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Energy system analysis of Volvo Penta's micro grid with optimized battery storage

An energy analysis of the micro grid test-site Krossholmen

Master thesis project report in the Programme Sustainable energy systems

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Cover: Krossholmen test site from above.

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Abstract

This thesis investigates the integration of battery storage solutions within marine micro grid environments, focusing on the Krossholmen test site operated by Volvo Penta. A systematic literature review employing integrative and meta-analysis approaches establishes the theoretical foundation, covering topics such as linear optimization, energy-systems modeling, and future energy scenarios. Detailed descriptions of the Krossholmen micro grids technical specifications, including demand profiles and energy system components, are documented to facilitate accurate modeling. Future energy scenarios, reflecting variations in electricity markets and renewable energy adoption, are developed to assess the effectiveness of battery energy storage solutions under different conditions. Linear optimization techniques, implemented through Python-based modeling modules, are utilized to determine the optimal operation of the micro grid. A minimize-cost objective function, incorporating various constraints, guides the modeling process, with provisions to incorporate non-linear data, such as battery degradation, in later stages. The project encompasses seven major milestones, each aligned with specific deliverables, ensuring the project's successful execution within the allocated timeframe. Through this comprehensive approach, the thesis contributes to advancing understanding and practical applications of battery storage within marine micro grid contexts.

Keywords: Microgrid, Energy Storage, Solar PV, Wind turbines, Electrification, Electrical motor boats, Test site

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I want to especially thank my two supervisors, David Steen - researcher within Electric Power Engineering at Chalmers University and Rickard Stefanson - Chief Engineer Site Management for Krossholmen, who have helped me throughout this work. David has been provided a lot of knowledge within the energy modeling field which has been instrumental for the progress of this thesis. Rickard have helped guide me through the organization at Volvo Penta and introduced me to the ongoing development at Krossholmen. I would also like to thank the development team out at Krossholmen, Gustaf, Fredrik, Aniko and Simon, for welcoming me to their review meetings and answering all my questions about Krossholmen. Lastly I would like to thank my fiance Hannah for always standing at my side and supporting throughout this work as well as taking care of the puppy while I finish writing this thesis. Thank you all!

Jonathan Sjölander, Gothenburg, 2024

List of Acronyms

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

BES	Battery Energy Storage
DOD	Depth of Charge
ES	Energy System
LP	Linear Programming
MILP	Mixed Integer Linear Programming
MPRESS	Volvo Penta's prototype battery storage container
PV	Photovoltaic
RES	Renewable-based Energy Sources

Nomenclature

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

Sets

$t \in \text{hours}$ Set of time periods in hours during a year hour

Parameters

C_{\max}	Maximum battery capacity	kWh
C_{initial}	Initial battery capacity	kWh
Ch_{rate}	Maximum charge rate of the battery	kW
Dch_{rate}	Maximum discharge rate of the battery	kW
k^{calendar}	Calendar aging coefficient	-
k^{cycling}	Cycling aging coefficient	-
E_a	Activation energy	J/mol
R	Universal gas constant	J/(mol · K)
θ	Temperature	°K
η^{bat}	Battery efficiency	%
η^{boat}	Boat battery efficiency	%
Av_t	Availability status at time t	binary value (0 or 1)
P_{\max}^{diesel}	Maximum diesel power capacity	kW
P_{\max}^{grid}	Maximum grid power capacity	kW
π_t	Grid power price at time t	\$/kWh
π^{diesel}	Diesel power price	\$/kWh
P_t^{wind}	Wind power at time t	kWh/h
P_t^{solar}	Solar power at time t	kWh/h
D_t	Load demand at time t	kWh/h
D_t^{boat}	Boat charge demand at time t	kWh/h
D_t^{car}	Car charge demand at time t	kWh/h

Variables

SOC_t	State of charge of the battery at time t	kWh
Ch_t	Charging rate of the battery at time t	kW
Dch_t	Discharging rate of the battery at time t	kW
A_t^{calendar}	Calendar aging at time t	-
A_t^{cycling}	Cycling aging at time t	-
A_t^{total}	Total aging at time t	-
C_t^{eff}	Effective capacity of the battery at time t	kWh
$\text{SOC}_t^{\text{boat}}$	State of charge of the boat battery at time t	kWh
Ch_t^{boat}	Charging rate of the boat battery at time t	kW
Dch_t^{boat}	Discharging rate of the boat battery at time t	kW
P_t^{diesel}	Diesel power at time t	kWh/h
P_t^{grid}	Grid power at time t	kWh/h

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1

Introduction

1.1 Background

Volvo Penta, along with the rest of the Volvo Group, is forging ahead with the electrification of its industry and products. This initiative aligns with the United Nations Sustainability Goals 7 and 13:

7. Ensure access to affordable, reliable, sustainable, and modern energy for all 13.

Take urgent action to combat climate change and its impacts

UN Sustainability Goals [1] [2]

The electrification of global industry, transport, and production is an essential prerequisite for increasing the share of renewable energy in the global energy mix efficiently. Without the implementation of Renewable-based Energy Sources (RES) technologies, society will continue to rely on fossil fuel-based energy production. The current infrastructure needs to be updated to move away from this heavy reliance on fossil fuels to reduce greenhouse gas emissions in time to mitigate disastrous climate change. Projects like the one described in this paper help create knowledge about best practices for regulating battery storage technologies coupled with RES, which have significant variations in energy availability.

Volvo Penta has embraced these sustainability goals, among others. The company is committed to reducing its emissions by 50% by 2030 and achieving net-zero emissions by 2050. Additionally, Volvo Penta aims to create resource circularity in its operations and improve safety conditions for its employees and customers [3]. Volvo Penta has signed up for the Science Based Targets initiative (SBTi), which includes actions to electrify maritime transportation within the transport sector [4]. These guiding initiatives have driven Volvo Penta to invest in the infrastructure of their test site to demonstrate the benefits of micro grid applications with battery storage. As more RES solutions are integrated into the Swedish electricity grid, there is a growing need for solutions that can manage the increasing variation in energy availability and electricity prices. The primary beneficiaries of this project are boat owners and marinas, who will gain from cheaper electric charging. Additionally, there is potential to provide ancillary services to the grid with battery storage. Volvo Penta envisions assisting their customers in the marine business by constructing a state-of-the-art electric charging test site for boats at Krossholmen. Customers will be invited to this test site to engage with Volvo Penta's latest knowledge and developments regarding electric charging at marinas.

The test site's main goal will be to replicate realistic conditions for an average marina, supplemented by local power generation from solar and wind. Most marinas

have very limited transport capacity to and from the national grid and relatively small budgets for electricity generation. This project aims to understand the opportunities available from the optimal use of energy storage under these constraints, using the developing energy solutions at Volvo Penta.

1.2 Purpose

The main goal of this master thesis is to analyze and evaluate the potential of micro grid applications of vehicle charging and energy storage in a marine context using linear optimization programming of energy models.

1.3 Goals

The Krossholmen test site is currently in the early stages of developing its control systems. With this in mind, the project is heavily focused on the initial phases of modeling and conceptualizing the energy model, using rough estimations of future potential. The following seven chronological goals are to be achieved, aiming to provide valuable insights for Volvo Penta regarding the use of micro grids.

1. **A literature study** of available control technologies available for micro grid management and how to utilize them with tools such as machine learning/AI at the test site.
2. **A detailed description** of the entire energy and electrical system at the Krossholmen test site from a consumer and producer perspective. Including a summary of short-term challenges.
3. **Design a model** to simulate different future energy scenarios for 2035 and 2050 that showcase the role and potential benefits of battery storage.
4. **Analysis of cost optimized use of the energy storage solutions**, with regards to grid connected batteries, Boat2Grid technologies and when to buy or sell electricity to the national grid from the Krossholmen test site.
5. **A graphic representation** of how the different components and actors will interact within the test site's ES for the different energy scenarios mentioned in delivery 3. The representation should be at a laymen level of complexity.
6. **A suggestion for the future development** of the energy system at the Krossholmen test-site.

1.3.1 Priority of the goals application

The evaluation of Krossholmen can be conducted in various ways, depending on the underlying objectives of the work. To align the results with Volvo Penta's vision for the test site, an interview was conducted with the site manager of Krossholmen, Rickard Steffansson. Based on his insights, the following priority list was created.

1. Maintain a stable energy supply to the operation at Krossholmen.
2. Limit the energy input as much as possible.
3. Create a digital clone of the site to enable long term planing.

4. Maintain an energy storage backup security on site that can sustain major changes in loads and availability from the grid.
5. Economic profitability of the micro grid.

1.4 Limitations

The energy model analysis is limited to micro grid conditions and utilizes real-life data from the Krossholmen test site, as well as synthetic data from ongoing research at Chalmers University. Parameters outside this system's boundary are limited to market-related data, such as electricity and diesel prices.

For the purpose of evaluating battery storage as an energy storage solution, and not necessarily as an ancillary service for frequency regulation, the project is limited to an hour-to-hour time domain. There is potential for calculations in faster domains if the possibility of selling ancillary services to the grid is to be analyzed, but this is outside the scope of this project.

The main aim of this project is to evaluate the role of battery storage within a marine context for different energy scenarios. Therefore, the current business model through which the Volvo Group purchases electricity is not considered. Contracts, hedging policies, and grid fees change drastically over the time span in which this project compares different energy scenarios. Instead, the cost of electricity is derived from the marginal cost of energy production, according to ongoing modeling work by PhD Simon Öberg at Chalmers University [20].

A technical limitation that affects the time schedule and accuracy of the energy model analysis is the availability of measurements within the system. As the project progresses, more data will become available. Even after this master's thesis is concluded, there will still be benefits from adding more up-to-date data once the Krossholmen test site is finished.

Another technological restriction of the energy model is the use of the Python coding language. Since the conclusions from this work will be handed off to Volvo Penta for further development, it is important that the implementation can be easily integrated into their existing operations. Although coding languages such as GAMS and Julia have the potential for more efficient energy system modeling, they were discarded for this project due to the aforementioned reason.

1.4.1 Implications on Society

Developments in the energy field affect all aspects of modern society. Innovations such as solar PV, nuclear power, and the water wheel have significantly changed how humans live and perceive the world. Therefore, it is important to consider the implications of enabling the electrification of society as a result of this master thesis.

1.4.1.1 Ecological Aspects

The main advantage of using battery storage is to shift power load on the grid from high-demand peak periods to low-demand periods, usually from day to night in most residential and industrial areas. This enables more stable use of renewable energy

sources, which have variable availability due to seasonal and daily changes. Any development that brings us closer to electrification and reduces dependence on fossil fuels is beneficial. However, the negative aspect of battery technologies and their associated control systems is the increased demand for rare materials such as cobalt, copper, silicon, and others needed for components. The environmental footprint of increased extraction of these materials needs to be balanced with the benefits gained. This argument is similar to the current electric vehicle debate [6], where the mitigation of fossil fuel usage will eventually offset the higher production footprint. As climate change is an ongoing process, it may not be enough to electrify the transport sector alone to prevent disastrous damage to society. However, batteries could also be used as energy storage when vehicles are parked, smoothing energy demand across a day and between seasons.

1.4.1.2 Ethical and Societal Aspects

The implications of new insights regarding the efficient use of battery storage in micro grids vary depending on the region where they are applied. In developed countries, this practice presents new business opportunities for the electrified transport sector. In developing countries, it may be critical for households to transition to clean energy supplies for home appliances. Modern grid-connected batteries are still expensive, and any measures to improve the payback period on the investment may aid the electrification of institutions that would otherwise be unable to bear the risk. The ethical aspects of mining the necessary materials for these technologies in developing countries, where people work under questionable conditions, as well as the safety regulations surrounding the operation of grid batteries on-site, are important but beyond the scope of this master thesis to thoroughly investigate. This thesis will be conducted with these aspects in mind, but no significant actions will be taken within the planned time frame.

1.5 Disposition

This report covers the entirety of the master thesis project. Chapter 2 Theory, includes the theoretical background for the chosen methodology. The method by which the project was performed is described in Chapter 3, Method, divided into the different sub-tasks of the project. The description of Krossholmen's energy system is presented in Chapter 4. The results of optimizing the different energy scenarios are provided in Chapter 5. Finally, the analysis of the results is summarized in Chapter 6.

2

Theory

In this chapter the governing principles for energy analysis is described. Firstly the basics of mathematical programming models and how it is used to to set up an optimization model. Then the energy modelling topics regarding the markets and batteries are described in the context of this work.

2.1 Mathematical programming models

It is beneficial to summarize complex mathematical relationships in ES into abstract models for several reasons. It reveals previously unknown relationships for people that are not directly involved in the entire system, provides and mathematically analysis's the aspects of the model to determine future actions and preform experimentation that is not economically or otherwise possible in real life. Just like a dish is only as good as its ingredients, the usefulness of the mathematical model is dependent on the data in which it describes the relationship in between. It is important to distinguish *mathematical programming models* from *computer programming*. The programming refers to *planing* and do not necessarily have anything to do with computers. Several programming languages are however a very efficient way of setting up a mathematical model which is why its usually close connected in most contexts. Models are usually produced with the purpose of optimizing a certain performance value wither by *minimizing* or *maximizing* something. [10]. The data collection and utilization of mathematical programming models are performed in three characteristic steps as described in the following subsections.

2.1.1 Defining objectives

Depending on what is the aim, one can apply different objectives to a given set of data and constraints to find different optimal solutions. Different relevant parameter such as cost, profit, utility, Net Present Value(NPV) and so on can be maximized/minimized under the given constraints for the model. Single objective functions are usually expressed such as Equation 2.1 were x_{ij} is the number of i products made with process j to meet demand D_i for product i .

$$\sum_j x_{ij} = D_i \quad \text{for all } i \quad (2.1)$$

Such a minimize cost function would likely result in the best solution being to produce nothing without further context. By instead of determining that the demand

is a constant set but rather a variable d_i , the objective can instead be expressed as a maximize profit function as follows in Equation 2.2.

$$\sum_j x_{ij} - d_i = 0 \quad \text{for all } i \quad (2.2)$$

By implementing a profit coefficient P_i to this function, it can derive the optimal value for d_i . The profit may however be depended on variable d_i which would then mean that the function has entered the non-linear realm. The objective function is in this manner further developed to suit a certain aim. It can for example be adapted for different time periods and scenarios by discounting future monetary gains and change the models conditions in what is known as dynamic models. As there is a cost associated to the process j to produce product i , the prices should be added to the function. In the case of this project there are several products that can fulfill the demand D_i . By studying the energy systems different producers, storage solutions and prices for different energy sources we arrive at the equations for demand balance Equation 3.12 and the minimize cost function Equation 3.1

Several objectives may be relevant to apply for a single model. In these cases one can solve the objectives one after another resulting in two different solutions to be weighed against each other. Another method to handle these situations is to comprise a linear combination of all objective functions. This will result in that some relative weight to each of the objectives which the programmer of the model needs to be aware of and clearly state to actors taking part in the results. When combining the objectives one may arrive in the conclusion that these are in conflict. A general way to resolve the conflict is to formulate the conflicting objective as constraining goals instead. In the case of this project the prioritization between different, possibly conflicting, goals has been established in Chapter 1.3.1 in line with the vision of Volvo Penta's operation at Krossholmen.

2.1.2 Defining constraints

The key to successfully calculating accurate results when using a programming model is to define the constraints of the model in accordance to the relevant resolution of the case being studied. In this case the constraints reflect the technical specification of the site and how each component functions in relation to the rest of the system. There are some typical constraint categories that describe the ones used in this model. Productive capacity constraints that restrain how much energy that can feasibly be produced in order to satisfy the given demand for the site such as the transmission capacity from the national grid or the charging rate of batteries. Then there is market demands and limitations that dictates the dynamics of how a produced commodity will sell. In this model, the demand is a hard constraint that is to be satisfied strictly to ensure that the operation at the Krossholmen workshops can continue without hindrance. The electricity price is also a set value for each hour that depends on market factors. In models that are significantly greater in scope than this project there would be impacts in the market price by the decisions of the model that needs to be accounted for [10].

2.2 Energy modeling

The definition of an energy model is a computer-based model that comprehensively describe energy flows within a set of boundaries. These boundaries can be geographical, within a certain energy system such as electricity or heat, economical zones and so on. The mathematics that lies behind the model also differ between models. For instance this project utilizes normative models for optimization purposes[15]. The main benefit of using this methodology is to summarize the complex system in which you want to optimize in a way that is simple yet representative of reality. Other gain comes from the increased understanding of the system that lead to better decision making and planing when developing the energy system under new conditions. It is beneficial to develop energy models iteratively by comparing it to the real system and customer demands as represented in Figure 2.1. One can never take the results of a model at face-value, but use it for its intended purpose to provide insights rather then to draw direct conclusions. For the model to improve the understanding of the involved actors they need to be consulted continually as the model is developed [17].

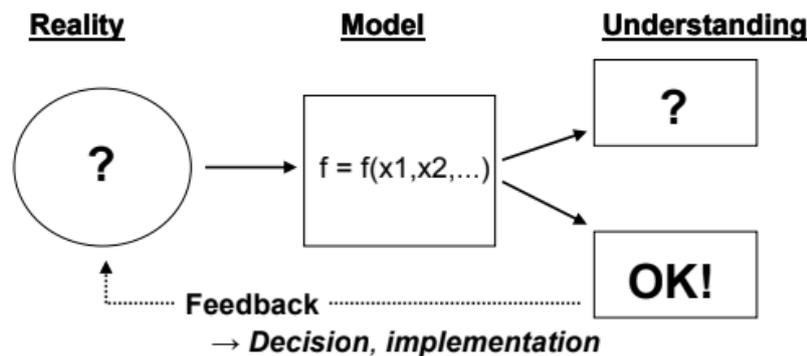


Figure 2.1: Modelling processes [15]

2.3 Definition of a micro grid

A definition of micro grids is established in order to ground this broad concept specific context. A micro grid is a localized group of electricity sources and loads that operates with a limited connection to the national power grid or independently as an isolated entity. It typically includes local production with renewable energy sources, such as solar panels and wind turbines, combined with traditional generators and energy storage systems, like batteries. MG:s are designed to enhance energy reliability, improve power quality, and increase energy efficiency. They can supply power during main grid outages, support the integration of renewable energy, and provide localized control over energy resources. This is a typical setup for remote marines where a majority of leisure boats are harboured. As these boats switch to electric drive lines there will be an increase in micro grid practices to accommodate the charging of these vessels.

2.4 Electricity markets

In this project the electricity market in the Nordics is studied which is organized as a day ahead spot market by Nordpool. This means that energy producers bid their energy offer 24 hours ahead of a certain demand hour. The price is then determined by the producer on the margin of the demand. This is what is called marginal cost[16] for the consumer. As demand change throughout the day the marginal cost moves along the aggregate supply curve that the producers have offered as seen in Figure 2.2. During two hours on 14th of February 2024 the price across all economic zones in Sweden change significantly due to the sudden change in demand as the population wakes up and starts to increase the consumption of electricity by turning on lights, breakfast cooking and industrial machines starting at the beginning of production shifts. The availability also changes depending on the producers ability to supply the grid. Sweden, consuming a significant share(about 20% currently [18]) of wind power, have significant variation in power availability which means that the supply curve change over time and thereby also affect the spot price. The optimization model for this project determine when during a full year it is most beneficial to draw energy from the electricity to the grid when the price is low and when its better to save as much energy as possible when prices are high, also known as load following or peak shaving. The model uses total cost for an entire year as an objective variable and can therefor find the optimal utilization of on-grid batteries for either daily or seasonal variation.

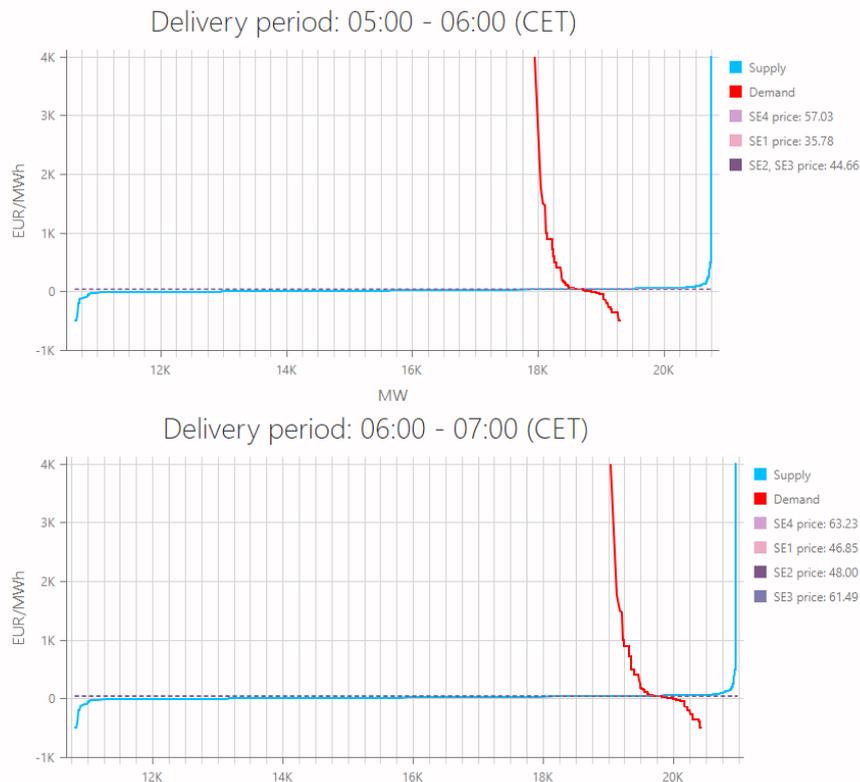


Figure 2.2: Spot price 2024-02-14 for 05:00-06:00(CET) and 06:00-07:00(CET) [8]

2.5 Battery degradation

The potential wear and tear on batteries that are utilized for peak shaving is a significant drawback of the practice that the owner of the unit needs to take into account. The significance and scale of this drawback is considered a vital factor to account for in this analysis as it is one main argument against investments in vehicle electrification. Battery degradation is defined as the gradual loss of the battery's ability to hold charge and deliver power over time. This is due to the undesired reaction happening in electrolyte solvent, damages in electrode material or loss of connection between the lithium-containing active electrode material and the bulk electrode [22].

Two of the most significant factors for a battery that charges and discharges regularly is calendar aging and cycle aging. Calendar aging refers to the degradation that occurs over time depending on the state of charge of the battery. The amount of degradation is also influenced by factors such as temperature, storage conditions, and how the chemical composition processes that naturally occur within the battery over time. Cycle aging occurs as a result of the actual charging and discharging cycles that a battery undergoes during its operational life. Each charge-discharge cycle causes stress on the battery's electrodes and electrolyte, leading to chemical and physical changes that can diminish the battery's capacity and overall lifespan. Factors such as depth of discharge, charging rate, and operating temperature can also influence the rate of cycle aging. From a recent study it is calculated that the implementation of V2G practices results in only a slight increase in cycle aging[19]. The battery degradation has been modelled in a simplified manner in order to enable linear programming to be used for this analysis. The expressions used to determine the total battery degradation during a given year of optimal operation are declared in Chapter 3.13 and Chapter 3.14.

3

Methods

The different methodologies used to derive the results of this project is described in this chapter.

3.1 Literature review

At the start of the project, appropriate information sources relevant to the purpose of this project are identified through a literature review to establish a sound basis for the work. The literature review will be conducted using two different approaches for the descriptive and analytical parts of the project. The descriptive part pertains to goal #2, which aims to create an extensive description of the micro grid at Krossholmen. An integrative search strategy, as suggested by H. Snyder [7], is the appropriate approach for gathering existing specifications and applying them to the energy modeling methodology.

Volvo Penta has already collected a wealth of information in the development of the micro grid at Krossholmen. However, not all the data needed for the necessary conclusions for the linear optimization is available at the start of the project, as many components of the EMS system are yet to be delivered. Once the available data and the data that needs to be artificially produced are collected, the resource planning and scope of tasks for the project can be established. Previous findings and assumptions regarding the micro grid will be critically reviewed as part of the integrative review to create a new framework that meets the needs of the analytical part of the literature review.

The linear optimization of the micro grid's ES is a new research area for the development at Krossholmen. For this purpose, a systematic approach to the research question is most suitable [7]. The topics researched in this paper are relevant to the energy modeling of the micro grid.

- Linear optimization
- Energy-systems modelling
- Energy-systems modelling modules for Python
- Future energy scenarios
- Future potential of the developing technologies

The best practices for modeling the Krossholmen case will be identified using the meta-analysis methodology for the aforementioned technological and mathematical topics. The scope of the review is limited to the established technological limitations outlined in Section 1.4.

3.1.1 Graphic representation

For the final delivery, a graphic representation of the entire system and its operation under different conditions is being produced. The aim of this representation is to showcase the profitability for marinas that adapt their operations to support boat charging using local grid batteries. The graphic will be designed for display at Volvo Penta's demo center at Krossholmen for visiting customers to view.

3.2 Future energy scenarios

The general public has become increasingly aware of the variability in energy prices over the past year. With the continued introduction of RES technologies, the availability of affordable power will also remain variable. Innovation and long-term planning are necessary for micro grids to handle these new challenges. All scenarios will be divided into two distinct time periods: on-season and off-season. The operation of marinas is distinctly different in the summer, when leisure boats are used the most, compared to the winter, when they are on land for 6-8 months. This seasonal variation presents different opportunities for energy storage. Using the best available estimates of future energy technologies and electricity market developments, five different energy scenario variations have been determined for analysis. The hypothesis is that BES solutions will become more profitable in the future under these new conditions and that local storage will have significant profitability in relation to investment costs. Each of the five scenarios modeled and analyzed in this project is described below.

3.2.1 Current Conditions

The current conditions are modeled using average market prices from the past couple of years, applied to the currently planned specifications of the Krossholmen test site. The data is based on the electricity costs during 2023 from the Nordpool database for SE3, where the test site is located [8].

3.2.2 Electricity Markets of 2030 and 2040

As Volvo Penta looks to future developments within an electrified society, the best available prognosis of the Swedish energy market is applied to the analysis. This data is based on the ongoing work by PhD Simon Öberg [20], which predicts that the energy mix will become more electrified in the coming years, while demand and electricity prices steadily increase. The energy model in this project only considers the marginal cost of producing electricity as the cost, and does not take into account business practices such as price hedging, taxes, or day-ahead bids being much higher or lower than the cost of production.

3.2.3 Impact of Local Renewable Energy Production

A common characteristic of remote micro grids is their poor connection to a national grid, with a focus on security and local production. Volvo Penta has decided to demonstrate this potential for its customers' marinas by installing a 4.5 kW wind turbine and 37 kW worth of solar panels at the Krossholmen test site. These have been implemented into the energy model to highlight the role of these producers within the micro grid and their interaction with local battery storage.

3.2.4 Impact of Local Energy Storage with On-grid Batteries

The Volvo Group is currently developing a BES container known as MPRESS. The unit dedicated to the test site's micro grid has a capacity of 500 kWh and is capable of delivering 350 kW, with the purpose of reducing electricity costs for operations at Krossholmen and providing short-term backup in case of a blackout. This project, a collaboration between Volvo Penta and Volvo Energy, aims to give lithium-ion batteries from electric trucks a second life as an ancillary service. This technology has been considered in the energy model to demonstrate its capabilities within a marine micro grid context.

3.2.5 Impact of Boat2Grid

Since leisure boats usually remain on land for most of the year and is usually used around 40-80hours in total during a full year, there is great potential for the batteries to be used as energy storage for the grid. The appropriate number of boats and their specifications was determined through interviews with Volvo Penta's staff, as shown in Chapter 4.1.1.5, and a charging schedule was then generated using a Python script, see Appendix A.

3.3 Linear optimization

To determine the optimal operation of the micro grid under different conditions, modern linear programming is used [10]. Since the micro grid consists of many different systems, optimizing its operation becomes quite complex. With several interrelations and conflicting constraints between production and storage systems within the micro grid, it is essential to analyze opportunities across different time dimensions (seasonal, daily, milliseconds, etc.). By applying linear optimization tools, the problem can be handled efficiently, encompassing a variety of functions to meet the project's aims. The Energy System (ES) of Krossholmen is defined as a cost-minimization linear objective function with multiple constraints [10]. The cost of the operation's energy usage is the single objective function, while all other variables are treated as constraints.

All model inputs are divided into four categories: decision variables, objectives, explicit constraints, and implicit constraints. Once all relevant inputs are identified

and properly defined for constructing a linear optimization model, they are implemented in a suitable Python optimization module. The project will be conducted in Python, and the appropriate module will be determined by the literature review mentioned in Chapters 1.4 and 3.1. Once all functions and constraints are properly set up, the model will determine the best possible use of the micro grid, including when and how much the different batteries in the system should be used to minimize monetary costs.

Insights from the ongoing Boat2Grid project at Volvo Penta may also be incorporated as the initiative develops in parallel to this work. Given that the most significant conclusions are expected to be derived from simplified linear relationships, this will be a priority in terms of resource management.

3.3.1 Objective function

Within the system, the micro grid needs to purchase energy in two ways to meet the demand: power from the grid, denoted as $P_{\text{grid},t}$, and diesel for the GENSET unit, denoted as $P_{\text{diesel},t}$. These are priced at their respective prices, the hourly rate of π_t for grid power and set rate π_{diesel} for diesel. To minimize these costs, the following function is used to optimize the system:

$$\min \sum_{t \in \text{hours}} \left(\pi_t^{\text{grid}} \cdot P_t^{\text{grid}} + \pi^{\text{diesel}} \cdot P_t^{\text{diesel}} \right) \quad (3.1)$$

This objective function aims to minimize the total cost of energy by summing the costs of grid power and diesel power over all hours.

3.3.2 Constraints

The appropriate constraints for performing the energy optimization are outlined below. These constraints reflect the technical capabilities of the various components at Krossholmen and their interactions with one another.

3.3.2.1 Battery Capacity Constraint

This constraint ensures that the state of charge (SOC) of the battery in kWh at time t does not exceed the maximum battery capacity.

$$\text{SOC}_t \leq C_{\text{max}} \quad (3.2)$$

3.3.2.2 State of Charge (SOC) Constraint

The constraint below defines the state of charge (SOC) of the battery in kWh at any time t . It considers the initial charge/discharge at $t = 0$ and the subsequent SOC as a function of previous SOC, charge, and discharge.

$$\text{SOC}(t) = \begin{cases} \text{Ch}_t^{\text{bat}} - \text{Dch}_t^{\text{bat}} & \text{if } t = 0 \\ \text{SOC}_{t-1}^{\text{bat}} + \text{Ch}_t^{\text{bat}} - \text{Dch}_t^{\text{bat}} & \text{if } t > 0 \end{cases} \quad (3.3)$$

3.3.2.3 Battery Charge Constraint

This constraint ensures that the charging rate of the battery at time t does not exceed the maximum charge rate.

$$\text{Ch}_t^{\text{bat}} \leq \text{Ch}_{\text{rate}}^{\text{bat}} \quad (3.4)$$

3.3.2.4 Battery Discharge Constraint

This constraint ensures that the discharging rate of the battery at time t does not exceed the maximum discharge rate.

$$\text{Dch}_t^{\text{bat}} \leq \text{Dch}_t^{\text{bat}} \quad (3.5)$$

3.3.2.5 Boat Battery Capacity Constraint

This constraint ensures that the state of charge (SOC) of the boat battery at time t does not exceed its maximum capacity. The actual charge demand is determined by Equation 3.12 (Demand Balance Constraint) and is sourced from the specified boats listed in Section 4.4.

$$\text{SOC}_t^{\text{boat}} \leq C_t^{\text{boat}} \quad (3.6)$$

3.3.2.6 Boat SOC Constraint

This constraint defines the state of charge (SOC) of the boat battery at any time t . It considers the initial charge/discharge at $t = 0$ and the subsequent SOC as a function of previous SOC, charge, and discharge. Here it should be mentioned that this constraint only applies to the hours when the boats are available for charging as stated in Equation 3.8.

$$\text{SOC}_t^{\text{boat}} = \begin{cases} \text{Ch}_t^{\text{boat}} - \text{Dch}_t^{\text{boat}} & \text{if } t = 0 \\ \text{SOC}_{t-1}^{\text{boat}} + \text{Ch}_t^{\text{boat}} - \text{Dch}_t^{\text{boat}} & \text{if } t > 0 \end{cases} \quad (3.7)$$

3.3.2.7 Boat Battery Charge Limit

This constraint ensures that the boat battery is only charged if the boat is available, and limits the charging rate when it is unavailable.

$$\text{Ch}^{\text{boat}}(t) = \begin{cases} \text{Ch}_t^{\text{boat}} = 0 & \text{if } \text{Av}_t = 0 \\ \text{Ch}_t^{\text{boat}} \leq \text{Ch}_{\text{rate}}^{\text{boat}} & \text{if } \text{Av}_t > 0 \end{cases} \quad (3.8)$$

3.3.2.8 Boat Battery Discharge Limit

This constraint ensures that the boat battery is only discharged if the boat is available (described above as the binary variable Av_t), and limits the discharging rate

when it is unavailable.

$$Dch^{\text{boat}}(t) = \begin{cases} Dch_t^{\text{boat}} = 0 & \text{if } Av_t = 0 \\ Dch_t^{\text{boat}} \leq Dch_{\text{rate}}^{\text{boat}} & \text{if } Av_t > 0 \end{cases} \quad (3.9)$$

3.3.2.9 Diesel Power Constraint

This constraint ensures that the diesel power generated at time t does not exceed the maximum diesel power capacity.

$$P_t^{\text{diesel}} \leq P_{\text{max}}^{\text{diesel}} \quad (3.10)$$

3.3.2.10 Grid Power Constraint

This constraint ensures that the grid power used at time t does not exceed the maximum grid power capacity.

$$P_t^{\text{grid}} \leq P_{\text{max}}^{\text{grid}} \quad (3.11)$$

3.3.2.11 Demand Balance Constraint

This constraint ensures that the total power supply from wind, solar, the grid, diesel, and discharging batteries meets the total demand from load, boat charging, and car charging at time t . Specifically, wind, solar, and the three demand values are static and based on data from the site, while the grid power, diesel, and battery charging values are variables. A complete list of which values are static parameters and which are variables subject to optimization can be found at the beginning of this document in the front matter.

$$\begin{aligned} & P_t^{\text{wind}} + P_t^{\text{solar}} + P_t^{\text{grid}} + P_t^{\text{diesel}} \\ & + \left(Dch_t^{\text{bat}} \cdot \eta^{\text{battery}} - \frac{Ch_t^{\text{bat}}}{\eta^{\text{bat}}} \right) \\ & + \left(Dch_t^{\text{boat}} \cdot \eta^{\text{boat}} - \frac{Ch_t^{\text{boat}}}{\eta^{\text{boat}}} \right) \\ & = D_t + D_t^{\text{boat}} + D_t^{\text{car}} \end{aligned} \quad (3.12)$$

3.3.3 Expressions

Battery aging is calculated using expressions rather than binding constraints in this model. This approach is due to the limitations in computational time when using an open-source solver on local machines. However, the calculations provided offer insight into how the battery will be affected in a given year under optimal operation, even though the cost of lost capacity is not included in the objective function.

3.3.3.1 Calendar Aging Expression

The following expression calculates the calendar aging of the battery at time t , taking into account the state of charge, charging and discharging levels each hour,

temperature data from the Gothenburg weather station for 2023 provided by SMHI [23], and the constants for calendar aging. This simplified approach to modeling calendar aging is based on the Arrhenius model [24], which describes the temperature dependence of reaction rates. In the context of battery aging, the Arrhenius equation is adapted to model the degradation mechanisms affecting the battery over time. The specific factors included in the equation are based on empirical data and a theoretical understanding of how these factors influence battery aging.

$$A_t^{\text{calendar}} = k^{\text{calendar}} \cdot e^{-\frac{E_a}{R \cdot \theta}} \cdot \left(\frac{\text{SOC}_t}{C_{\text{initial}}} \right) \quad (3.13)$$

3.3.3.2 Cycling Aging Expression

This expression calculates the cycling aging of the battery at time t , taking into account the depth of discharge as well as the amount of charge and discharge. It is based on empirical studies of battery degradation due to cycling. Cycling aging models aim to quantify the wear and tear on the battery from repeated charging and discharging cycles, which are influenced by both the depth of discharge and the total amount of charge and discharge [25].

$$A_t^{\text{cycling}} = \begin{cases} k^{\text{cycling}} \cdot \text{Ch}_t & \text{if } t = 0 \\ k^{\text{cycling}} \cdot \frac{|\text{SOC}_t - \text{SOC}_{t-1}|}{C_{\text{initial}}} \cdot (\text{Ch}_t + \text{Dch}_t) & \text{if } t > 0 \end{cases} \quad (3.14)$$

3.3.3.3 Total Aging Expression

With this expression the total aging of the battery at time t is computed by summing the calendar and cycling aging.

$$A_t^{\text{total}} = A_t^{\text{calendar}} + A_t^{\text{cycling}} \quad (3.15)$$

4

Krossholmen description

4.1 Detailed description of Krossholmen

A detailed description of Krossholmen is essential for accurately modeling the Energy System (ES). In addition to a general description of the test site, specific representations are either requested by Volvo Penta or necessary to establish the appropriate boundary conditions for the linear optimization.

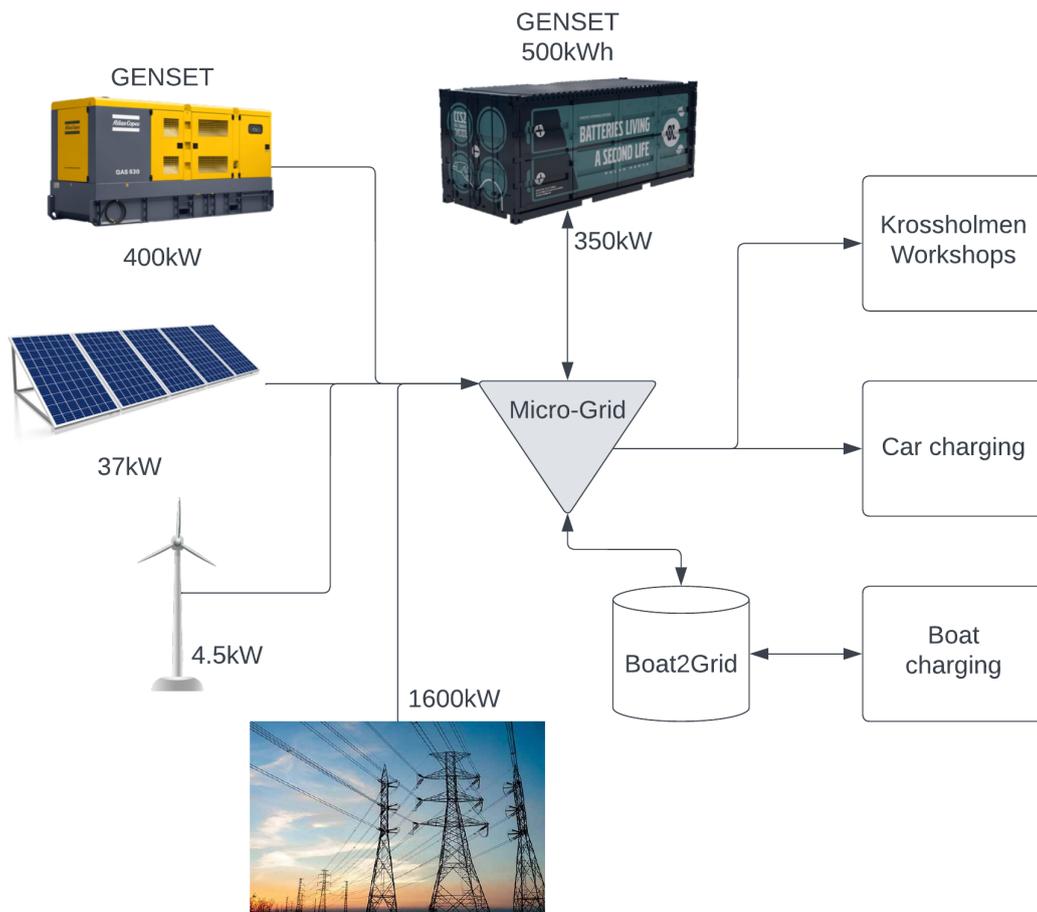


Figure 4.1: A simple schematic of how the different technologies at Krossholmen interact

4.1.1 Technical specification

The micro grid consists of several components, each with specifications that impact their role in the ES. These specifications reveal attributes such as energy storage capacity, transformer capacity, power output, and relevant meteorological conditions. All of these attributes need to be mapped and categorized to establish the boundary conditions for the linear optimization.

4.1.1.1 Demand

At the Krossholmen test site, the model considers three distinct load demands, which are met by drawing power from the national grid, utilizing local power production, or discharging grid-connected batteries on site. These demands include the power required for the site’s facilities, charging needs for cars, and charging needs for marine vessels. The facility’s power demand primarily stems from electrical heating and heavy machinery used in the boat workshop. Data for these demands, with hour-to-hour resolution, has been provided by the electricity provider for Volvo Group from the past year.

Table 4.1: Total, peak and average energy demand of the three different consumers at Krossholmen

Demand groups			
Demand	Total[kWh/yr]	Peak[kWh/h]	Average[kWh/h]
Facilities	907 000	250	95
Cars	212 540	158	24
Boats	199 459	320	23

4.1.1.2 Power grid

The Krossholmen test site is unique among marinas due to its substantial transmission capabilities. The site features a 10kV connection with a contracted maximum power delivery of 1600 kW—conditions that are not commonly found at marinas in Sweden. To make the results more broadly applicable to future electric boat owners, the model should be adjusted to reflect more typical conditions. However, the analysis in this project is focused solely on the Krossholmen test site to validate the results and ensure that the Python code can be easily transferred between programmers for future development.

4.1.1.3 Producers

Based on data from the online simulation tool Renewables.ninja [21] and the technical specifications of the planned energy producers at the test site (see Table 4.2), load profiles for wind and solar power production were generated for the analysis, as shown in Figure 4.2. The energy produced, along with purchased energy from the grid and diesel reserves, is used to meet the site’s energy demand while optimizing the use of the grid-connected batteries.

Table 4.2: Solar and wind production data

	Solar Panels	Wind Turbine
Capacity (kW)	37	4.5
Yearly Use (kWh)	35500	15100

4.1.1.4 Batteries

Three different types of energy storage are available on the site:

1. **On-grid Battery Container (MPRESS):** This system uses recycled batteries from the automobile industry.
2. **Diesel Generator (GENSET):** Primarily used as a backup for security purposes, the GENSET is also modeled to optimize normal operations. It is included in the model to determine when it is more economical to use diesel energy instead of electricity, or when it is profitable to charge the on-site batteries using diesel, especially when diesel prices are lower.
3. **Electric Boats:** All connected electric boats function as a unified battery, similar to the MPRESS. However, their usage is constrained by the charging habits of the boat owners, unlike the MPRESS, which discharges only to meet the micro grid's demand as described in Equation 3.12.

Table 4.3: Generator and Boats Performance

	MPRESS	GENSET	Boat2Grid
Power capacity (kW)	350	400	320
Storage capacity (kWh)	500	3170	1185

4.1.1.5 Boat2Grid

For the accuracy of the model, it is crucial that the boats in the marina are modeled to reflect future energy scenarios where fully electric boats have become more common. Since current designs for such vessels have not yet reached the market, rough estimates have been made about their potential operation. These estimates are based on interviews with the workshop manager, Robin Andersson, and data on the current usage of leisure boats.

The estimates, including some standard deviation on charging habits, are used to create a realistic charging profile based on the vessels described in Table 4.4 below. The data set includes two types of boat characteristics: prototype boats that operate year-round, and leisure boats that are inactive during the winter. These operational characteristics are specified as the start and end dates of the active boating season, as well as the number of trips per week.

4. Krossholmen description

Table 4.4: Specification of each of the 10 simulated boats for the Krossholmen test-site micro grid

Boat Number	Number of Trips Per Week	Max Charging Power	Battery Capacity	Charging Habit	Start Date	End Date
1	6	42	150	0.95	'01-01'	'12-30'
2	6	22	150	0.95	'01-01'	'12-30'
3	6	22	110	0.95	'01-01'	'12-30'
4	6	42	120	0.9	'01-01'	'12-30'
5	6	42	120	0.9	'01-01'	'12-30'
6	0.5	22	100	0.8	'04-01'	'11-01'
7	2	22	100	0.5	'05-01'	'10-01'
8	0.2	22	110	0.6	'04-01'	'10-01'
9	1	42	115	0.5	'05-01'	'10-01'
10	4	42	110	0.7	'05-01'	'09-01'

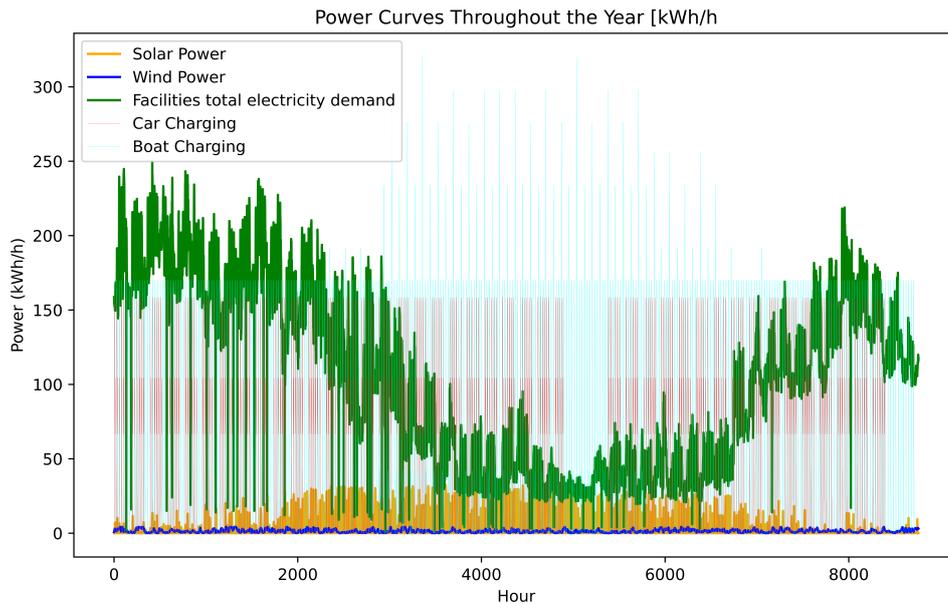


Figure 4.2: The initial conditions for the energy model, that is, the set of parameters that are predetermined

5

Results

5.1 Reviewing different Python libraries for energy optimization applications

Pyomo is determined to be the most suitable Python library for this project based on user reviews [12] and reference cases [13]. Pyomo is commonly used at Chalmers university and was used as a baseline value for the evaluation of alternative solvers. The libraries relative performance to Pyomo is indicated by + (just as good), ++ (better then) or - (worse) in Table 5.1 below. The three different factors were considered when researching the most common Python libraries, user-friendliness, the capability of the solver and if its an established tool within the energy industry. The user-friendliness is defined as the ease of use and similarity to the baseline. The library's ability to produce a suitable energy model in this case is defined as the capability. Lastly, weather or not the library was found to be used in similar case studies within the ES field. The Pulp solver stand out as a potential improvement over Pyomo. In regards to how easily it is learnt, the general consensus is that Pulp is more intuitive to read [14] which may motivate it being a stronger candidate for integration in Volvo Penta's future operation. However, since Pyomo both have a wider library of solver methods and its practiced for energy modeling at Chalmers University it is still the selected Python module.

Table 5.1: A table consisting of the resulting evaluation of different Python libraries.

Library	User-friendliness	Capabilities	Established in the ES field
Pyomo	+Good	+Wide range of solvers	+Most widely used +micro grid applications
Pulp	++Great	-Less range of solvers +Open source	+Applied in several ES cases
Scipy	-Poor	-Not specialized of ES applications +Similar to CVXPY	++Used in many different fields
CVXPY	-Poor	-made for general convex optimization +Similar to Scipy	+Used in ES applications
Gekko	+Good	-Focused on Machine learning applications	+Commonly used for ES applications
OR-Tools	-Poor	-Specific non-energy system applications ++Made by google	-Widely used in other fields

5.2 Optimization of energy scenarios

The results of the retroactive optimization for each energy scenario are presented through stacked graphs and tables in this chapter. Each scenario has been optimized over a full year at an hourly resolution. Instead of displaying the entire year, as seen in Figure 5.1, each scenario is shown for a single week to better visualize the differences between them.

One notable observation from this view is that peak generation has increased significantly throughout the year due to battery charging during low-price hours. This operation could lead to diminishing returns if the electricity provider imposes higher fees for certain peak limits, which is a common practice in the Swedish electricity market.

Week 15 was chosen for analysis as it typically has average temperature and wind levels that are representative of the entire year. In addition to the graphs, each scenario's economic results are presented in a table, which includes the total cost for the year, the total savings from each measure, the usage of energy storage, and the resulting battery degradation of the MPRESS battery container.

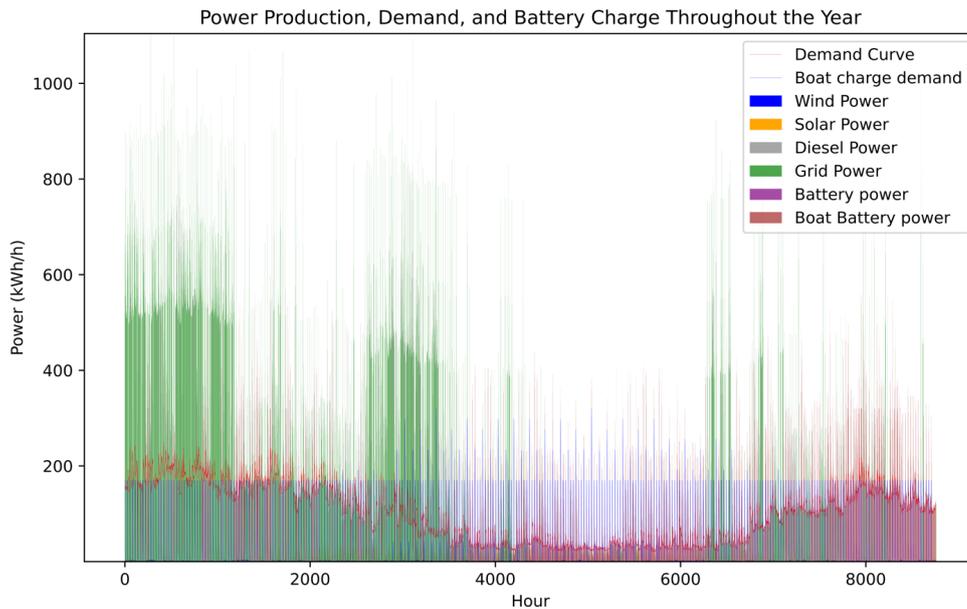


Figure 5.1: Example of a full year graph including of all the different power demands and generation on Krossholmen

5.2.1 Base case - No renewables, No battery capacity

A base case was established to compare the impact of implementing renewable energy production and battery storage on the system's economic benefits and drawbacks. In this base case, the test site is solely supplied with energy from the national grid, with the GENSET diesel generator available as a backup. However, the model determined that activating the GENSET was unnecessary, as diesel is significantly more expensive than electricity per kWh at all hours in the reference years.

In Figure 5.2, the red line represents the total demand at Krossholmen, while the bars below it indicate the production supplied within the micro grid. This production either meets the demand or charges the grid-connected batteries, according to the balance Equation 3.12.

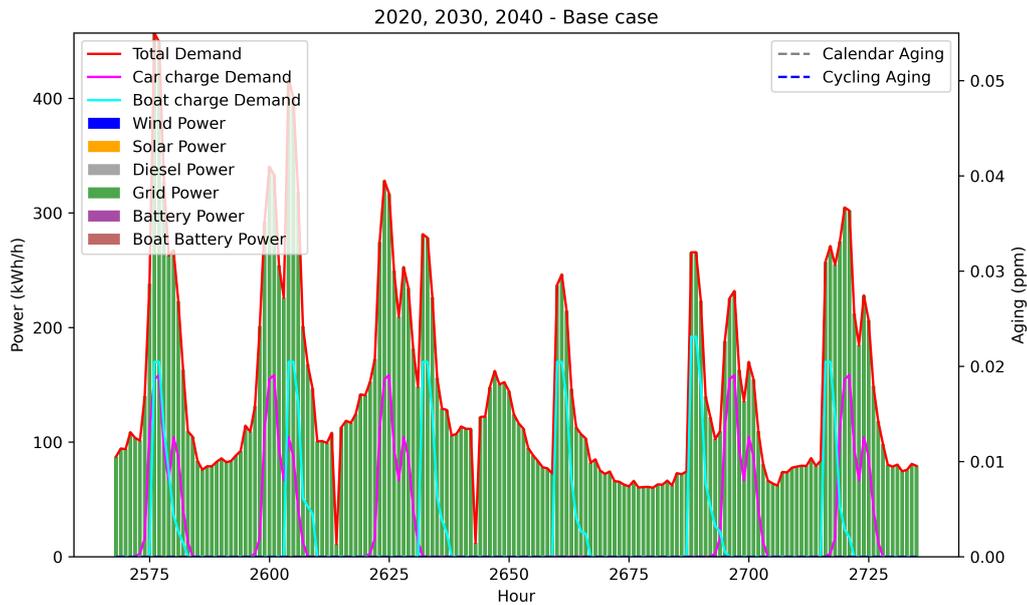


Figure 5.2: The base analysis case showing the demand and grid power use for week 15 during the years 2020, 2030 and 2040

Below are the total costs of purchasing electricity from the national grid, based on the marginal cost for each of the three reference years, as well as the amount of energy consumed at the test site. Comparing the total costs for each year reveals trends in the energy market for those years. The early 2020s have been marked by several crises, including the pandemic and the war in Ukraine, which have contributed to an energy crisis in the European market. Analyzing these results, 2020 can be characterized as a "crisis year," providing insight into how the system is impacted by extreme market fluctuations.

By 2030, it is anticipated that the energy market in Sweden will be more stable compared to 2020. According to Simon Öberg's work [20], there should be a significant increase in renewable energy sources in Sweden's power mix by that time. This shift will likely increase the variation in energy availability and, consequently, in pricing. As electricity demand continues to rise due to increased electrification in transport, industry, and society's efforts to move away from fossil fuels, electricity prices are expected to reach higher levels by 2040, as shown in Table 5.2.

Table 5.2: The base case without any local renewable energy production or flex measures on the test-site

Total grid use: 1313.9MWh		
2020	2030	2040
Total cost: 651.4 kSEK/yr	Total cost: 419.0 kSEK/yr	Total cost: 517.6 kSEK/yr
Total car charging: 212.6MWh, Total boat charging:199.5MWh		

5.2.2 Impact of Renewables

Local energy production is a crucial aspect when discussing microgrids. Figure 5.3 below illustrates the impact of incorporating two types of renewable power generation: a 4.5 kW wind turbine (represented by blue bars) and 37 kW of solar panels (represented by yellow bars).

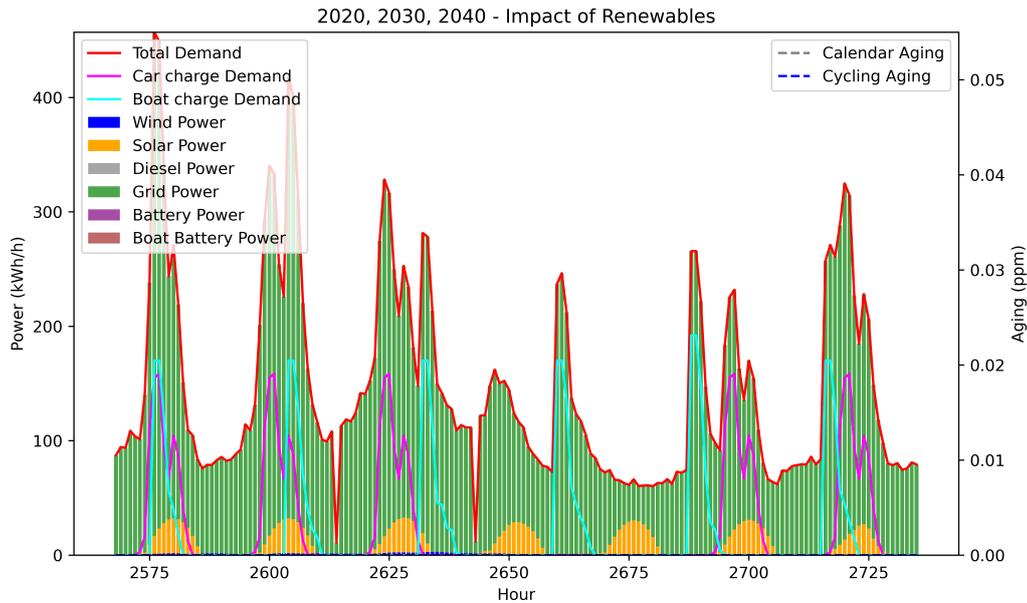


Figure 5.3: Graph showing the impact of renewables for a week 15 of the study

The renewable energy production at the test site is relatively modest compared to the overall demand. Wind power, in particular, requires a substantial amount of space and cannot be easily integrated into existing infrastructure, such as being placed on rooftops like solar panels; it necessitates a dedicated foundation. However, wind power is more efficient in terms of energy output relative to its installed capacity. As shown in Table 5.3, the wind turbine generates 2.75 MWh/kW of energy per installed capacity annually, compared to 1.19 MWh/kW for the solar panels. Despite its efficiency, wind power is a costly investment for harbor owners due to its long payback period and maintenance requirements. While the financial implications of this investment are beyond the scope of this thesis, the aim of this analysis is to demonstrate the potential of local energy production and its role in micro grid systems.

5.2.3 Impact of the on-grid battery container - MPRESS

The MPRESS system reduces onsite energy costs by offering flexibility in energy delivery. The following graphs—Figure 5.4, 5.5, and 5.6—illustrate how the MPRESS charging and discharging behaviors vary across different years, as represented by the purple bars. This variation arises because the model employs a peak-shaving

Table 5.3: The resulting savings from implementing local renewable production

Total grid use: 1261.2MWh (-4.0%)		
2020	2030	2040
Total cost: 623.0 kSEK/yr Yearly savings: -26.9kSEK/yr	Total cost: 407.3 kSEK/yr Yearly savings: -11.7kSEK/yr	Total cost: 504.1 kSEK/yr Yearly savings: -12.6kSEK/yr
Total solar Energy: 40.6 MWh		
Total wind energy: 12.4 MWh		

strategy, and electricity prices fluctuate differently each year. Notably, in the "crisis year" of 2020, the potential savings from having an on-grid battery are the highest. As electricity price volatility and availability fluctuations increase, the value of energy storage becomes more pronounced.

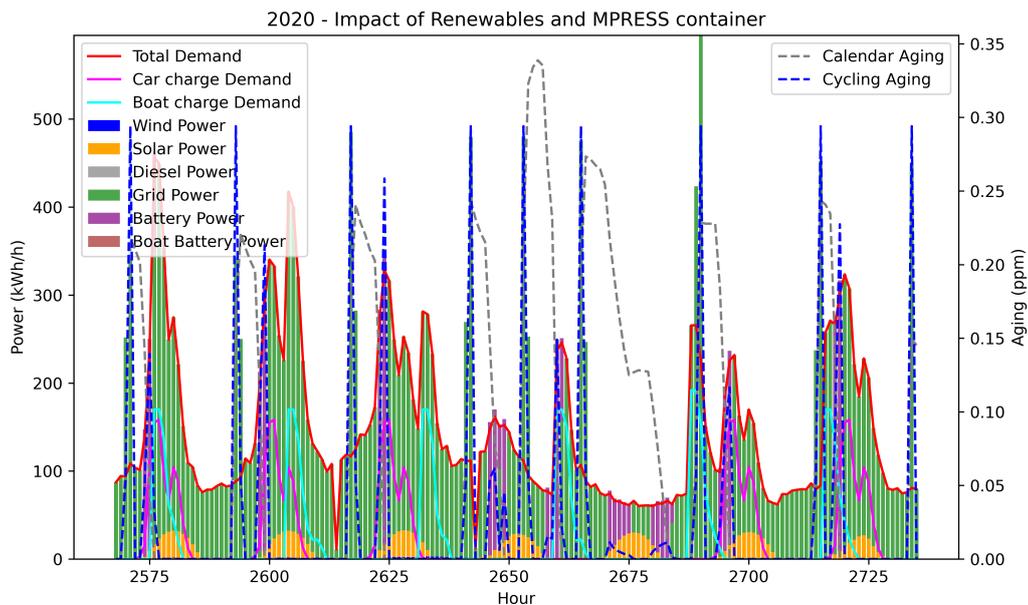


Figure 5.4: Graph of the resulting dispatch of different energy sources from implementing an MPRESS battery container to the site in the year 2020

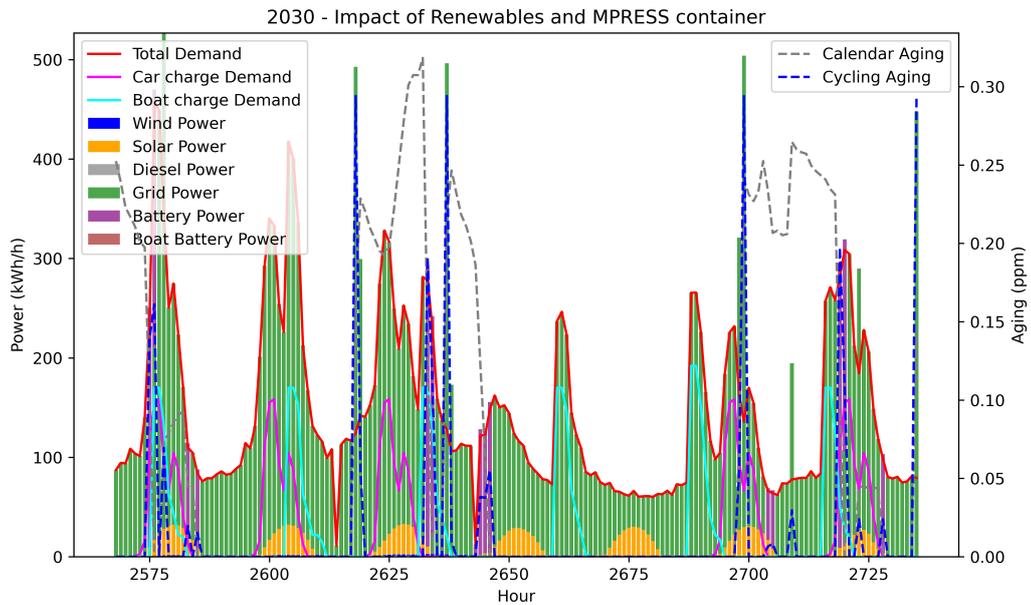


Figure 5.5: Graph of the resulting dispatch of different energy sources from implementing an MPRESS battery container to the site in the year 2030

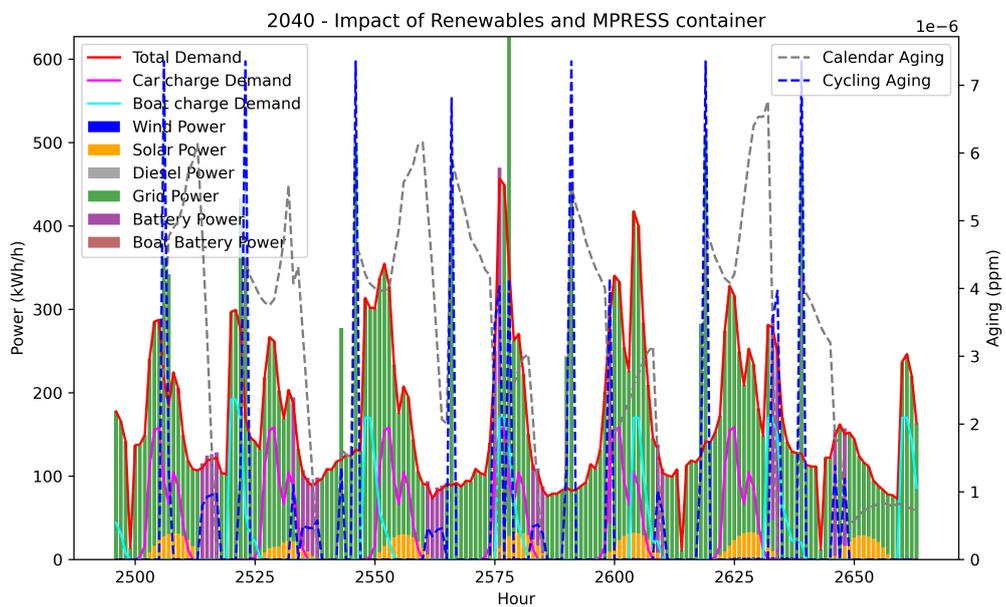


Figure 5.6: Graph of the resulting dispatch of different energy sources from implementing an MPRESS battery container to the site in the year 2040

Using the MPRESS battery without optimizing for minimal degradation but rather for maximizing annual energy usage leads to the following capacity losses. These

losses are determined using Equations 3.13 and 3.14, which account for the material properties of lithium-ion batteries, the state of charge (SOC), and the rate of charging. As shown in Table 5.4, the aging process results in an annual capacity loss of approximately 2%, consistent with previous research [19]. Calendar aging is the most significant factor, primarily due to the battery holding a charge, as indicated by the gray dashed plot in the graphs above. Cycling aging, resulting from the reactions occurring during charging and discharging, contributes between 10% and 30% to the total degradation, as shown by the blue dashed lines in the graphs above.

Table 5.4: The resulting savings from utilizing the MPRESS battery in a harbour with local renewable production

Total grid use: 1280.7MWh (-2.6%)		
2020	2030	2040
Total cost: 598.6 kSEK/yr Yearly savings: -52.8kSEK/yr	Total cost: 394.1 kSEK/yr Yearly savings: -24.9kSEK/yr	Total cost: 472.4 kSEK/yr Yearly savings: -45.2kSEK/yr
MPRESS usage: 194.1 MWh	MPRESS usage: 59.6MWh	MPRESS usage: 68.8MWh
Battery degradation: 2.4% Cyc: 2.8kWh Cal: 9.2kWh	Battery degradation: 1.9% Cyc: 0.9kWh Cal: 8.9kWh	Battery degradation: 2.1% Cyc: 1.0kWh Cal: 9.4kWh

5.2.4 Impact of Boat2Grid

Lastly, the batteries of the docked boats are made available to the micro grid for bi-directional charging. The key difference between the MPRESS battery and the boat batteries is their availability. The MPRESS battery is dedicated solely to supporting the micro grid, while boat batteries are temporarily unavailable when boats are charging to their owners' desired levels or when they are away from the harbor.

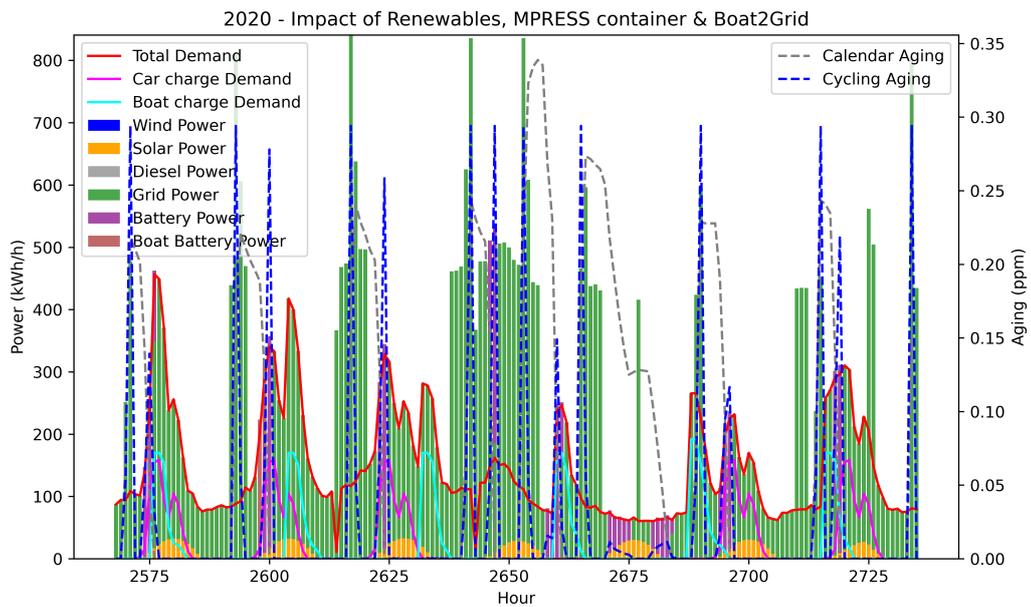


Figure 5.7: Graph of the resulting dispatch from implementing an MPRESS battery container to the site as well as using the harbored boats as on-grid batteries in the year 2020

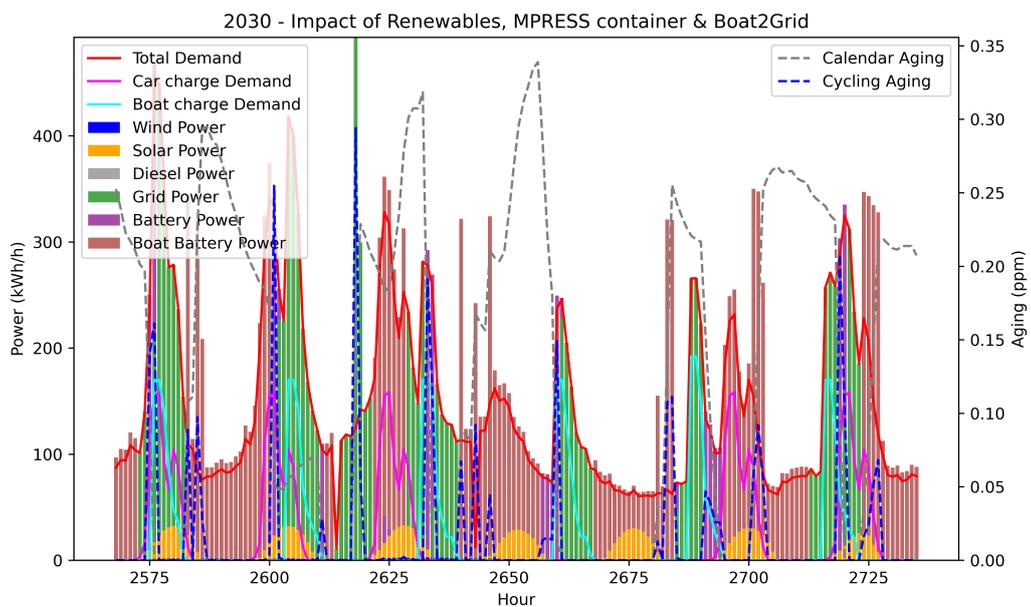


Figure 5.8: Graph of the resulting dispatch from implementing an MPRESS battery container to the site as well as using the harbored boats as on-grid batteries in the year 2030

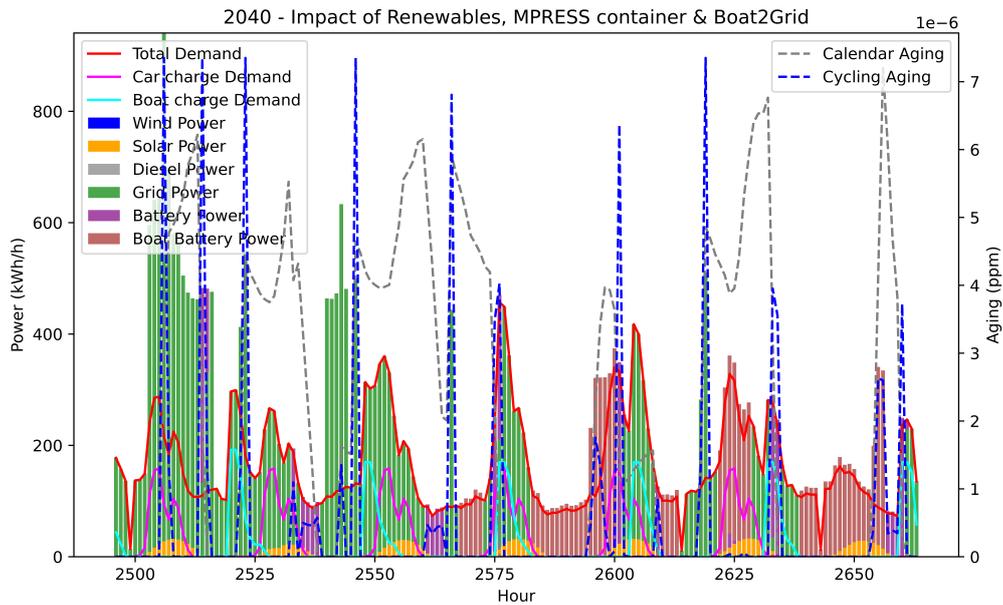


Figure 5.9: Graph of the resulting dispatch from implementing an MPRESS battery container to the site as well as using the harbored boats as on-grid batteries in the year 2040

The total battery capacity available from the 10 boats simulated in the harbor is 1,185 kWh. This integration further reduces the system's cost by providing additional flexibility. When Boat2Grid technology is available, the reliance on the MPRESS battery is reduced. The priority between these two energy storage systems depends on the contract between the harbor owner and the individual boat owners, as increased usage can lead to greater wear and tear on the batteries. In this study, the prioritization of energy storage technologies is based on whichever system minimizes the total cost most effectively over the course of a year.

Table 5.5: The resulting savings from utilizing the MPRESS battery and Boat2Grid in a harbour with local renewable production

Total grid use: 1308.6 MWh (-0,4%)		
2020	2030	2040
Total cost: 537.2kSEK/yr Yearly savings: -86.7kSEK/yr	Total cost: 371.5kSEK/yr Yearly savings: -47.2kSEK/yr	Total cost: 412.1kSEK/yr Yearly savings: -93.9kSEK/yr
MPRESS usage: 166.2 MWh	MPRESS usage: 54.3 MWh	MPRESS usage: 65.5 MWh
Boat2Grid usage: 198.6 MWh	Boat2Grid usage: 106.2 MWh	Boat2Grid usage: 129.1 MWh
Battery degradation: 2.5% Cyc: 2.5kWh Cal: 9.8kWh	Battery degradation: 2.0% Cyc: 0.9kWh Cal: 9.2kWh	Battery degradation: 2.0% Cyc: 1.0kWh Cal: 9.2kWh

6

Conclusion

The analysis and optimization of various energy scenarios for the Krossholmen test site have provided valuable insights into the effectiveness of different strategies for enhancing energy efficiency and reducing costs. This section summarizes the key findings from the study.

6.1 Python Libraries for Energy Optimization

Based on user reviews and reference cases, Pyomo was identified as the most suitable Python library for this project. Despite its complexity, Pyomo's comprehensive range of solvers and its established use in energy modeling at Chalmers University make it the preferred choice. However, the Pulp solver also demonstrates potential for future integration due to its user-friendliness and good performance in energy optimization applications.

6.2 Comparing Future Scenarios

In the base case scenario, where the test site relies solely on the national grid without local renewable sources or battery storage, the analysis highlighted the economic impact of external factors such as the energy crisis. The cost of energy varied significantly across the years 2020, 2030, and 2040, with the highest costs observed in 2020 due to the European energy crisis. This scenario emphasized the importance of incorporating flexibility and local energy production to mitigate such fluctuations.

6.3 Impact of Renewable Energy

The integration of a 4.5 kW wind turbine and 37 kW of solar panels demonstrated the potential benefits of local renewable energy production. Although the overall contribution of renewables was relatively modest compared to total demand, it resulted in a 4.0

6.4 Impact of MPRESS Battery Container

The implementation of the MPRESS battery container led to significant cost savings by enabling peak shaving and optimizing energy usage during periods of high

electricity prices. The savings were most pronounced in 2020, reflecting the benefits of a flexible energy storage system during times of market volatility. Battery degradation analysis indicated an annual capacity loss of approximately 2

6.5 Impact of Boat2Grid

The Boat2Grid concept, which utilizes the batteries of harbor boats for bi-directional charging, further enhanced the flexibility and cost-effectiveness of the energy system. This approach provided additional energy storage capacity, resulting in further reductions in energy costs and grid dependency. The combined use of MPRESS and Boat2Grid systems achieved the greatest cost savings and improved overall energy management at the test site.

6.6 Summary

The study demonstrates that integrating renewable energy sources, battery storage systems like MPRESS, and innovative concepts such as Boat2Grid can significantly enhance the energy efficiency and economic performance of microgrids. While renewable energy and storage solutions offer substantial benefits, their combined implementation provides the most robust strategy for reducing costs and ensuring energy security. This knowledge will aid in guiding the real-world implementation of energy storage solutions in this and future harbor projects.

6.7 Future Work

There are several potential improvements and developments for this project. Enhancing the model's accuracy based on available data is crucial, as the Krossholmen test site is still in early development. As the site progresses, more data and insights about the planned energy system's operation will become available. Specific improvements are listed below:

6.7.1 Commercial MILP Solver

Currently, the results are limited to LP solutions. Using a commercial solver like Gurobi to enable Mixed Integer Linear Programming (MILP) would allow for more accurate calculations of battery degradation, which could be used as an additional objective function alongside the cost function. The open-source solver GLPK was chosen for this thesis to ensure the Python code can be easily transferred to Volvo Penta or a future researcher without requiring additional licenses.

6.7.2 GUI Development, API, and Portability

To make the energy model more accessible to a layperson, it would be beneficial to develop an intuitive GUI for display at the test site's demo center. Converting the

model into a packaged .exe program or a web application would further enhance usability. As development continues at the Krossholmen test site, the model could potentially integrate with the local monitoring system to continuously update its data from Krossholmen and the web databases used in this project.

6.7.3 Real-World Data on Fully Electric Boats

The development of fully electric leisure boats is still in its early market stages, meaning little is known about their future operation. As the market becomes more saturated and real-world data becomes available to Volvo Penta, the energy model can transition from the "boat charging script" currently used to estimate charging habits to more accurate input. Additionally, investigating the value that individual boat owners could gain from participating in a Boat2Grid contract with harbors could deepen the understanding of this subject.

6.7.4 Implications for Society

The project's results suggest that implementing on-grid batteries has a net positive impact both economically and environmentally. However, several factors must be considered before making investment decisions. As discussed in 1.4.1, the significant carbon footprint of modern battery production, including emissions from mining, production, and transportation, should be weighed against the potential energy savings and resulting emissions reductions. While a life cycle analysis of battery storage is beyond the scope of this project, the results can be used to calculate the total ecological impact of flexibility measures in future microgrid developments at Krossholmen.

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A

Appendix 1 - Python Code

Listing A.1: Example Python code

```
import math

import pandas as pd
import matplotlib.pyplot as plt
import numpy as np
import openpyxl
import os
from pyomo.environ import (ConcreteModel, Param, Var, Objective,
                           Constraint, Expression, SolverFactory, Binary,
                           NonNegativeReals, minimize, Set, value, SolverStatus,
                           TerminationCondition, inequality, RangeSet)
from boat_charging_script import generate_charging_data

# import gurobipy

# %% Generate boat data

# Load boat data from Excel
excel_path = r'data\Boats_user_data.xlsx'
boat_user_data = pd.read_excel(excel_path)

for index, row in boat_user_data.iterrows():
    boat_number = row['BoatNumber']
    number_of_trips_per_week = row['NumberOfTripsPerWeek']
    max_charging_power = row['MaxChargingPower'] # kW
    battery_capacity = row['BatteryCapacity'] # kWh
    charging_habit = row['ChargingHabit'] #value between 40-90%
    start_date = row['StartDate']
    end_date = row['EndDate']

    generate_charging_data(boat_number,
                           number_of_trips_per_week, max_charging_power,
                           battery_capacity, charging_habit, start_date, end_date)
```

A. Appendix 1 - Python Code

```
# %% Load data from CSV files
load_data = pd.read_csv('data/load_data.csv', header=None,
names=['load_demand'])
wind_data = pd.read_csv('data/wind_data.csv', header=None,
names=['wind_percentage'])
solar_data = pd.read_csv('data/solar_data.csv', header=None,
names=['solar_percentage'])
price_data = pd.read_csv('data/price_data_2040.csv', header=None,
names=['price'])
car_charge_data = pd.read_csv('data/car_charging.csv', header=None,
names=['car_charging'])
temperature_data = pd.read_csv('data/temperature.csv', header=None,
names=['temperature'])

# Initialize DataFrame for total charging data and availability data
boat_data = None
availability_data = None

# Number of boats (this should be set appropriately)
num_boats = len(boat_user_data)

# Loop through each boat's data
for i in range(1, num_boats + 1):
    file_path = os.path.join(r'data', f'boat_charging_data{i}.csv')
    boat_data_i = pd.read_csv(file_path, header=0,
names=['Date', 'kWh/h', 'Availability'],
    parse_dates=['Date'], index_col='Date')

    if boat_data is None:
        boat_data = boat_data_i[['kWh/h']].copy()
        availability_data = boat_data_i[['Availability']].copy()
    else:
        boat_data = boat_data.add(boat_data_i[['kWh/h']], fill_value=0)
        availability_data =
        availability_data.add(boat_data_i[['Availability']], fill_value=0)

# Sum up the charging data for all boats
boat_data['kWh/h_total'] = boat_data['kWh/h']

# Save the summed availability data to a separate CSV file
availability_data.to_csv(os.path.join('data', 'total_availability.csv'),
header=True, index=True)

# Plot the total boat charging data
plt.figure(figsize=(10, 6))
plt.plot(boat_data.index, boat_data['kWh/h_total'],
```

```

label='Total□boat□charging', color='orange')
plt.title('Boat□Charging□Data')
plt.xlabel('Date')
plt.ylabel('Power□(kWh/h)')
plt.legend()
plt.savefig('boat_charging.png', dpi=2400)
plt.show()

# Plot the availability data
plt.figure(figsize=(10, 6))
plt.plot(availability_data.index, availability_data['Availability'],
label='Availability', color='blue')
plt.title('Availability□Data')
plt.xlabel('Date')
plt.ylabel('Availability')
plt.legend()
plt.savefig('availability.png', dpi=2400)
plt.show()

# Convert availability data to dictionary for use in constraints
num_hours = len(load_data)
boat_charge_dict = {i: boat_data['kWh/h_total'].iloc[i]
if i < len(boat_data) else 0 for i in range(num_hours)}
availability_dict = {i: availability_data['Availability'].iloc[i]
if i < len(availability_data) else 0 for i in range(num_hours)}

# Define Pyomo model
model = ConcreteModel()

# %% Sets
hours = range(len(load_data))
model.hours = Set(initialize=hours)

# %% Parameters
model.load_demand = Param(model.hours,
initialize=load_data['load_demand'].to_dict())
model.load_solar = Param(model.hours,
initialize=solar_data['solar_percentage'].to_dict())
model.load_wind = Param(model.hours,
initialize=wind_data['wind_percentage'].to_dict())
model.boat_charge = Param(model.hours,
initialize=boat_charge_dict)
model.car_charge = Param(model.hours,
initialize=car_charge_data['car_charging'].to_dict())
model.availability = Param(model.hours,
initialize=availability_dict)

```

```

model.temperature = Param(model.hours ,
initialize=temperature_data[ 'temperature' ].to_dict())
# Temperature (K)

# Energy Production
model.wind_power_capacity = 4.5 # kW 4.5
model.solar_power_capacity = 37 # kW 37
model.grid_capacity = 1600 # kW
model.diesel_power_capacity = 400 # kW
model.diesel_price = 19 # SEK/kWh

# MPRESS
# model.battery_capacity = 500 # kWh 500
model.battery_capacity = Param(initialize=500)
model.battery_capacity_initialy = Param(initialize=500)
model.battery_charge_rate = 350 # kW
model.battery_discharge_rate = 350 # kW
model.battery_efficiency = 0.95
model.battery_EOL = 0.5
model.battery_SOC_max = 0.9
model.battery_SOC_min = 0.1
model.battery_SOC_init = Param(initialize=375)
model.discount = 0.05

# Boat battery
Number_of_boats = len(boat_user_data) # st
model.boat_battery_charge_rate =
boat_user_data[ 'MaxChargingPower' ].sum() # kW
model.boat_battery_discharge_rate =
boat_user_data[ 'MaxChargingPower' ].sum() # kW
model.boat_battery_efficiency = 0.9

# Battery degradation
k_calendar = 1.7e-1 # Calendar aging rate constant
k_cycling = 3e-8 # Cycling aging rate constant
Ea = 24.5e3 # Activation energy (J/mol)
R = 8.314 # Universal gas constant (J/mol/K)

# %% Plot initial conditions

plt.figure(figsize=(10, 6))
plt.plot(solar_data[ 'solar_percentage' ]
* model.solar_power_capacity ,
label='Solar Power', color='orange')
plt.plot(wind_data[ 'wind_percentage' ]
* model.wind_power_capacity ,

```

```

label='Wind_Power', color='blue')
plt.plot(load_data['load_demand'],
label='Demand_Curve', color='green')
plt.plot(car_charge_data['car_charging'],
label='Car_Charging', color='red', linewidth=0.1)
plt.plot(boat_data['kWh/h_total'],
label='Boat_Charging', color='cyan', linewidth=0.1)
plt.title('Power_Curves_Throughout_the_Year_[kWh/h]')
plt.xlabel('Hour')
plt.ylabel('Power_(kWh/h)')
plt.legend()
plt.savefig('inital_cond.png', dpi=2400)
plt.show()

```

```
# %% Variables
```

```

model.battery_charge
= Var(model.hours, within=NonNegativeReals,
initialize=0)
model.battery_discharge
= Var(model.hours, within=NonNegativeReals,
initialize=0)
model.battery_SOC
= Var(model.hours, within=NonNegativeReals,
initialize=model.battery_SOC_init)
model.boat_battery_capacity
= Var(model.hours, within=NonNegativeReals,
initialize=0) # boat_user_data['BatteryCapacity'].sum() # kWh

```

```

model.boat_battery_charge
= Var(model.hours, within=NonNegativeReals, initialize=0)
model.boat_battery_discharge
= Var(model.hours, within=NonNegativeReals, initialize=0)
model.boat_battery_SOC
= Var(model.hours, within=NonNegativeReals, initialize=0)

```

```

model.grid_power
= Var(model.hours, within=NonNegativeReals, initialize=0)

```

```

model.diesel_power
= Var(model.hours, within=NonNegativeReals, initialize=0)

```

```
# %% Constraints
```

```
# MPRESS
```

```
def battery_capacity_constraint_rule(model, t):
    return model.battery_SOC[t] <= model.battery_capacity
```

```
model.battery_capacity_constraint = Constraint(model.hours,
rule=battery_capacity_constraint_rule)
```

```
def soc_current(model, t):
    if t == 0:
        return model.battery_SOC[t]

        == model.battery_charge[t] - model.battery_discharge[t]
    else:
        return model.battery_SOC[t]
        == model.battery_SOC[t - 1] + model.battery_charge[t]
        - model.battery_discharge[t]
```

```
model.battery_SOC_constraint = Constraint(model.hours,
rule=lambda model, t: soc_current(model, t))
```

```
def calendar_aging_expr(model, t):
    return k_calendar * math.exp(-Ea / (R * model.temperature[t])) * (
        model.battery_SOC[t] / model.battery_capacity_initialy)
```

```
model.calendar_aging
= Expression(model.hours, rule=calendar_aging_expr)
```

```
def cycling_aging_expr(model, t):
    if t == 0:
        return k_cycling * model.battery_charge[t]
    else:
        dod = abs(model.battery_SOC[t] - model.battery_SOC[t - 1]) /
        model.battery_capacity_initialy
        return k_cycling * dod
        * (model.battery_charge[t] + model.battery_discharge[t])
```

```
model.cycling_aging = Expression(model.hours,
```

```

        rule=cycling_aging_expr)

model.total_aging = Expression(model.hours,
                               rule=lambda model, t:
                               model.calendar_aging[t] + model.cycling_aging[t])

def effective_capacity_expr(model, t):
    if t == 0:
        return model.battery_capacity
    else:
        return model.battery_capacity
        - sum(model.total_aging[i] for i in range(t))

model.effective_capacity =
    Expression(model.hours, rule=effective_capacity_expr)

model.battery_charge_constraint = Constraint(model.hours,
                                             rule=lambda model, t: model.battery_charge[t]
                                             <= model.battery_charge_rate)

model.battery_discharge_constraint = Constraint(model.hours,
                                                rule=lambda model, t: model.battery_discharge[t]
                                                <= model.battery_discharge_rate)

# Boats
model.boat_battery_capacity_constraint = Constraint(model.hours,
                                                  rule=lambda model, t: model.boat_battery_SOC[t]
                                                  <= model.boat_battery_capacity[t])

def boat_soc_current(model, t):
    if t == 0:
        return model.boat_battery_SOC[t]
        == model.boat_battery_charge[t]
        - model.boat_battery_discharge[t]
    else:
        return model.boat_battery_SOC[t]
        == model.boat_battery_SOC[t - 1]
        + model.boat_battery_charge[t] - \
        model.boat_battery_discharge[t]

model.boat_battery_SOC_constraint =
    Constraint(model.hours, rule=boat_soc_current)

```

```

def boat_battery_charge_limit(model, t):
    if model.availability[t] > 0:
        return model.boat_battery_charge[t] == 0
    else:
        return model.boat_battery_charge[t]
        <= model.boat_battery_charge_rate

model.boat_battery_charge_constraint =
    Constraint(model.hours, rule=boat_battery_charge_limit)

def boat_battery_discharge_limit(model, t):
    if model.availability[t] > 0:
        return model.boat_battery_discharge[t] == 0
    else:
        return model.boat_battery_discharge[t]
        <= model.boat_battery_discharge_rate

model.boat_battery_discharge_constraint = Constraint(model.hours,
rule=boat_battery_discharge_limit)

# GENSET
model.diesel_power_constraint
= Constraint(model.hours,
             rule=lambda model, t: model.diesel_power[t]
             <= model.diesel_power_capacity)

# Grid
model.grid_power_constraint = Constraint(model.hours,
                                         rule=lambda model, t: model.grid_power[t]
                                         <= model.grid_capacity)

# Renewables
model.solar_power = solar_data['solar_percentage']
    * model.solar_power_capacity
model.wind_power = wind_data['wind_percentage']
    * model.wind_power_capacity

# Demand balance
model.demand_balance_constraint = Constraint(model.hours,
                                             rule=lambda model, t: model.wind_power[t]
                                             + model.solar_power[t]

```

```

+ model.grid_power[t]
+ model.diesel_power[t]
+ ((model.battery_discharge[t]
* model.battery_efficiency)
- (model.battery_charge[t]
/ model.battery_efficiency))
== model.load_demand[t]
+ model.boat_charge[t] + model.car_charge[t])
# + ((model.boat_battery_discharge[t]*model.boat_battery_efficiency)
# - (model.boat_battery_charge[t])/model.boat_battery_efficiency)

# Objective function (minimize total cost)
model.total_cost = Objective(
    expr=sum(
        price_data['price'][t] * model.grid_power[t]
        + model.diesel_price * model.diesel_power[t]
        for t in model.hours),
    sense=minimize
)

# %% Solve the optimization problem

# Gurobi
# solverpath_folder = r'C:\gurobi1102\win64\lib'
# solverpath_exe = r'C:\gurobi1102\win64\lib\gurobi.jar'
# os.environ['PATH'] += os.pathsep + solverpath_folder
# solvername = 'gurobi_direct'

solvername = 'glpk'
solverpath_folder =
r'C:\Users\jonat\PycharmProjects\Krossholmen\glpk-4.65\w64'
solverpath_exe =
r'C:\Users\jonat\PycharmProjects\Krossholmen\glpk-4.65\w64\glpsol'
solver = SolverFactory(solvername, executable=solverpath_exe)
solver.solve(model)

# Print all values for aging
def print_aging(model):
    for t in model.hours:
        print(f"Hour_{t}: Calendar Aging
        {value(model.calendar_aging[t])}, Cycling Aging
        {value(model.cycling_aging[t])},
        Total Aging {value(model.total_aging[t])}")
    print_aging(model)

```

```

results = solver.solve(model)

if (results.solver.status == SolverStatus.ok) and (
    results.solver.termination_condition
    == TerminationCondition.optimal):
    print("Solver found a feasible solution")
elif results.solver.termination_condition
== TerminationCondition.infeasible:
    print("Solver solution is infeasible")
else:
    print("Solver status:", results.solver.status)

# %% Print out of results
print("Optimal Total Cost:", model.total_cost())

print("\nOptimal Grid Power Schedule")
total_power = 0
for t in model.hours:
    power = model.grid_power[t]()
    total_power += power
    # print(f"Hour {t + 1}: {power} kWh")
print(f"Total Battery Charge: {total_power} kWh")

print("\nDemand")
total_demand = 0
for t in model.hours:
    demand = model.load_demand[t]
    total_demand += demand
    # print(f"Hour {t + 1}: {demand} kWh")
print(f"Total load demand: {total_demand} kWh")

print("\nSOC")
total_SOC = 0
for t in model.hours:
    SOC = model.battery_SOC[t]()/model.battery_capacity_initially
    total_SOC += SOC
    print(f"Hour {t+1}: {SOC}%")
print(f"Total load demand: {total_demand} kWh")

print("\nSolar")
total_solar = 0
for t in model.hours:
    solar = model.solar_power[t]
    total_solar += solar

```

```

    # print(f"Hour {t + 1}: {demand} kWh")
print(f"Total_solar_energy: {total_solar} kWh")

print("\nWind")
total_wind = 0
for t in model.hours:
    wind = model.wind_power[t]
    total_wind += wind
    # print(f"Hour {t + 1}: {demand} kWh")
print(f"Total_wind_energy: {total_wind} kWh")

print("\nOptimal_MPRESS_Battery_Charge_Schedule:")
total_charge = 0
for t in model.hours:
    charge = model.battery_charge[t]()
    total_charge += charge
    # print(f"Hour {t + 1}: {charge} kWh")
print(f"Total_Battery_Charge: {total_charge} kWh")

print("\nResulting_MPRESS_capacity_loss:")
total_loss = 0
total_cal = 0
total_cyc = 0
for t in model.total_aging:
    loss = model.battery_capacity * model.total_aging[t]()
    cal = model.battery_capacity * model.calendar_aging[t]()
    cyc = model.battery_capacity * model.cycling_aging[t]()
    total_loss += loss
    total_cal += cal
    total_cyc += cyc
    # print(f"Hour {t + 1}: {loss} ppm")
percentage = total_loss / 500
print(f"MPRESS_battery_capacity_loss:
{total_loss} kWh, Cycling: {total_cyc} kWh, Calendar: {total_cal} kWh")
print(f"Which_correspond_to {percentage}% of the total capacity")

print("\nOptimal_MPRESS_Battery_Discharge_Schedule:")
total_discharge = 0
for t in model.hours:
    discharge = model.battery_discharge[t]()
    total_discharge += discharge
    # print(f"Hour {t + 1}: {charge} kWh")
print(f"Total_Battery_Charge: {total_discharge} kWh")

print("\nBoat_Charging")
total_bCharge = 0

```

```

for t in model.hours:
    bCharge = model.boat_charge[t]
    total_bCharge += bCharge
    # print(f"Hour {t + 1}: {bCharge} kWh")
print(f"Total_Boat_Charge: {total_bCharge} kWh")

print("\\nCar Charging")
total_cCharge = 0
for t in model.hours:
    cCharge = model.car_charge[t]
    total_cCharge += cCharge
    # print(f"Hour {t + 1}: {bCharge} kWh")
print(f"Total_Boat_Charge: {total_cCharge} kWh")

print("\\nBoat battery Charging")
total_bBatCharge = 0
for t in model.hours:
    bBatCharge = model.boat_battery_discharge[t]()
    total_bBatCharge += bBatCharge
    # print(f"Hour {t + 1}: {bCharge} kWh")
print(f"Total_Boat_Charge: {total_bBatCharge} kWh")

# Week 12 stacked plot
# Filter data for week 12
start_index = 15 * 24 * 7 - 24 # Assuming each week has 24 * 7 hours
end_index = start_index + 24 * 7 # Considering 24 hours for 7 days

hours_array = np.arange(start_index, end_index)
wind_power_array
= np.array([value(model.wind_power[t]) for t in hours_array])
solar_power_array
= np.array([value(model.solar_power[t]) for t in hours_array])
diesel_power_array
= np.array([value(model.diesel_power[t]) for t in hours_array])
grid_power_array
= np.array([value(model.grid_power[t]) for t in hours_array])
battery_discharge_array
= np.array([value(model.battery_discharge[t]) for t in hours_array])
boat_battery_discharge_array
= np.array([value(model.boat_battery_discharge[t])
for t in hours_array])
load_demand_array
= np.array([value(model.load_demand[t]) for t in hours_array])
boat_charge_array
= np.array([value(model.boat_charge[t]) for t in hours_array])
car_charge_array

```

```

= np.array([value(model.car_charge[t]) for t in hours_array])

# Extract calendar and cycling aging values for the specified week
calendar_aging_array
= np.array([value(model.calendar_aging[t]) for t in hours_array])
cycling_aging_array
= np.array([value(model.cycling_aging[t]) for t in hours_array])

# Calculate cumulative sum of non-zero values
wind_cumulative
= np.cumsum(np.ma.masked_equal(wind_power_array, 0))
solar_cumulative
= np.cumsum(np.ma.masked_equal(solar_power_array, 0))
diesel_cumulative
= np.cumsum(np.ma.masked_equal(diesel_power_array, 0))
grid_cumulative
= np.cumsum(np.ma.masked_equal(grid_power_array, 0))
battery_cumulative
= np.cumsum(np.ma.masked_equal(battery_discharge_array, 0))
boat_battery_cumulative
= np.cumsum(np.ma.masked_equal(boat_battery_discharge_array, 0))

# Calculate the total demand
total_demand = load_demand_array + boat_charge_array + car_charge_array
car_demand = car_charge_array
boat_demand = boat_charge_array

# Plotting
fig, ax1 = plt.subplots(figsize=(10, 6))

# Plot the stacked bars
ax1.bar(hours_array, wind_power_array,
label='Wind Power', color='blue')
ax1.bar(hours_array, solar_power_array,
bottom=wind_power_array,
label='Solar Power', color='orange')
ax1.bar(hours_array, diesel_power_array,
bottom=wind_power_array + solar_power_array, label='Diesel Power',
color='gray', alpha=0.7)
ax1.bar(hours_array, grid_power_array,
bottom=wind_power_array + solar_power_array + diesel_power_array,
label='Grid Power', color='green', alpha=0.7)
ax1.bar(hours_array, battery_discharge_array,
bottom=wind_power_array + solar_power_array
+ diesel_power_array + grid_power_array, label='Battery Power',
color='purple', alpha=0.7)

```

```
ax1.bar(hours_array, boat_battery_discharge_array,
        bottom=wind_power_array + solar_power_array
        + diesel_power_array + grid_power_array + battery_discharge_array,
        label='Boat_Battery_Power', color='brown', alpha=0.7)

# Plot the total demand
ax1.plot(hours_array, total_demand,
         label='Total_Demand', color='red')
ax1.plot(hours_array, car_demand,
         label='Car_charge_Demand', color='magenta')
ax1.plot(hours_array, boat_demand,
         label='Boat_charge_Demand', color='cyan')

# Set labels for the first y-axis
ax1.set_xlabel('Hour')
ax1.set_ylabel('Power (kWh/h)')
ax1.legend(loc='upper_left')
ax1.set_title('2040 - Impact of Renewables and MPRESS container')

# Create a secondary y-axis
ax2 = ax1.twinx()
ax2.plot(hours_array, calendar_aging_array,
         label='Calendar_Aging', linestyle='—', color='gray')
ax2.plot(hours_array, cycling_aging_array,
         label='Cycling_Aging', linestyle='—', color='blue')

# Set labels for the second y-axis
ax2.set_ylabel('Aging (ppm)')
ax2.legend(loc='upper_right')
ax2.set_ylim(bottom=0)

# Save and show the plot
plt.savefig('Stacked_PLOT.png', dpi=600)
plt.show()
```

B

Appendix 2 - Boat charging function

Listing B.1: Example Python code

```
import os
import pandas as pd
import numpy as np
import math
from datetime import datetime, timedelta

def generate_charging_data(boat_number, number_of_trips_per_week,
max_charging_power, battery_capacity, charging_habit,
                           start_date, end_date):
    # Convert start_date and end_date to Timestamp objects
    start_date = pd.to_datetime(start_date)
    end_date = pd.to_datetime(end_date)

    # Create date range for the entire year
    start_year = pd.Timestamp(start_date.year, 1, 1)
    end_year = pd.Timestamp(start_date.year + 1, 1, 1)
    full_year_range =
pd.date_range(start=start_year, end=end_year, freq='h')

    # Initialize DataFrame with zeros for the entire year
    data = {'Date': full_year_range,
'kWh/h': [0] * len(full_year_range), 'Availability': [0]
* len(full_year_range)}
    df = pd.DataFrame(data)
    df.set_index('Date', inplace=True)

    # Calculate charging frequency based on number of trips per week
    charging_frequency = 1 / number_of_trips_per_week
    if number_of_trips_per_week != 0 else 0

    # Generate charging data for boat season
    for index, date in enumerate(full_year_range):
        if start_date <= date <= end_date and index
```

B. Appendix 2 - Boat charging function

```
% (24 * 7 * charging_frequency) == 0:
    variation = np.random.normal(charging_habit ,
    charging_habit * 0.1) # 10% standard deviation
    remaining_capacity = battery_capacity * variation
    # Remaining capacity to charge
    total_duration =
    math.ceil(remaining_capacity / max_charging_power)
    # Total number of hours required

    # Mark availability for the 3 hours before charging starts
    for hour in range(3):
        pre_charge_time = date - timedelta(hours=hour + 1)
        if pre_charge_time in df.index:
            df.at[pre_charge_time, 'Availability'] = 1

    for hour in range(total_duration):
        charging_time = date + timedelta(hours=hour)
        if remaining_capacity >= max_charging_power:
            charging_power = max_charging_power
        else:
            charging_power = remaining_capacity

        df.at[charging_time, 'kWh/h'] = max(0, charging_power)
        df.at[charging_time, 'Availability'] = 1
        remaining_capacity -= charging_power
        if remaining_capacity <= 0:
            break

# Save to CSV
save_path =
os.path.join('data', f'boat_charging_data{boat_number}.csv')
df.to_csv(save_path, header=True, index=True)
```

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