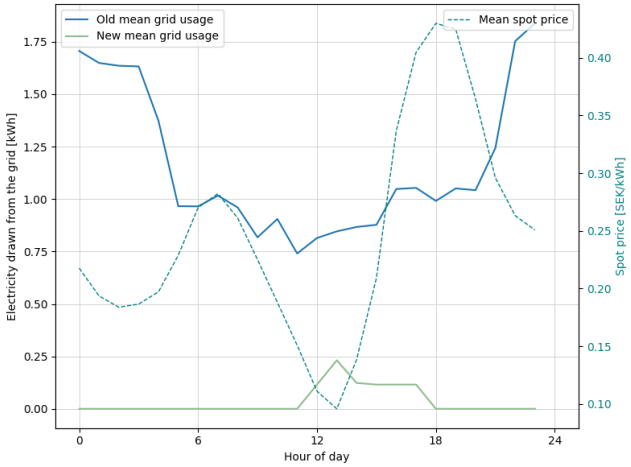
(a) Weekday during winter.



(b) Weekend during winter.



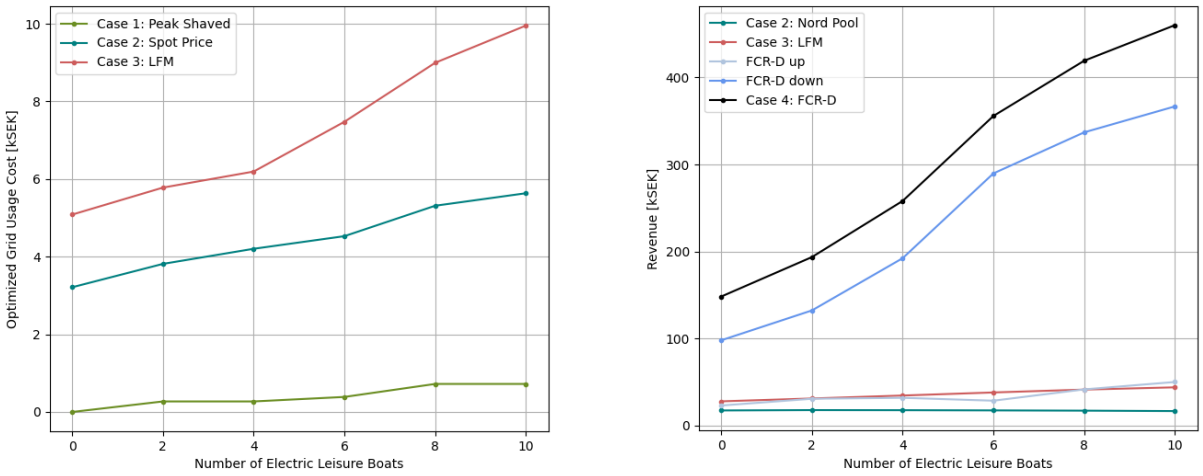
(c) Weekday during summer.



(d) Weekend during summer.

Figure 29: Electricity profile of an average day of the week and weekend for both the winter and summer in Bessekroken.

In Figure 30 the optimized grid usage cost and the solely generated revenue with the number of boats is illustrated. The optimized grid usage cost, in Figure 30a, is lower than the reference cost, presented in Table 17. However, it increases with an increased number of electric leisure boats. In case 3 the electricity usage increases due to more electricity needed for participating in the LFM and the use of energy arbitrage. In similarity, the electricity usage of Case 2 increases due to the utilized energy arbitrage. More detailed numbers are presented in Tabel 18. The results in Figure 30b indicates an increased revenue with increased amount of electric leisure boats, where FCR-D down generates a significantly higher revenue than the rest of the markets.



(a) Optimized grid usage cost

(b) Revenue

Figure 30: The new cost of electricity and revenue, for the different simulated cases in Bessekroken.

To further analyse the BESS and boat participation in the different markets the electricity throughput has been studied, and the results are found in Table 16. The electricity throughput for BESS decreases while the number of boats increases. This is due to the availability of more capacity to participate in the different markets. The electricity throughput of the boats was calculated as an average value, hence the value is what one single boat charges in average annually. The values in the table do not trespass the maximum energy throughput for the BESS between 325-375 MWh and 60-70 MWh for the boat.

Table 16: Electricity throughput for BESS and average per boat, for different numbers of boats simulated in Bessekroken with all methods applied.

Number of boats	**Electricity throughput BESS [MWh]**	**Electricity throughput boat mean value [MWh]**
0	23.8	0
2	14.3	4.6
4	9.9	3.3
6	9.9	2.2
8	8.2	1.8
10	7.4	1.4

In Table 17 all costs and savings are presented when all methods are applied, hence case 4. In similarity to the other two marinas, a reference cost was calculated, using Equation 17, to compare it with the final cost. To calculate the final cost Equation 13 was used. When comparing the reference cost to the final cost there is a significant reduction of cost, hence the negative sign. In this marina, when participating in all markets, a large revenue is generated. To further analyse the total savings per boat, a boat participation factor was calculated. The total savings per boat, presented in Equation 16, reflect the extent to which each boat battery

contributes to cost reduction for the marina and revenue generation through electricity sales on Nord Pool, participation in the LFM, and remuneration for availability in the FCR-D up and down markets. As mentioned before, for this marina a special allowance was made to sell surplus self-produced electricity directly at the market, the revenue for that is presented in the table as well.

Table 17: Costs and savings per simulated number of boats for Bessekroken, applying all the cases.

Number of of boats	**Reference cost [kSEK]**	**Final cost [kSEK]**	**Boat participation factor [%]**	**Total savings per boat [kSEK]**	**Self-produced electricity sold [kSEK]**
0	24.3	-143.0	0	0	9.5
2	25.6	-187.7	39.0	41.6	9.48
4	27.0	-251.9	57.1	39.8	9.47
6	28.4	-348.3	57.0	35.8	9.45
8	29.8	-410.3	64.0	35.2	9.46
10	31.1	-450.3	66.3	31.9	9.45

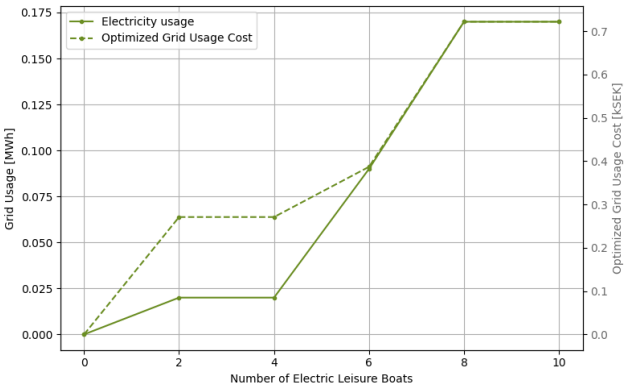
Even though there is a significant reduction of electricity usage there is still some electricity supplied from the grid, which could be seen in Figure 28 but is also presented in Table 18. This is due to the BESS and boat participating in the LFM November to March. Since most of the self-produced electricity is solar power, during winters there is a need for electricity from the grid to participate in LFM. The amount of sold self-produced electricity is presented in the table.

Table 18: The total electricity drawn from the grid, for different numbers of boats simulated in Bessekroken for case 4.

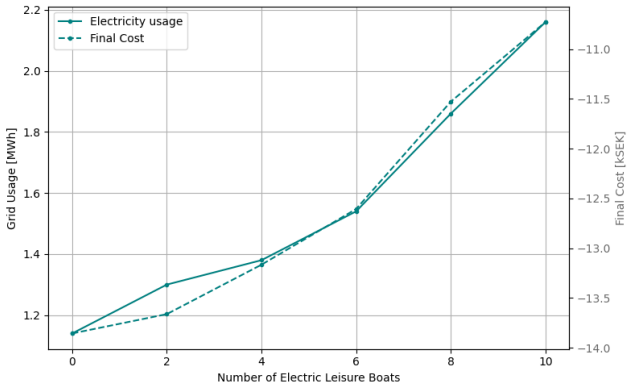
Number of boats	**Reference grid usage [MWh]**	**Optimized grid usage [MWh]**	**Self-produced electricity sold [MWh]**
0	13.1	2.4	24
2	14.6	3.0	23
4	16.2	3.3	23
6	17.7	4.2	23
8	19.3	5.0	23
10	20.8	5.5	23

Lastly, the optimized grid usage was analysed and compared to the cost reduction. This is presented in Figure 31. For case 1 the optimized grid usage was compared to the optimized grid usage cost due to the case not generating any revenue. For the rest of the cases, the optimized grid usage was compared to the final cost. For case 1 and 2, see Figure 31a and Figure 31b, the cost increases with the increased amount of electric boat as well as the grid

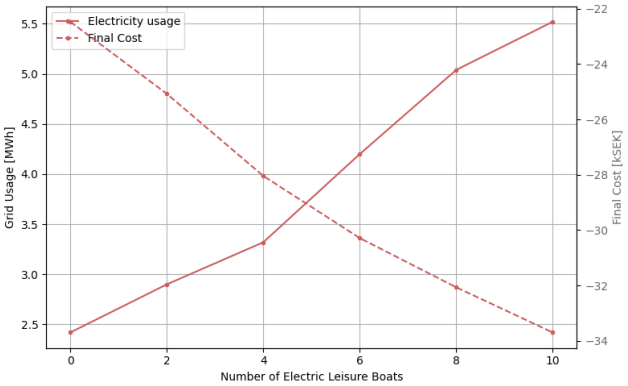
usage. In the two last cases, see Figure 31c and 31c, the final cost decreases with the increased amount of electric leisure boat while the grid usage increases.



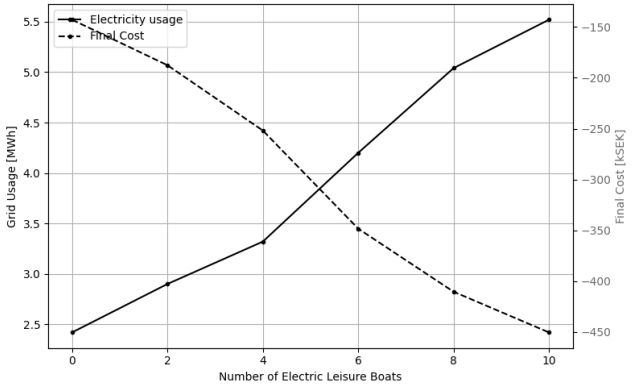
(a) Case 1: peak shaving



(b) Case 2: allowing electricity to be sold a Nord Pool



(c) Case 3: particiapting in the LFM



(d) Case 4: participating in FCR-D up and down

Figure 31: Comparison of the grid usage and the final cost for all cases in Bessekroken. All the cases are building upon each other, meaning case 2 consist of both peak shaving and selling electricity at Nord Pool etc.

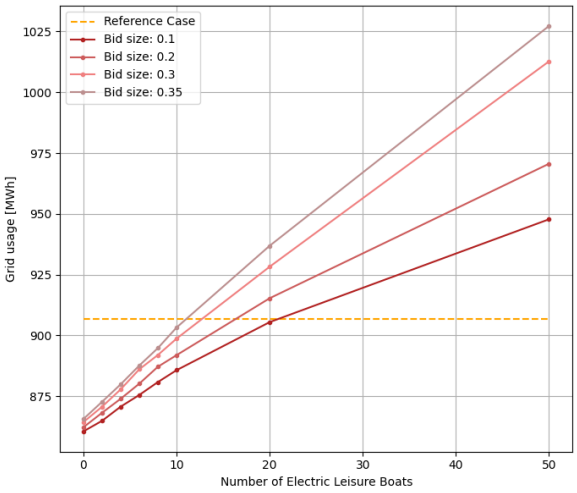
5.3 Sensitivity analysis

The result of the sensitivity analysis is presented in the following section, where the bid size $P_{bid,LFM}$ was the changed parameter. Initially 10% of the capacity was set as bid size, see Equation 12. Subsequently, 20%, 30% and 35% of the capacity were set as bidsize when simulating the sensitivity analysis. Since the bid size of the local flexibility market was the changed parameter only case 3 is studied in the sensitivity analysis.

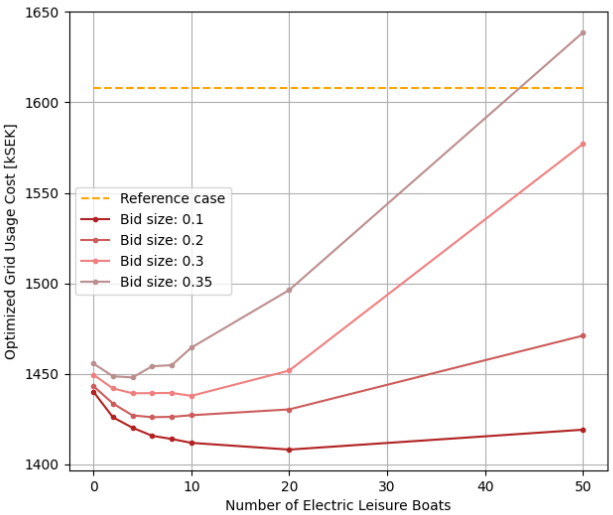
5.3.1 Case 3: Effekthandel väst

In Figure 32a the optimized grid usage in case 3 is presented with the respectively different sizes of bids. The dashed yellow graph presents the reference case, meaning the initial grid usage. When changing the bid size placed at the LFM there is a significant change in grid usage. Notably for simulation with 20 and 50 electric leisure boats where the grid usage is higher than the initial. Furthermore, the optimized cost of grid usage with the various sizes of bids is presented in Figure 32b. In similarity to Figure 32a the dashed yellow graph in Figure 32b presents the initial cost of grid usage. The first notable observation is the cost simulated for 50 electric leisure boats with a bid size of 35% which has a higher cost than the initial cost.

The second observation is the reduction in grid usage cost when adding electric leisure boats to the simulations. This is due to the higher capacity in the system being able to participate in the markets. However, when simulating for 20 ad 50 electric leisure boats for all different bid sizes the grid usage cost increases.



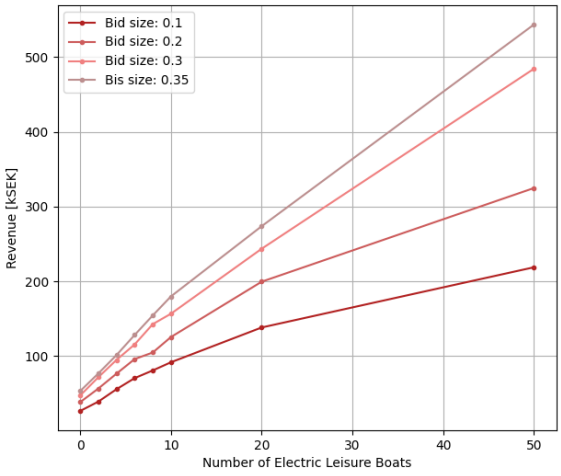
(a) Optimized grid usage



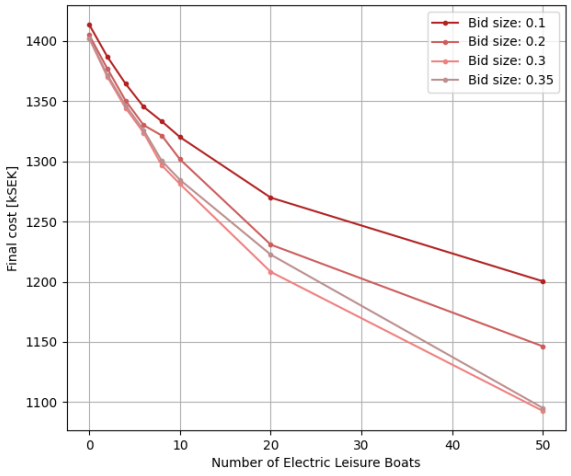
(b) Optimized grid usage cost

Figure 32: The optimized grid usage and optimized grid usage cost simulated for case 3 with different sizes of bids.

Furthermore, the revenue and final cost with the different bid sizes are presented in Figure 33a and 33b. When changing the bid size the generated revenue increases, as expected, and the final cost reduces. However, there is a significant increase of revenue and final cost when changing the bid sized from 10% of the capacity to 35%.



(a) Revenue



(b) Final Cost

Figure 33: The generated revenue and final cost for case 3 with the different sizes of bids.

Figure 34 represent the hourly grid usage at Krossholmen for case 3, when the bid size is 35%

of the capacity. One major observation is the large peaks in the beginning of the year and at the end of the year.

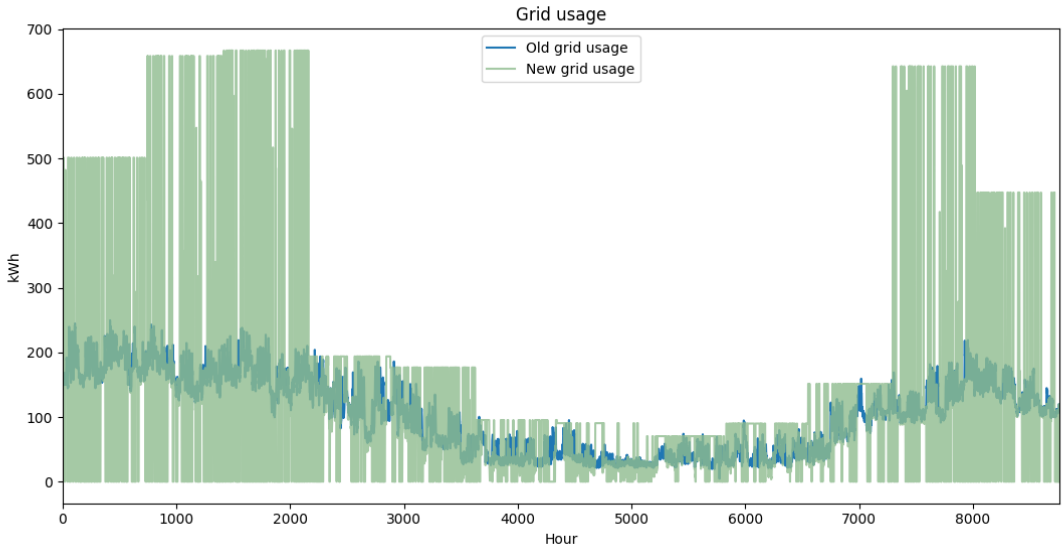


Figure 34: The yearly grid usage in Björkö, after applying the different methods and with a bid size of 35% of the capacity simulating for 50 boats.

6 Discussion

In this Section the chosen method, presented in Section 4, and the given results, presented in Section 5 will be discussed.

6.1 Discussion About the Chosen Methodology

The model is based on data from 2023, which implies that if data from another year had been used, the outcome would likely have varied. As all simulated marinas in this thesis are located in Gothenburg, the retrieved weather data was from monitoring stations in the Gothenburg area. Applying the model and simulating for a marina located elsewhere in Sweden, the weather data would be needed to change. Another relevant aspect to consider is the battery size of the BESS, boats and B2G-charger which are set to 533 [kW], 100 [kW] and 60 [kW]. Although the model is capable of adjusting the capacity of the batteries and the rate of the charger, in this thesis these values are fixed, meaning the same values are used for all simulations. It is important to note that different values for the battery capacity and charge rate could influence the outcome of the simulation.

In addition, the usage pattern of the electric leisure boats in the model is based on results from a master's thesis that was a pre-study to this thesis [14]. Had a different usage pattern been implemented in the optimization model, the outcome would be different. These assumptions were necessary to be able to continue with the project and since the assumption were based on a pre-study to this thesis, the assumptions were considered reasonable. Additionally, three different boat usage patterns were developed, where the starting day of the longer trip varied, to get some variance of the boat trips. However, these assumptions do not reflect reality and the usage pattern of a leisure boat is more random. There are many factors that decide if an individual uses its boat, such as weather, the boat owners' availability, and money.

The primary objective of the simulation model is to minimize the cost of electricity, which is successfully achieved. The electricity supplied from the grid for every case was optimized to lower the cost of electricity compared to the reference case. However, the degree of cost reduction varied across cases, indicating different levels of successful optimization. One example of this was the addition of the ability to sell self-produced electricity directly to the grid, which was needed for Bessekroken. When adding this constraint, the optimization model opted to sell self-produced electricity for all the marinas, even when doing so increases electricity needed from the grid and costs for Krossholmen and Björkö (Increases?). This behavior indicates a potential weakness in the model's ability to find the most cost-effective solution.

Moreover, the optimization model was found to be more effective when optimizing the grid usage based on the spot price, rather than minimizing the peaks. Therefore a limitation of the peaks was introduced as a penalty for drawing more electricity than 95% of the original peak level. This constraint was intended to ensure that some degree of peak shaving was achieved. This limit could have been set to a lower level, to achieve a stronger peak shaving.

During optimization code development, it was essential to add the ability for the batteries to charge directly from the grid, making sure that the required SOC could be reached. The addition was essential to make sure that the required SOC was reached for the times when bids were placed on the LFM. However, when applying only this constraint, the model disproportionately prioritized charging the batteries from the grid. To mitigate this behavior, a cost of battery cycling was introduced, which slightly limited this overuse of charging from the grid. A further limitation was included, allowing a maximum of only 10% of the batteries capacity to charge from the grid for every hour. This served as an additional limitation to ensure that the model

operated in a more realistic manner.

It is also worth noting that the electricity drawn from the grid serves two purposes: meeting the marinas load demand and charging the batteries. The distribution between the load and the batteries is determined by what the solver for the optimization model finds is the best solution, according to the objective function. No prioritization was added for this constraint, but this is an area for future studies to continue with.

In order to model participation in the LFM market, certain assumptions were necessary. It was assumed that all bids were accepted and placed between 07-09 in the morning and 17-19 in the evening every second week and that 13% of the bids were activated. While this simplification enables modeling participation in the market, the actual dynamic of the market is not presented. These assumptions hides the complexity of the market which must be taken into consideration when evaluating the result. Another assumption regarding the LFM is the bid size. The bid size is set to 10% of the capacity to ensure that there is sufficient capacity which meets the requirement of minimum bid size. Two hours before the bids are placed, the batteries start charging. The capacity is then reserved for the purpose to participate at the LFM, meaning the batteries are not available for PS or energy arbitrage. This is a strict constraint in the model that must always be satisfied, and this means the model may skip certain actions, such as PS, in order to comply with it.

Furthermore, only owners of flexibility resources and operations with high electricity demand within the electricity area Gothenburg can participate in this market. This is not the case for Bessekroken and Björkö, since their location is oustide of the electricity area. However, it was still considered valuable to simulate their participation in the LFM to explore how such a market could function in the future at the island of Björkö.

In case 4 it is important to note that the model was not designed to optimize participation in the FCR-D up and down market. Instead, availability in BESS and boats was analyzed after electricity usage had already been optimized in case 3, which includes PS, electricity sales to Nord Pool, and participation in the LFM. The assumption was necessary due to limitations of the optimization model. When trying to integrate FCR-D participation directly into the optimization, the problem became non-linear and could not be solved efficiently. In consultation with the supervisor at Volvo and representatives from Varberg Energi, one reasonable workaround was to evaluate the availability of BESS and boats post-optimization, assuming that no bids would be activated in the FCR-D market based on low activation rates from historical data.

The assumption that no FCR-D bids are activated was considered reasonable due to the relatively low activation rate observed in practice. However, it must be acknowledged that this does not always hold true in reality. Similarly, the model assumes that all placed bids are accepted, which also simplifies the complexities of actual market dynamics. The FCR-D market is weather-dependent and closely tied to fluctuations in renewable electricity production, making it difficult to predict the exact need for ancillary services. By assuming full bid acceptance and no activation, the model suggest a theoretical maximum revenue from FCR-D participation. Assuming full bid size acceptance was considered acceptable, especially due to the low bid volumes simulated for most cases, it becomes more questionable at higher bid sizes. When simulating scenarios with 20 or 50 electric leisure boats, the resulting bid volumes become quite large.

The FCR-D down market is also a relatively new market and has not yet matured, meaning the prices are relatively high in the beginning. As mentioned in the beginning, the model has been simulated with data from 2023, except for FCR-D up and down, for which data from 2024

were chosen due to the high prices in 2023. This assumption was thought to be reasonable since prices in the FCR-D down market will decrease in time when the market matures.

Lastly, it should be emphasized that the optimization model relies on the availability of historical data for self-production, spot prices and the marinas load. But in reality, such data is not always available. However, there are ways to predict these numbers with forecasts and historical data. For example, spot prices become available one day in advance, making it difficult to determine far ahead how the battery should be best utilized. Nevertheless, the aim for this masters thesis has been to investigate the opportunities with B2G rather than to predict future opportunities. Thus, the model presents an insight to the potential of B2G-implementation.

6.2 Simulation Results

This section will analyze and discuss the validity of the results given from the simulation model. Results given will be discussed based on comparison between the numbers of boats simulated and the different bid sizes placed on the LFM.

When utilizing BESS and electric leisure boats in the marinas, the electricity supplied from the grid changes significantly. Notably, the highest peaks are reduced, which can be seen for all cases in Figures 20, 24 and 28. Despite the reduction in peak demand, both Krossholmen and Björkö experience maximal consumption levels on numerous occasions. Additinally, the results illustrates that the electricity supplied from the grid reaches zero multiple times. This occurs when the batteries are capable to supply the marina with electricity or when there is enough power from self-production to supply the marina with electricity. During the summer, Krossholmen and Björkö experience a slight decrease in the electricity supplied from the grid, due to the power production from solar panels and wind turbine. For Bessekroken, the electricity drawn from the grid is almost non-existent during the summer months due to the high production of solar power. Due to the high solar production i Bessekroken, some electricity is directly sold to the grid and in Table 18 the excess solar power production that is sold to the grid is presented.

From Figures 21, 25 and 29, presenting the average elecitricy usage of a winter and summer weekday as well ass weekend, it is clear that adding batteries both in form of a BESS and electric leisure boats allows an optimized electricity usage from the grid. The estimated grid usage is higher when the spot price is low, and the opposite for when the spot price is high. The reason for this is the basics of the model, the objective function, where the goal is to lower the cost of electricity. By using batteries, the marina is able to avoid buying electricity when prices are high and instead charge the batteries when electricity is cheaper. There are two figures that differs from the rest, which is Bessekroken during the summer, presented in Figure 29c and 29d. Since Bessekroken has a high self-production compared to the marinas load, during the weekdays no electricity at all is needed from the grid, and for the weekends some electricity is supplied from the grid, when the boats are unavailable. Therefore, a smaller battery capacity is available to supply the marina with electricity and a slight demand for electricity from the grid arises when the boats are unavailable.

The results in Figures 22, 26 and 30 indicate that there is an increased revenue with increased numbers of leisure boats. The new cost of electricity however, increases with an increased number of electric leisure boats in Björkö and Bessekroken but not in Krossholmen, where it is minimized. In Björkö, for case 1 when applying PS, the new cost of electricity reduces in the beginning but increases for more than 10 boats. This is due to the fact that there is a greater demand for electricity when charging more than 10 boats in the marina. When comparing Bessrekroken with Björkö, for case 1 when only PS, the new cost of electricity always increases

with increased amount of electric leisure boats. This is due to the fact that Bessekroken has significantly higher self-produced electricity and smaller load profile. Therefore, when adding boats to the simulation of case 1 the grid usage increases to support the increased demand. For case 2 and 3, when selling electricity at Nord pool and participating in the LFM, the new cost of electricity increases for all simulated boats in Björkö. When participating in the LFM, hence case 3, this occurs as a result of charging all the boats to meet the requirements for placing bids in the market. Since the model is based on placing 10 % of the capacity, the bid size becomes quite large when simulating for 50 boats, hence the increased grid usage and higher costs. Similar arguments can be used for Bessekroken when analyzing the new cost of electricity in Figure 30a.

When further analyzing Figures 22b, 26b and 30b, presenting the revenue for participating in the different markets, the revenue from FCR-D down is significantly higher then the rest of the generated revenues. This is due to the market being introduced in 2022 and not matured, meaning the prices are higher compared to FCR-D up, which has existed longer. However, it is important to note the ongoing discussion about potential future market saturation, likely driven by large-scale BESS and wind power, which could lead to decreased prices in both markets.

Furthermore, the electricity throughput for the BESS and boat, presented in Tables 10, 13 and 16, is analyzed. The result indicates that the electricity throughput never trespass the maximum electricity throughput. This means that the capacity of the batteries are not fully used in regard to battery health and have the potential to be used further.

In Tables 12, 15 and 18, the electricity supplied from the grid for the reference case is compared to case 4. There is a main difference between the reference case and the new grid usage, which is the self-production of wind and solar power. Hence, electricity delivered to the marina is not only the electricity supplied from the grid, but also the electricity produced by solar panels and wind turbines. With a smaller number of boats, the electricity supplied from the grid is lower, but as the number of boats rises, the electricity supplied from the grid rises to supply the electric boat batteries need to charge before trips. Another reason for the increased use of electricity from the grid with a higher number of boats is due to the need for charging the batteries as well as not use the energy in the batteries when bids are placed on the local flexibility market.

Figures 23, 27, and 31 indicate that in most cases, the final cost decreases as grid electricity usage increases, however, there are a few exceptions to this trend. The first one is the case of peak shaving in Björkö, presented in Figure 27a where the cost of electricity rises with the addition of more than ten boats. The reason for this is that a higher number of boats results in a higher demand of electricity, such that at a certain time, the demand for electricity exceeds the savings generated by peak shaving and therefore, the cost increases. For the case of allowing electricity sales on Nord Pool for Björkö, presented in Figure 27b, the presence of more than 20 boats leads to an increase of the final cost. This is due to the high number of boats and additional the electricity demand from the electric leisure boats, resulting in an additional cost of electricity, that the savings from peak shaving and revenue from sold electricity cannot offset, thereby generating a higher final cost. For the corresponding cases for Bessekroken the final cost also rises as the number of boats increases, presented in Figures 31a and 31b. The reason for these cases is that the cost of electricity required to charge the boats exceeds the savings from optimizing the grid usage with fewer boats and the revenue generated from selling electricity on the spot price market.

To further analyze the result, Tables 11, 14 and 17 can be studied. It is notable that all the marinas costs are reduced. For Krossholmen there is always a cost of electricity due to the high electricity usage but it is significantly reduced. For Björkö and Bessekroken the final cost is negative, meaning the marinas are profiting in participating in the different markets. Moreover,

the total savings per boat was calculated. These results align with numbers given from Varberg Energi, where they have estimated that a boat can generate 60,000 SEK in revenues per year. The results in this thesis are slightly lower due to the boats being limited in their ability to participate in the markets during the summer, when they are used for leisure purposes. When further analyzing costs and saving in Bessekroken, see Table 17, there is an even more significant reduction of final cost and the marina generates the highest profit compared to the other two other marinas. As discussed before, this depends on the small load profile and high self-produced electricity. Table 17 also presents the amount of sold self-produced electricity; this is not included in the final costs and savings, meaning that the marina could profit even more if these were added.

It is important to highlight that the code is unable to find an optimal solution for more than ten boats for Bessekroken. Since the maximal allowed electricity supplied from the grid for Bessekroken is 13.8 kW which limits the possibility to charge more than 10 boats before the planned trips.

Lastly, the sensitivity analysis indicates that the choice of bid size in the LFM significantly affects the results. Especially when changing the bid size from 10% of the capacity to 35%. In Figure 32a there is a notable difference in utilizing electricity from the grid compared to the bid sizes when simulating 20 and 50 boats. All bid sizes except 10% of the capacity are greater then the grid usage in the reference case. This can be explained with the hard constraint, mentioned above, forcing the batteries to charge the needed capacity for participating in the market. This can further be analyzed in Figure 34. In this figure one can see the high peaks in the beginning and at the end of the year, when the LFM market is open. This result indicates uncertainties of the model when simulating for a larger bid sizes with an increased amount of electric leisure boats.

6.3 Ethical and Sustainability Aspects

The transition from traditional combustion engines to electric motor boats contributes to the reduction of GHG emission. However, the use of electric leisure boats also involves some less sustainable aspects. For instance, there are some concerns regarding extraction of lithium and cobalt which are two key components in batteries. First of all, lithium and cobalt are scarce resources, meaning they are geographically limited. When the materials are extracted in other countries, specifically in developing countries, there are some ethical concerns regrading human rights. Second of all, large amount of energy is required to extract the material but also to produce batteries and if renewable energy is not used there is concern regarding the environmental sustainability. Lastly, if the electric leisure boats are charged with an electricity mix consisting of majority fossil fuels and not renewable this is also an environmental concern, thus this is not the case in Sweden. Regarding the three concerns mentioned above, it is of importance that the production of batteries are produced sustainable throughout the whole supply chain, meaning suppliers must fulfill strict requirements from Volvo.

From a local point of view, electric leisure boats reduce underwater noise, meaning marine life will not be negatively affected compared to traditional combustion engines. In addition to marine ecosystems, people living near marinas or waterways also experience less noise disturbance. Furthermore, the electric leisure boats reduce hazardous emissions.

However, purchasing electric leisure boats are costly today and boats with traditional combustion engines are often the cheaper choice. But, by utilizing B2G and participate in various markets a revenue can be generated. This creates incentives for individual to purchase an electric leisure boats, as well as reducing fuel costs to zero. Despite this, a notable concern

exists, if the marinas will profit on utilizing their customer's electric boats or if the customers themselves receive all the profit. Boat owners pay a fee to the marinas for them to winter store their boats, but it is the customer who purchase the electric boat. To make it more justifiable the boat owners should be able to take part of the profit somehow, but at the same time also the marinas due to them making sure the boat batteries can be utilized with B2G. In this thesis, the marinas receive all the profit which is something that could be reevaluated.

6.4 Limitations and Uncertainties of the Model

Limitations for how much the batteries may charge from the grid at every hour limits the possibility of fast charging. This gives an unrealistic presentation of how the batteries may charge, and therefore presents an uncertainty for the results simulated.

Regarding the peak shaving for the code, the grid usage often reaches the maximum or minimum levels, which is either 95% of the peaks reached for the reference case, or zero. This results in a grid usage quite different from the reference case, whether this is the most optimal solution or not is unclear. But the optimization solver seems to promote a usage at the extreme levels, i.e. maximal or minimal. Additionally, the code never peak shaves more than the limit that is penalized, even though this would result in a lower cost, minimizing the reliability of the simulation model.

LFM simulation may have contributed to potential inaccuracies. As mentioned in Section 6.1 assumptions had to be made which can have impacted the result. Furthermore, the sensitivity analysis indicates that there are uncertainties of the model when simulating for a larger bid size with an increased amount of electric leisure boats. This is due to the hard constraint when charging the batteris for participating in the LFM market. As mentioned throughout the discussion one notable uncertainty is dynamic mechanisms of the LFM market and FCR-D market.

6.5 Future Studies

The problems with the optimization model gives a few interesting aspects for future studies. One is to change the solver to a more advanced solver that would be able to have a better overview of the full year and then find better solutions. Especially interesting would be better solutions regarding charging the batteries, so that limitations to not overuse the batteries does not have to be applied. Another interesting area would be the peak shaving and to analyze how the grid usage would change when changing the solver. A further observation regarding the optimization model is that when the costs are high, the solver finds peak shaving important, but with a lower electricity usage, the importance of selling electricity to the grid is higher. For instance, the simulated results for Krossholmen shows a higher final cost for case 2 than case 1 when simulating 50 boats, but the possibility of only peak shaving for case 2 still exists. Switching to a more advanced solver might have found more reliable results.

For this masters thesis the battery degradation has only been taken into account for as a cost of charging and discharging the batteries. Future studies on degradation connected to different SOC-levels and degradation specific to charging, discharging or idle would not only produce more realistic results but also present a more sustainable approach of adding batteries to a marina.

Lastly, it would be of interest in the future to study the participation of other ancillary services such as FCR-N. Due to limitation of the optimization model, this was something that was chosen to be excluded from the thesis. When simulating all the different cases, they were build

upon each other, meaning in case 3 PS, selling electricity at Nord pool and participating in LFM were included. Due to this, it makes it more difficult to compare the cases to each other. Therefore, it would have been of interest to allocate the different methods and only simulate one market at a time. Furthermore, when the electric leisure boats are charging, no smart charging is modeled. For future studies, it would have been interesting to examine how smart charging could contribute to i.e. PS when for example simulating a marina with 50 electric leisure boats.

7 Conclusions

In this section, the thesis research questions are addressed, and conclusions are drawn based on the findings.

The findings of this thesis indicate that B2G integration has the potential to generate revenue. When PS is introduced, the electricity supplied from the grid changes significantly. Costs are reduced by shifting consumption to periods with low spot prices and utilizing stored battery electricity when prices are high. Adding the ability to sell electricity on the Nord Pool spot market generates additional revenue; however, it also leads to a slight increase in both grid usage and electricity costs. In summary, optimizing for PS and energy arbitrage forms a strong foundation for generating revenue while at the same time reducing electricity use in the marinas.

When participation in the LFM is included, electricity consumption increases slightly, as the batteries must be charged in advance to enable bidding. Nonetheless, this added service contributes positively to the overall economic outcome. Finally, integrating participation in the FCR-D market results in a significant increase in revenue. When all markets are added in the simulation, hence case 4, the total saving per boat is between 40,000-20,000 [SEK] which aligns with numbers given from Varberg Enerig where it is estimated an electric leisure boat can generate 60,000 [SEK] per boat and year. The electricity throughput never exceeds the maximum limit, indicating that the full battery capacity is not utilized in the simulation. However, there are several observations regarding these results that need further discussion.

First of all, to model the participation in the LFM as well as FCR upward and down several assumptions had to be made, which may have contributed to potential inaccuracies. Additionally, important market mechanisms are not captured in the model due to simplified assumptions, such as the complexities of market dynamics. Moreover, the result is notably weather dependent meaning if another year of data had been used when simulating, the outcome would have varied. All input parameters—such as solar irradiance, wind speed, spot prices, and prices for the LFM as well as FCR-D up and down—are affected by weather conditions. Second of all, the model is based on historical data and the development of the market in the future is always an uncertainty. However, it is expected that there will be an increased demand for flexibility in the power grid in the future, due to the rapid expansion of RES in the power system. Lastly, constraints in the model need to be taken into consideration when evaluating the results.

The results indicate that larger marinas benefit more from having a higher number of connected boats. In contrast, smaller marinas do not gain as much from scaling up B2G participation, as they may lack both the demand and the infrastructure capacity to fully utilize the flexibility offered. However, determining an optimal number of electric leisure boats for the marinas would require further studies.

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A Bilaga 1

Table 19: The power output of the wind power plant for different wind speeds

Wind speed [m/s]	Power output [kW]
2	0.1
3	0.2
4	0.35
5	0.5
6	0.8
7	1.3
8	2
9	2.7
10	3.7
11	5
12	6
13	6
14	6
15	6

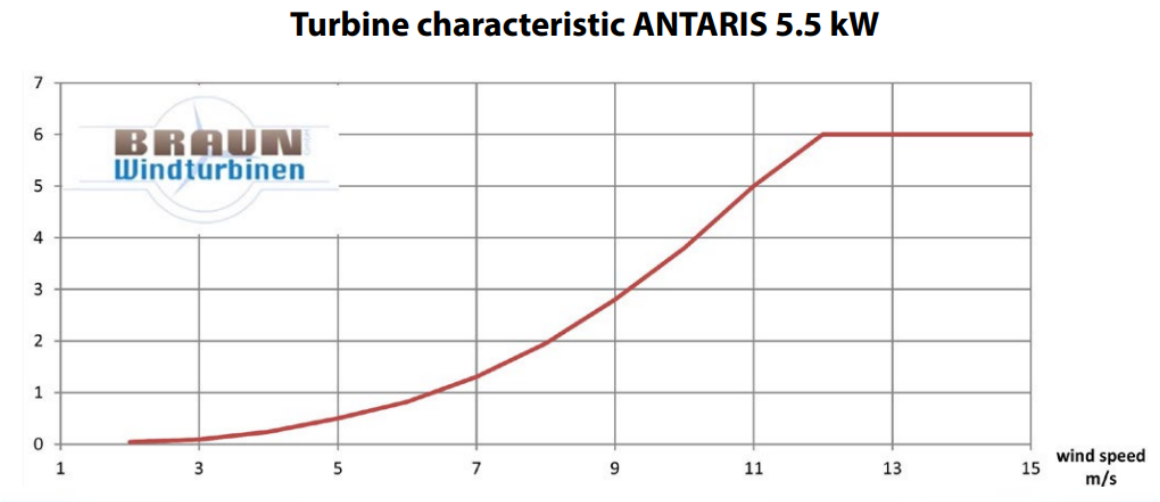

Figure 35: The wind turbine power curve

B Bilaga 2

Table 20: The power output of a daily boat trip

Operation	**Time [min]**	**Power output [kW]**
Un-docking	1	-3
Harbor Exit	3	-5
Slow Speed	2	-15
Top Speed	3	-150
High Speed Transit	19	-80
Watching Wildlife	90	-10
High Speed Transit	21	-80
Slow Speed	2	-15
Harbor Entrance	3	-5
Docking	1	-2