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Industrial Electrical Engineering and Automation

Renewable power generation and energy storage potential in Malmö harbor

- A preliminary study for renewable self-sufficiency of CMP's operations

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LUND UNIVERSITY

Master thesis at Lunds Tekniska Högskola
by Albin Ek & Fredrik Wiker

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Supervisor was Jörgen Svensson from the Division of Industrial Electrical Engineering and Automation.

Examiner was Olof Samuelsson from the Division of Industrial Electrical Engineering and Automation.

The project was carried out in cooperation with CMP, Jessika Cansund and Anders Jönsson.

Division of Industrial Electrical Engineering and Automation
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Abstract

The ongoing global energy transition calls for a larger share of renewable power generation. The variability of intermittent energy sources, like solar photovoltaic and wind power, is creating a demand for energy storage to balance electricity production and consumption. Copenhagen Malmö Port (CMP) is a port operator with the goal to become one of the world's most sustainable ports. In line with the current energy transition, CMP wants to become self-sufficient in renewable electricity.

In this thesis different renewable electricity production and storage technologies are evaluated. Energy profiles for CMP's consumption are found. One matching the current consumption and another approximating a future scenario where shore power is offered to docking ships. Using the assumption that total yearly production will match the annual consumption possible photovoltaic (PV), wind and battery storage systems are analyzed. The different systems are sized to optimize the amount of produced electricity that is utilized and the profitability of each systems is studied.

It is found that the current consumption can be met with PV on the company's suitable roofs. For the shore power scenario there is not deemed to be enough suitable area to meet the requirements with solely PV meaning that the addition of wind power would be required. In general, systems with wind in addition to PV are seen to increase the utilization and profitability compared to systems with only PV. The addition of battery energy storage can further increase the utilization but decreases profitability. For both consumption scenarios a system with PV, wind and battery storage is found to result in the highest utilization of 78% of total produced electricity.

Acknowledgements

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Contents

Abbreviations

Abbreviation	**Explanation**
AAR	Average annual return
BESS	Battery energy storage system
BMS	Battery management system
CMP	Copenhagen Malmö Port
CRF	Capital recovery factor
EIA	Environmental impact assessment
GCR	Ground coverage ratio
HESS	Hydrogen energy storage system
IRR	Internal rate of return
LCOE	Levelized cost of energy
NPV	Net present value
O&M	Operations & Maintenance
OBWAEC	Oscillating body WAEC
OWCWAEC	Oscillating water column WAEC
OWAEC	Overtopping WAEC
PCS	Power conversion system
PRV	Present value
PTO	Power take-off
PV	Photovoltaic
SoC	State of charge
TMY	Typical meteorological year
WAEC	Wave energy converters

1 Introduction

In this section the background, goals and delimitations of this thesis will be presented along with a short outline of the different chapters.

1.1 Background

Greenhouse gases such as carbon dioxide are released into the atmosphere from a wide range of human activities. These emissions are enhancing the greenhouse effect causing the global climate to get warmer and warmer every year. The last decade has most likely been the warmest decade in over 125 000 years. This increase in temperature are causing gradually more serious problems for the human society as well as the ecosystems and biodiversity around the planet. To reduce the risk for more serious irreversible consequences it is considered necessary to keep the global temperature rise at a level at least below 2°C but take efforts to keep it below 1.5°C. The greatest contributor to these emissions is the burning of fossil fuels for heat and electricity purposes. [1] Because of this the transition to renewable power generation will be one of the main enablers in being able to keep the global temperature rise below the required level.

However the transition to renewable energy sources does not come without its own problems. The biggest problem with renewables is that they are an intermittent form of power generation. Intermittent means that their production and availability is changing due to external factors and therefore cannot be controlled. This causes problems for the power grids which were not built with intermittent energy in mind, but rather to accommodate stable and controllable power generation. Grid operators have to ensure that the electricity supply reliably meets the demand at all times to avoid serious problems such as blackouts, which is a lot harder to control when intermittent energy is prevalent. To avoid this the renewable energy supplied to the grid has to become more stable and controllable. [2] A solution for this is to use energy storage. Energy storage can counteract the uncertainty of renewables by making the supply to the grid predictable.

Copenhagen Malmö Port (CMP) is one of Scandinavia's largest port operators, and a full-service port in the Öresund region. CMP has sustainability as an important factor in their operation and has a goal of leading the way for sustainable ports by becoming one of the worlds most sustainable ports by 2025. As mentioned above, renewable power generation is one of the main enablers of keeping the global temperature rise below the required level, so working towards this they want to become self-sufficient on self-produced renewable energy. They want to do this by researching the potential for renewable power generation and energy storage in their operational port areas.

1.2 Purpose and research questions

The aim of this thesis is to find solutions for generating and storing renewable energy in Malmö harbor to make CMP's operations energy self-sufficient on a yearly basis. By evaluating the possibilities and performance of different power generation and energy storage systems we find the technology combination that best fits the energy requirements and gives the best utilization of the produced electricity. This is done to give CMP insight in their potential for renewable power generation in their port areas. This to help them achieve their sustainability goals and become more environmentally friendly.

Research questions

- Which methods for electricity production and storage are of relevance for the operation of CMP?
- Can CMP's current annual energy requirements be met with renewable power generation and energy storage in their areas in Malmö harbor?
- Is it possible for CMP to accommodate an increased energy demand if shore power was offered to the vessels?
- Which of the relevant combinations of electricity production and energy storage have the highest utilization of the produced electricity?
- Are these combinations of electricity production and energy storage profitable?

1.3 Method

This thesis is structured into two main parts: a literary study which explores relevant research as a foundation for decisions, calculations and simulations as well as a case study of CMP to answer the research questions.

The literary study focus on the technologies for power generation and energy storage to build up knowledge on which technologies are relevant for the operations of CMP as well as other topics needed for calculations and simulations. The technologies considered are photovoltaic power, wind power, wave power, battery storage systems and hydrogen storage systems. The aim is to highlight the status, potential and challenges of each technology as well as give a basic understanding of each principle.

The case study is focused around CMPs energy requirement and how it could be met with different combinations of power generations and energy storage. The study examines how the utilization changes with the different technologies as well as assessing the profitability.

1.4 Delimitations

Given the time constraints of a master thesis some delimitaions had to be set to ensure that the thesis is feasible and achievable.

CMP has operations in Malmö, Copenhagen and Visby but this thesis focuses only on the operation in Malmö. The thesis focuses only on three different technologies for power generation, photovoltaic, wind and wave, and two different technologies for energy storage, battery and hydrogen, even though there are more renewable options to consider. This was decided from discussions with CMP on what area and what technologies was of most interest.

1.5 Outline of the report

- **Chapter 2 (Background):** This chapter aims to provide knowledge into photovoltaic power, wind power, wave power, battery energy systems and hydrogen energy systems. The status, potential and challenges are highlighted as well as the basic principle of each technology. The electricity market, electricity prices as well as economic formulas are also described to get a foundation for the profitability calculations.
- **Chapter 3 (Methodology and theory):** This chapter describes the methodology of the case study. Different scenarios involving consumption, technology and storage optimizations will be presented as well as the process behind energy mapping, site study, simulations, optimizations and economic analysis.

- **Chapter 4 (Results):** This chapter provides results for the simulations of the maximum potential in CMP's areas in Malmö harbor. Further it gives results for the different scenarios described in the methodology chapter with figures, tables and numbers for both power generation and economics. To improve readability the results are also initially discussed throughout this section.
- **Chapter 5 (Discussion):** This chapter aims to discuss and analyse the thesis. The discussions are divided into a results discussion where the results presented in chapter 4 are further discussed and analysed. As well as present a method discussion where the methodology used and the uncertainties present in the study are also discussed.
- **Chapter 6 (Conclusions and future work):** This chapter aims to conclude the findings made in the thesis and present our answers for the research questions as well as give a small discussion about future work.

2 Background

This section will provide basic knowledge about the different technologies for power generation and storage as well as theory about electricity price. When relevant, descriptions of Norra Hamnen are also presented.

2.1 Photovoltaic power

Photovoltaic (PV) takes advantage of the huge amount of energy our sun continuously sends towards our planet. The sunlight coming from the sun is a spectrum of photons which are distributed over a range of different energy levels. It is these photons the PV cells makes use off to make electricity. PV cells are made of semiconductors which have electrons weakly bonded in a band of energy called the valence band. If a certain amount of energy is applied to these electrons it will break the weak bonds making the electrons move to another energy band called the conduction band. In the conduction band it is now possible to collect and drive the electrons through an external circuit in which the now created electric current can be extracted and used to generate electrical power. The amount of energy needed for this to occur is called the band gap energy and it is this energy that the photons provide. The semiconductor materials typically used has a p-n junction, with the p-side having lots of positive charge and the n-side lots of negative charge to create a potential difference. [3] A sketch of a typical PV cell technology can be seen in Figure 2.1

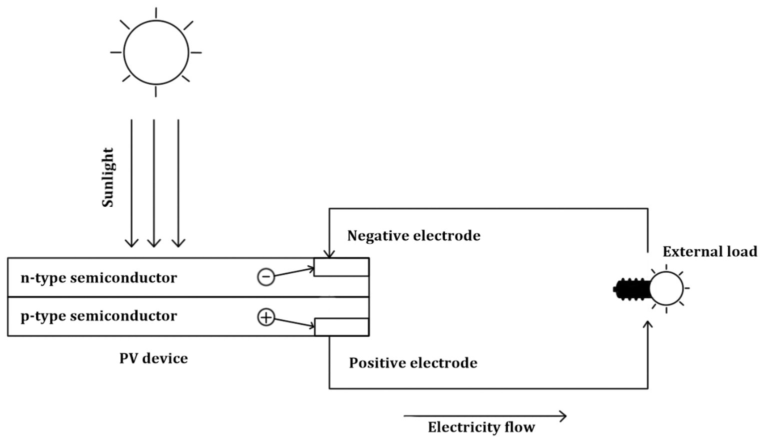

Figure 2.1: Typical PV cell technology.

2.1.1 PV systems

PV systems can be very different from site to site depending on the needs of that specific site. It could be a system only needed during the day. A standalone system using energy storage to be able provide energy when the PV cells does not produce electricity like during night time. A hybrid system which instead of or with energy storage has another power generator. A grid-tied system that does not use energy storage, or a grid-tied system which does use energy storage in case of an outage or for economical purposes.

The PV systems typically consists of an array of PV panels mounted on a structure to fixate them either on a roof or on the ground. The PV panels are made up of multiple modules consisting of multiple photovoltaic cells. Other components depends on which of the previously mentioned systems is present, but typically an inverter to convert the current from DC to AC and a electric meter to measure the electricity, is used. If the system uses energy storage with a battery, a charge controller to control the battery and the battery itself is present. In the case of a hybrid system the other power generator is also present, and with the grid-tied system there is also a connection to the grid. [4] A typical PV system with grid connection can be seen in Figure 2.2 .

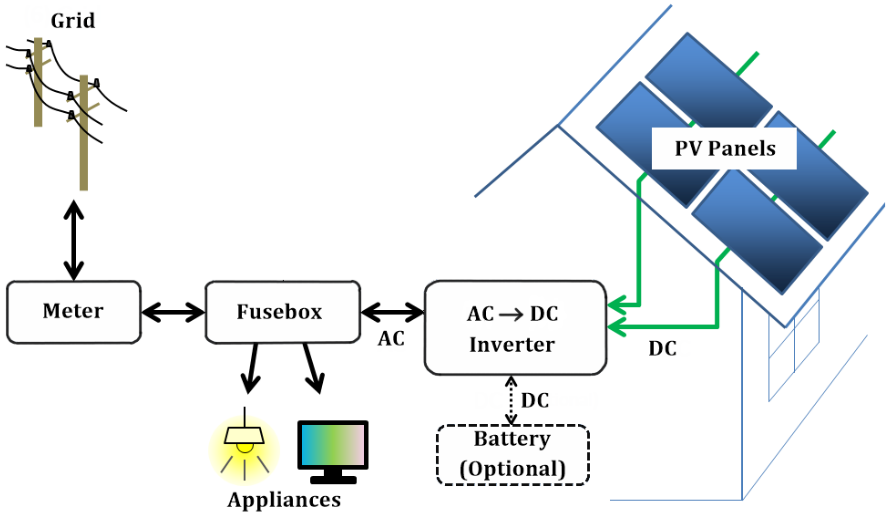

Figure 2.2: Typical grid-tied PV system.

The most important part of the PV system is the PV module. There is a lot of different types of technology when it comes to the photovoltaic cell. The first generation of PV cells are produced on silicon wafers and are today still the most popular solar cell technology because of their high power efficiencies. They can be categorized into mono-crystalline silicon cells and multi-crystalline silicon cells. The second generation PV cells consist of thin-film cells and are cheaper compared to the earlier generation. These consists of amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium gallium di-selenide (CIGS). The third generation PV cells are not yet at a commercial state but are promising new technologies. The ones that are most developed are nano crystal-based PV cells, polymer-based PV cells, dye-sensitized PV cells and concentrated PV cells. [5]

The second most important part of the system is the inverter. PV panels produce DC which means that an inverter is needed to change the current to AC. There are mainly three different types of inverters, which are string inverters, micro inverters and power optimizers.

String inverters have one centralized inverter and is the most standard type of inverter in the industry. Pros of this type is that it has a low cost and is the standard inverter, but the big con being that everything is coupled together meaning that if one panel is damaged, shaded, or facing another way, it will affect the whole panel system.

Microinverters are small inverters that are built into every individual solar panel to give each panel the ability to function at its peak without being dependent on the other panels. The pros of this is that it can handle damaging or shading of one panel without affecting the others and also if the panels are facing different directions. But this comes with the con of having a higher initial cost which might not be worth it if all panels are facing the same way and shading is not present.

Power optimizers is a type that is somewhere in the middle between the other two both in function and price. They have a component underneath each individual solar panel called "the optimizer" which optimizes the current but does not change it from DC to AC. The panel instead sends the current to a centralized inverter just like the string inverter. So the pros with power optimizers is that they are more efficient than the string inverters, this because of individual current optimizing which handles shading, while also being cheaper than the microinverters. Although, they are also like the microinverters not needed if all panels are facing the same way and shading is not present, as well it does not have the same ease for system expansion as the microinverters have because of the needed centralized inverter. [6]

2.1.2 Solar radiation

Solar radiation, which is the energy emitted by the sun, comes in three different components which can be seen in Figure 2.3. The direct or beam radiation which is the part of sunlight that directly reaches the surface, diffuse radiation which is sunlight that is scattered in the atmosphere and Albedo, or ground reflected radiation which is the part that is reflected by the Earth's surface. These three components make up the global radiation which is the same as the total solar radiation. The amount of the global radiation that is then received on a surface is called the global irradiation and is usually, when it comes to PV context, used as the global horizontal irradiation which means the global irradiation on a horizontal surface.[7]

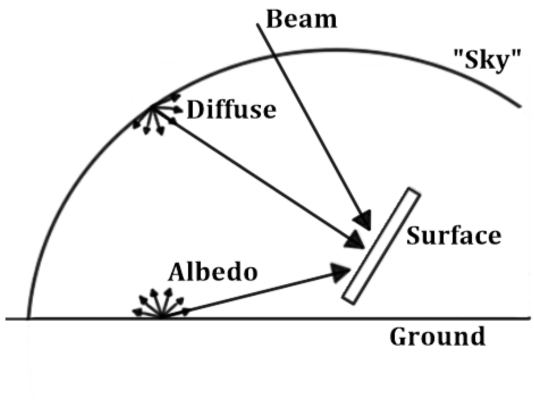

Figure 2.3: The three different components of solar radiation.

2.1.3 Status and potential

PV has a lot of potential to satisfy the global consumption of electricity. The global horizontal irradiation over the world and specifically southern Sweden can be seen in Figure 2.4.

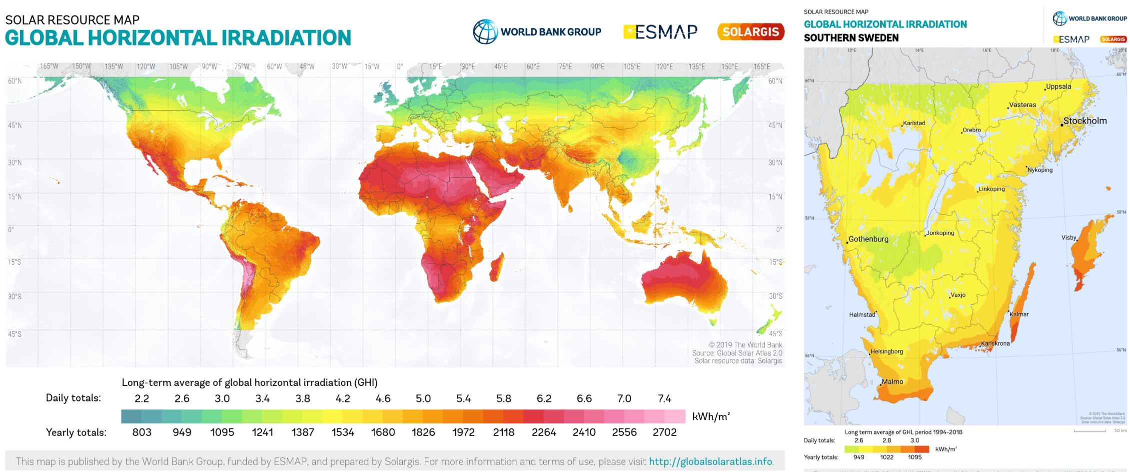

Figure 2.4: Global Horizontal Irradiation in the world and specifically southern Sweden. The text in the figure is not relevant, of note is that red areas have more irradiation whilst green and blue areas have less irradiation. Image taken from [8].

To get a better of picture of what PV system actually could produce with the irradiation we instead take a look at the PV power potential. This potential is defined as the amount of kWh electricity that is produced by a PV system with 1kW peak installed capacity in kWh/kWp,[9] where Wp is the power generated by a PV system at "standard test conditions" characterized by an irradiance of 1000W/m^2, cell temperature of 25°C and with an air mass 1.5. [7] The PV power potential over the world and specifically southern Sweden can be seen in Figure 2.5.

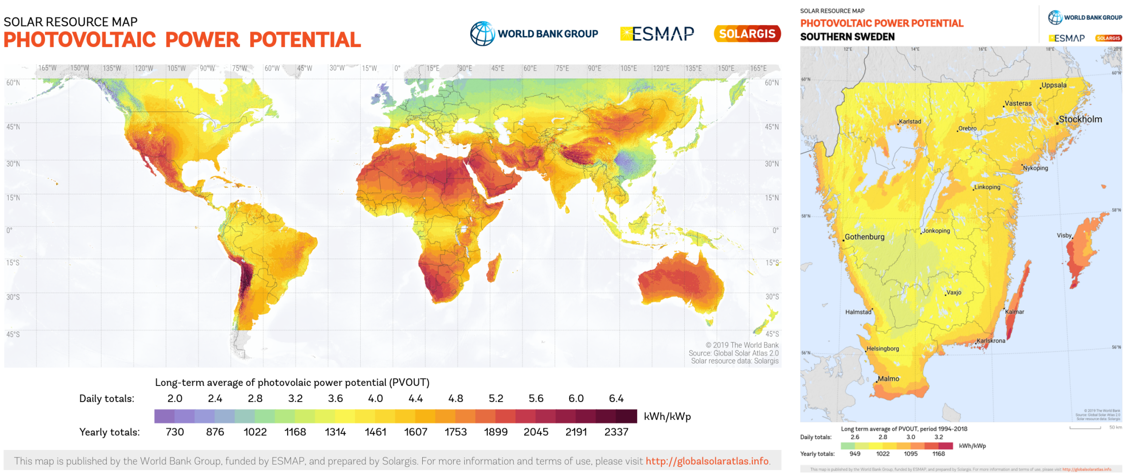

Figure 2.5: PV power potential in the world and specifically southern Sweden. The text in the figure is not relevant, of note is that red areas have more irradiation whilst green and blue areas have less irradiation. Image taken from [8].

Over the last decade, installed photovoltaic power has grown rapidly, which can be seen in Figure 2.6. The total installed power capacity is on trajectory to surpass the capacity of coal, becoming the largest in the world by 2027. [10]

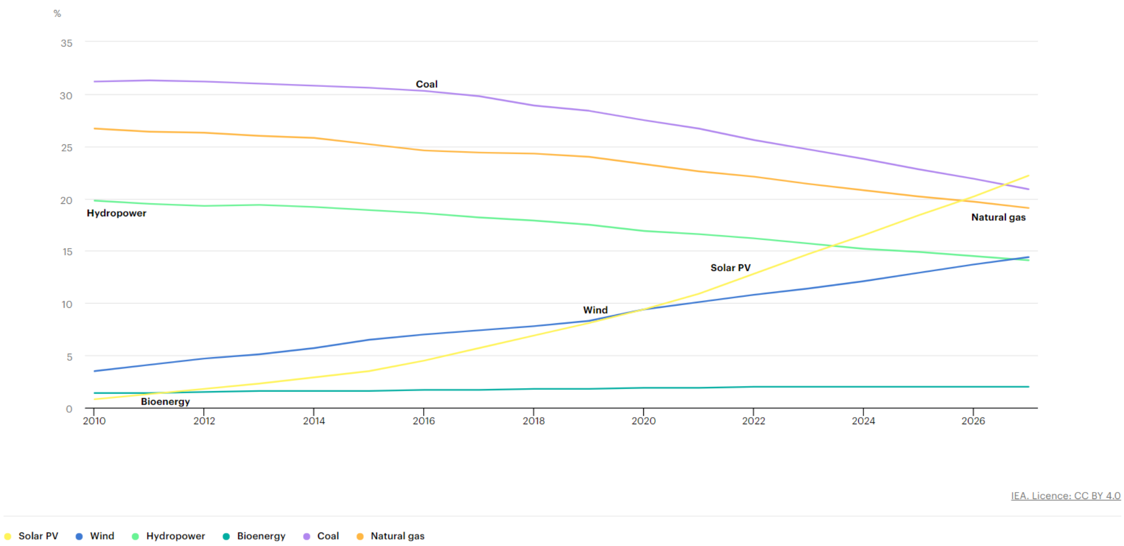

Figure 2.6: Share of cumulative power capacity by technology, 2010-2027. Image taken from [11]

In addition to the increased power capacity the power generation has also followed the same steep trend. In 2022 the power generation for PV increased by 26% compared to 2021 with a record breaking 270 TWh, which meant a total generation of almost 1300 TWh. With this increase PV power stood for 4.5% of the total global power generation during 2022. PV power is still the third largest technology for renewable power generation but the generation increase in 2022 displayed the largest increase for all renewable that year surpassing wind power for the first time. [10]

Sweden

If we take a look at how PV power performs in the total power generation in Sweden it has a pretty low percentage of the total generation at only 1.18%. But Sweden is still following the rapid increase in PV power. The power generation increased by 75% between 2021-2022, increasing from 1,1 TWh to 2,0 TWh. [12] The power generation over the last couple of years from PV power in Sweden can be seen in Figure 2.7.

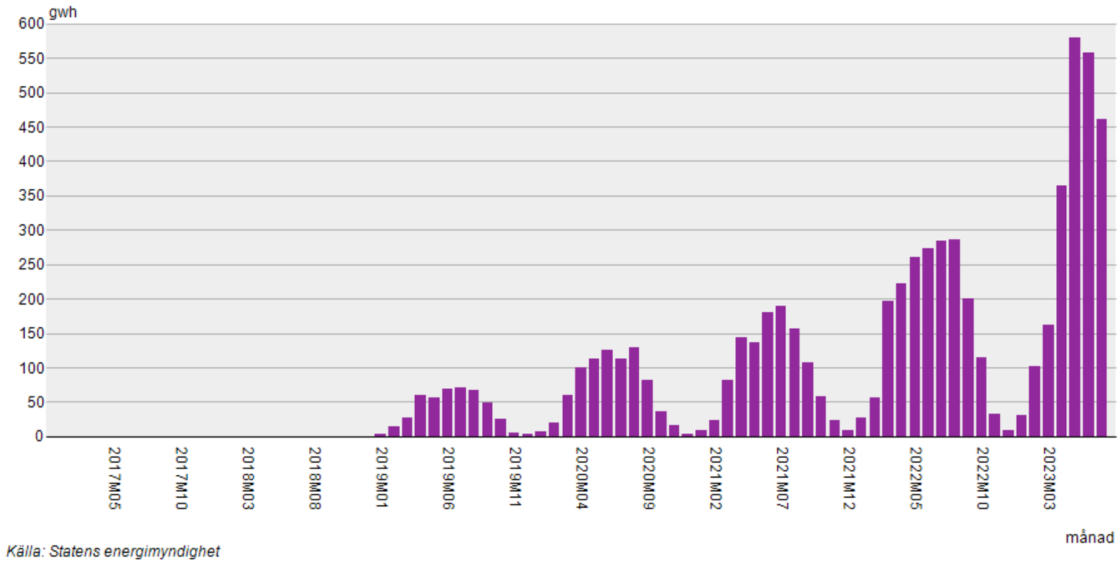

Figure 2.7: Monthly power generation from PV in Sweden. Image taken from [13]

2.1.4 Drawbacks of PV

Even though the future for PV looks promising it does not mean that the system comes without any drawbacks. The main drawbacks of PV is its weather, time and location dependency, but it also has some environmental impacts that are significant.

Weather and time dependency

The photovoltaic cells needs photons from the sun to produce electricity meaning that when it is night or cloudy it is not possible for the cell to produce any electricity, and when its bright and sunny the system might instead overproduce. This means that a PV system produces more electricity in the summer than during the winter which can be seen in Figure 2.8 showing the production from a PV system over a year. If we instead take a look at a daily perspective we can see in Figure 2.9 that PV systems also has quick variations in power for example during a cloudy day where clouds covering the panels are making the power quickly drop and then rise again when they are gone.

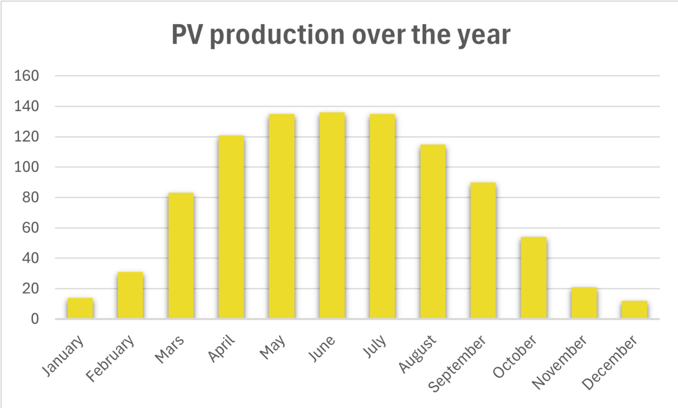

Figure 2.8: PV production over the year from a 1kWp system at 35 degrees tilt in Stockholm. Data taken from [14]

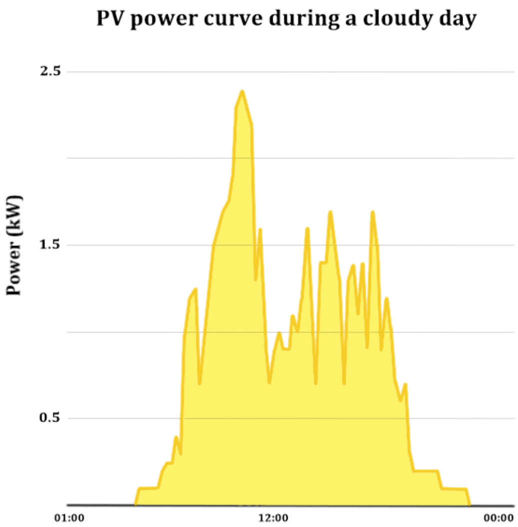

Figure 2.9: Power curve from a 4.2kW PV system during a cloudy day. Data taken from [15]

With all of this it means that the PV system is usually in need or could benefit from some type of energy storage. [16] Batteries are usually the preferred method but other storage types like hydrogen storage systems could also be used. Both of these will be covered later in the theory.

Location dependency
As seen in Section 2.1.3, the location is important. Different amounts of solar radiation has the potential to hit the cells depending on the position and distance to the sun in relation to the cell and this is dependent on the time of the day and the year, and also on where on Earth the cells are located. [17] Because the intended physical location is usually hard to change, the panels tilt and azimuth are the parameters that have to be optimized to get as much production out of the panels as possible.

Environmental impacts
The main environmental impacts from PV comes from its energy demand when being produced, its use of hazardous chemicals and problems arising with recycling. There is substantial amount of energy needed when producing PV cells and panels from the different processes involved such as mining, manufacturing and transportation. Depending on if this energy comes from renewable sources or not will heavily impact the CO_2 footprint from the production. It is typical to use hazardous chemicals when processing semi-conductors to the solar-grade silicon. This means that

there will also be a difference in the environmental impact in this aspect depending on if the manufacturer disposes these chemicals properly or not. Currently recycling is not a major problem because not much PV panels are being recycled yet, but when the need for panels being recycled rises a good solution needs to be present. Currently, countries having a robust e-waste disposal uses this system for the PV panels. [18]

2.1.5 Economics

Data for an economical analysis of a typical PV system can be seen in Table 2.1. Data for Operations & Maintainence (O&M) costs were given in swiss franc (CHF) and converted to SEK with the currency conversion 1 CHF = 11.8 SEK.

Table 2.1: Economical data for PV [19][20][21][22]

	Roof	Ground
Capital cost (SEK/kWp)	10300	13200
O&M* (SEK/kWp)	314	314
Degrading (%/Year)	0.5	0.5
Lifetime (Years)	30	30

*Includes change of inverter, cleaning every year and repairs

2.2 Wind power

Wind turbines harvest energy from wind and convert it into electricity. Wind is, simply put, created as the sun heats air close to the surface which causes it to rise. Colder, denser air from adjacent areas then move in to the high pressure areas created by the heating. This movement is the basic principle of wind. [23]

2.2.1 Wind turbines

A wind turbine consists of four main parts: the foundation, the tower, the nacelle and the rotor. [23]

Rotor

The rotor of a wind turbine most commonly consists of three blades. The wind speed and rotational speed of the blades generates a lift force that causes the rotor to rotate. The delivered power, P, first extracted from the wind by the rotor and then converted to electricity is

$$P = \frac{1}{2}\rho V_0^3 A C_p \eta_l, \tag{1}$$

where $\rho = 1.225 kg/m^3$ is the air density, V_0 is the wind speed, A is the area the rotor sweeps, C_p is a dimensionless power coefficient and η_l describes the internal losses of the turbine. The power coefficient, C_p, depends on blade geometry as well as the ratio between wind speed and tip speed of the blade. [23]

A power curve describes a specific turbines electrical power output as a function of wind speed. An example of a power curve is presented in Figure 2.10. This specification is provided by the manufacturer and takes into account the rotor, gearbox, generator and control systems as well all component efficiencies. Power production begins at the cut-in wind speed, reaches its maximum at the rated wind speed and stops at the cut-out speed. [24]

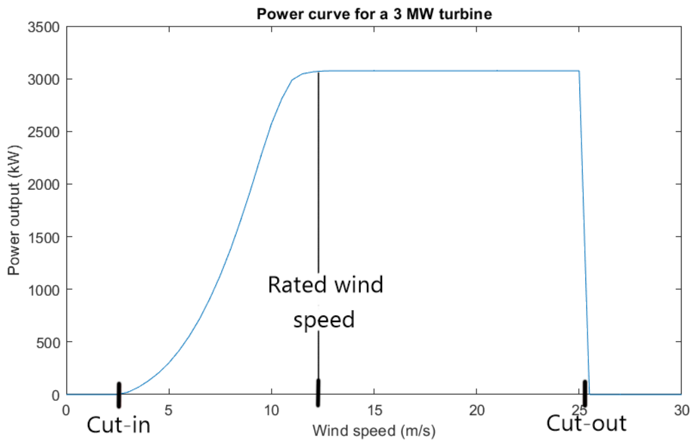

Figure 2.10: Example of a power curve with marked cut-in and cut-out wind speeds. Curve represents a 3 MW turbine.

Each point on the power curve can be calculated using Equation 1 and the C_p for the turbine and wind speed in question. As an example, for $V_0 = 9\,m/s$, a rotor diameter of 112 m, a given C_p of 0.440 and $\eta_l = 1$, a power output of $P = 1935.6kW$ can be calculated. In comparison, the power output presented for 9 m/s in Figure 2.10 is 1954 kW.

Nacelle

The nacelle is the housing at the top of the tower, on which the hub and rotor is mounted. The power extracted by the rotor is transferred through the hub into the nacelle. The hub is connected to a shaft that transfers the power, either through a gearbox into the generator or directly to the generator, see Figure 2.11. These components are contained within the nacelle along with the control systems for the turbine. Common control aspects are yaw angle (nacelle rotation), power limiting at higher wind speeds to avoid high loads or damage, starting, stopping, reducing noise and preventing shadow flicker from the rotating blades affecting nearby residents. [23]

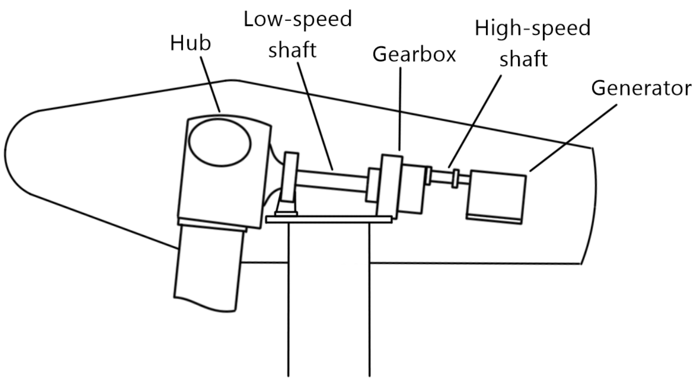

Figure 2.11: Schematic drawing of the components in a wind turbine with gearbox.

Foundation and tower

The foundation's purpose is to transfer loads into the ground and ensure that the turbine is stable. These loads come from self-weight of the turbine and the wind. For wind turbines on land, spread and pile foundations are most common. Spread foundations consist of a large reinforced concrete plate that spreads turbine loads into the soil. Where the soil is weaker a pile foundation is more commonly used. These consist of a plate with piles of reinforced concrete or steel going deeper into the soil. [25] Another type of pile foundation that is common in offshore applications is the monopile. The monopile is a steel tube of around 2.5 to 4.5 meters in diameter that is driven into the seabed or a drilled hole. A type of spread foundation that is also used for offshore wind turbines is the gravity foundation. It consists of a pile connecting to a concrete plate resting on the seabed and utilizes the self-weight of the foundation to keep the turbine stable. Multimember foundations consist of a tripod or four legged jacket structure that is anchored to the seabed by piles. [24]

2.2.2 Planning and installation

The first step towards building a wind power plant (WPP) is to assess the location to determine conditions and limitations at the site. [26] The wind conditions at the site are assessed to predict energy output of a potential WPP and what type of turbine to use. A wind speed database might be initially used to assess the wind and select suitable sites, see Figure 2.12. One or more meteorological masts (met masts) might be installed on site to measure the wind. In larger project areas more masts are needed to interpolate wind conditions across the site. If measurements cannot be made at hub height, multiple anemometers can be placed on the same mast at different heights to extrapolate the vertical wind profile. The vertical wind profile can be approximated using the power law:

$$U_2/U_1 = (z_2/z_1)^\alpha, \tag{2}$$

where U_i is the wind speed at height z_i and α is the shear index. The shear index represents the vertical features at the surface, such as the presence of trees, hills or buildings. [23]

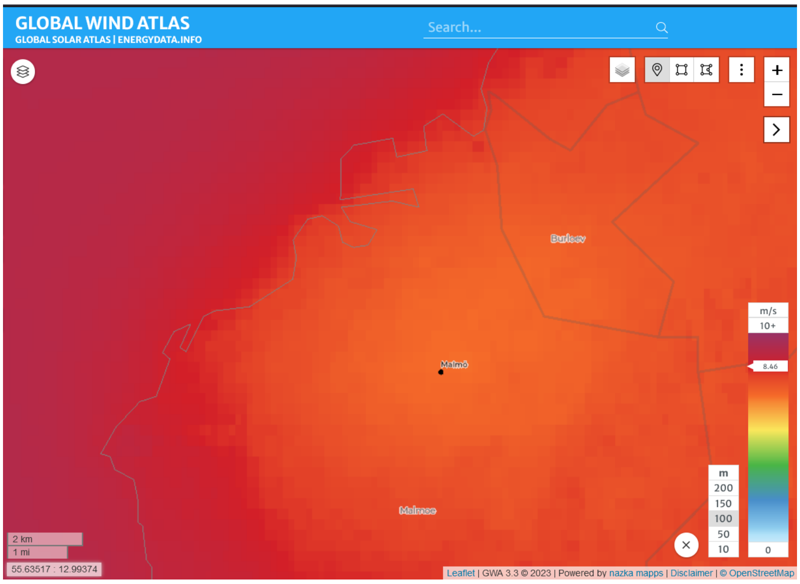

Figure 2.12: Wind database showing wind speeds in Malmö harbour at 100 m height. Map obtained from the Global Wind Atlas version 3.3, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU). The Global Wind Atlas version 3.3 is released in partnership with the World Bank Group, utilizing data provided by Vortex, using funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalwindatlas.info [27]

Environmental conditions at the site are also assessed. Possible impacts on animals and plants are listed and measures to protect these are developed if needed. Safety concerns and impacts on the public are also considered. Falling blades or tower parts as well as ice throw from freezing on the blades puts restrictions on minimum distance to roads or public areas. The rotating blades might, for certain sun angles, cast flickering shadows on nearby residences. This can put further restrictions on placement of the turbines and warrant stopped operation during a few hours in a year. Wind turbines also make noise, both aerodynamical from airflow around the blades and mechanical from the generator, gearbox and components like fans or motors in the nacelle and tower. Noise level limitations then put another restriction on distance between turbines and public spaces. Generally, shadow flicker and noise level distance restrictions are larger than those concerning falling debris or ice. [23]

After initial surveys and assessments consultation is held between authorities, local residents, the public and the contractor. Here, information on, effects of and opinions on the project can be exchanged. Using the information gathered as basis an application for an environmental permit is constructed. Along with this an environmental impact assessment is made, detailing the wind power plants' possible effects on humans and nature. Generally these are revised and updated before they eventually get approved. After permits are received detailed planning of the power plant begins. This is followed by decisions regarding investment and finally construction. [26] [28]

2.2.3 Status and potential

Wind power is the second largest renewable energy source, after hydroelectric power, with a production of over 2100 TWh in 2022. The installed capacity is increasing, as well as the rate of installation. Total installed capacity is 902 GW in 2022 and newly installed capacity is expected to reach a record amount of 107 GW in 2023. [29]

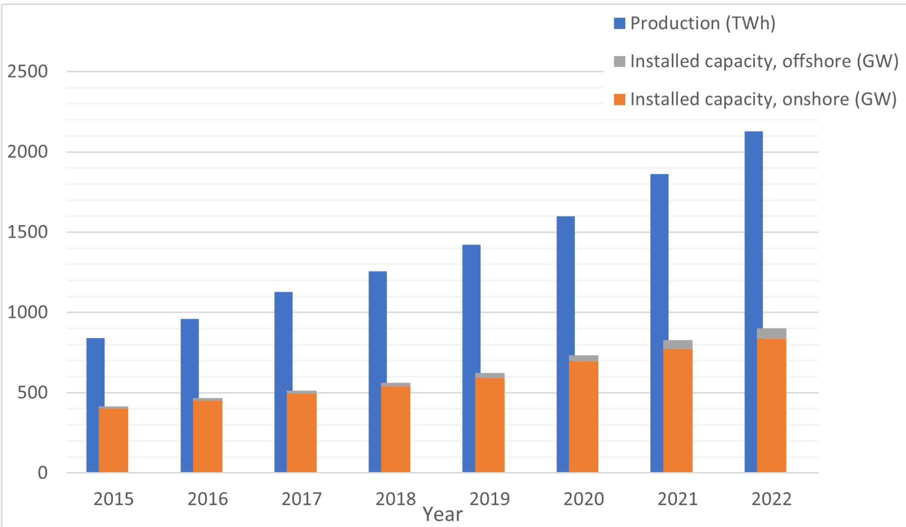

Figure 2.13: Global installed capacity and annual production from wind power. Image taken from [29].

The wind market is expected to grow with 15% per year until 2027. Additional onshore wind installations of 550 GW are expected during that period. These onshore installations will account for a majority of the growth but offshore installations are however expected to increase by a larger fraction but from a lower current installed capacity. [30]

Sweden
In Sweden the amount of wind power has rapidly increased in the last 15 years, as can be seen in Figure 2.14. In 2022 there were about 5250 wind turbines in Sweden and wind power accounted for 20% of the country's electricity production. [31]

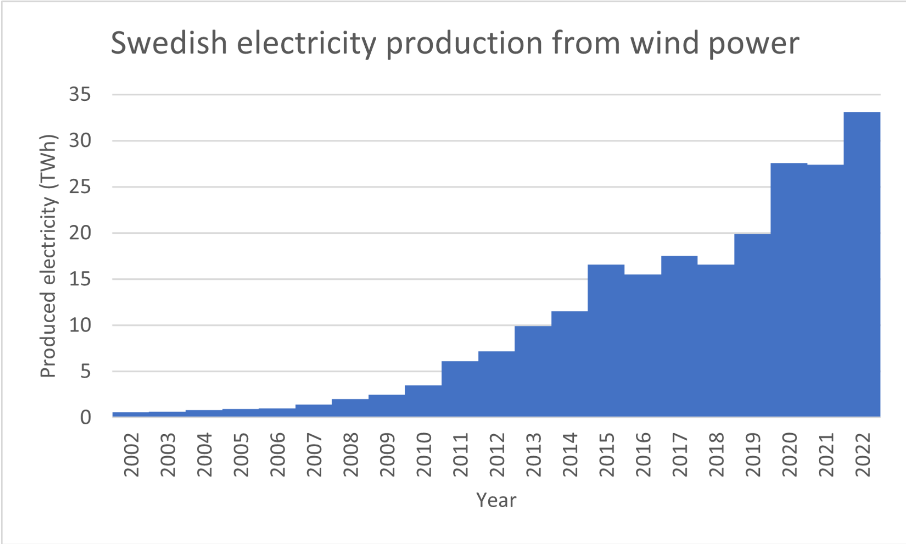

Figure 2.14: Electricity produced annually from wind power in Sweden during the period 2002 to 2022. Image taken from [32].

Wind power in Sweden is expected to keep growing, accounting for a majority of added production in the next 3 years. [33] On a longer timescale wind power is also projected to be the largest contributor to increased electricity production. [34]

2.2.4 Wind power in Malmö port

Plans to build wind power in Malmö port have existed since the late 1990's. [35] In connection to the housing exposition Bo01 in 2001 a wind turbine called Boel was built in Norra Hamnen. [36] It had a rotor diameter of 80 m, hub height of 80 m and produced 2 MW. Boel was dismantled in 2017. There is also currently a wind turbine of 45 kW running in Norra hamnen. [37] Currently, a plan to expand Norra Hamnen and construct two wind turbines is being processed. The proposition would allow wind turbines of 175 m maximum height to be installed and includes plans to expand the available land by filling a part of the harbor with material. Construction of two turbines on the expanded landmass are mentioned in the plan, see Figure 2.15. Further examination would be required to get permission to build these turbines. [38]

Figure 2.15: The proposed expansion (red outline) and wind turbine siting (black circles) in Malmö harbour. Map taken from [39].

An environmental impact assessment (EIA) has also been made for the proposition that handles wind turbines constructed on land. Bird life will not be seriously affected as the proposed sites are far enough away from Natura 2000-areas and wind turbines in Norra Hamnen are currently situated closer to these sensitive areas. The harbour area is less sensitive to cityscape aspects and turbines would fit in with the current industry landscape present there. Therefore, the effects of turbines on the cityscape are deemed acceptable. Noise additions from the turbines are not expected to exceed current noise levels from the harbour and the distance to residential zones, present and planned, are deemed sufficient. The risks from falling objects is negligible if proper mainenance is done. Proposed safety measures are ice detectors on the blades, information in the surrounding area as well as no parking within 200 meters of the turbines. [40]

2.2.5 Challenges

Wind turbine power generation may be a well developed and rapidly expanding market, but it still faces challenges. The most relevant for this thesis are intermittency related challenges, environmental impacts and issues in the permission process.

Intermittency

Wind is one of the most difficult meteorological phenomena to be forecast. It varies quickly on short timeframes, as illustrated in Figure 2.16. This inherent intermittency of wind causes problems in predicting the power output of a wind turbine. Day ahead predictions may be inaccurate, leading to the turbines having to curtail production if the prediction was lower than the actual available production. Maximum production may also not coincide with peak load-hours. Further, there is not an equal amount of wind during different times of the year, as shown by the differing productions during different months in Figure 2.17. Backup power, consisting of energy storage or inefficient traditional power plants, may then need to cover the lack of production. [41]

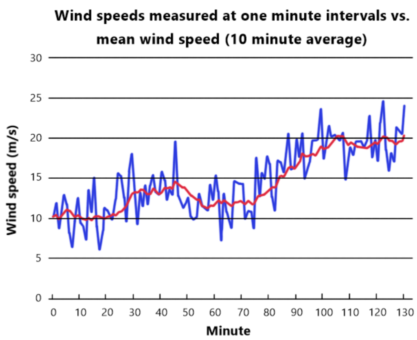

Figure 2.16: Measured wind speeds (Blue) plotted together with 10 minute mean wind speeds (Red).

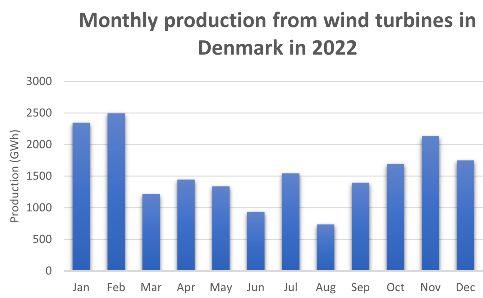

Figure 2.17: The monthly electricity production from wind turbines in Denmark in 2022. Data taken from [42]

Environmental impacts

Wind power plants require large areas for turbines and infrastructure like substations and power lines. This means they are often constructed in rural and natural areas where there is plenty of space leading to industrialization and loss of biodiversity. Construction of offshore turbines disturbs marine mammals and the turbines may cause detrimental effects on the seabed. Turbines are viewed to affect the scenery and may possibly negatively impact tourism if constructed in areas with natural scenery. Wind turbines also produce noise, however restrictions on sound levels are generally in place meaning damage to hearing is not a possibility. The turbines can also interfere with radar and telecommunication signals. [41]

Permissions
To get permission to build wind turbines in Sweden the municipality where the construction is to take place needs to agree to the project. It is believed that the general opinion on wind turbines, in particular those planned to be located close to or in view of residential areas, is poor. The environmental good a wind turbine can do may also not be accounted for by the public when reviewing potential turbine siting. Municipal politicians have had a tendency to deny applications, especially close to elections, and public opinion is likely why. In addition the Swedish armed forces have the right to deny any wind power plant application by referring to the safety of the country. [43]

2.2.6 Economics

Data for an economical analysis of a typical wind turbine can be seen in Table 2.2. The currency conversions used are $1 = 10.47 SEK and €1 = 11.44 SEK.

Table 2.2: Economical data for Wind power [44] [23]

	Onshore	Offshore
Investment cost (SEK/kW)	13300	36200
O&M (% of total investment cost)	3	3
Lifetime (Years)	30	30

2.3 Wave power

Ocean waves have a lot of potential when it comes to generating renewable energy. Although the studies vary a bit on how much of the wave energy that could actually be successfully utilized, some studies still conservatively estimate the amount to be around 10-20% of the global energy requirements. If these estimations could be legitimate it would mean that a considerable part of the total world power consumption could be saturated.[45] This potential has meant that wave energy has gradually gained more and more attraction over the years. The United States, China, India and Europe are leading the way for development of wave energy converters (WAEC) designed to utilize the wave energy for power generation. The design concepts of WAEC has many varied forms and structures based on different concepts and combinations, and the patents for different WAEC designs has exceeded 1000. [46] In the following segment the main WAEC technology concepts will be sorted into different types and the principle of each briefly explained.

2.3.1 WAEC technology

The process of converting the wave energy to electricity usually consist of three stages of energy conversion. Firstly the wave energy is converted into mechanical, pneumatic or potential energy. Following this, the second stage of conversion is conversion into useful mechanical energy using the specific power take-off (PTO). The third and final conversion is then a conversion from the useful mechanical energy into electricity by using a generator. A widely accepted classification method of the different types of WAEC divides it into three different types: oscillating body type, oscillating water column type and overtopping type. [46]

Oscillating body type
The ocean waves have random and irregular characteristics. Considering the desire of continuity in power generation, the oscillating buoy power generation technology uses the body's movement to drive the PTO. Depending on the shape, size and angle of the relative incident wave direction of the body, the oscillating body WAEC (OBWAEC) can be sorted into three different types: point absorber, attenuator and terminator. [46] A sketch of this principle can be seen in Figure 2.18.

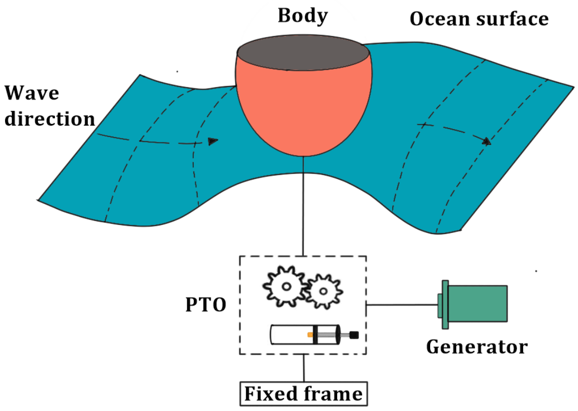

Figure 2.18: Basic principle of OBWAEC technology.

Oscillating water column type
The oscillating water column technology uses air as its conversion medium for its power generation. It has an air chamber that is open on the top and bottom where the upper opening is connected to the atmosphere and the lower opening connected to the ocean. When a wave passes through the air chamber it forces the water column to move in the vertical direction, this changes the volume of the air chamber creating an oscillating airflow which by the PTO drives the generator to produce electricity. The oscillating water column WAEC (OWCWAEC) using this technology can be divided into two different types: floating type and fixed type. [46] A principle sketch of this technology can be seen in Figure 2.19.

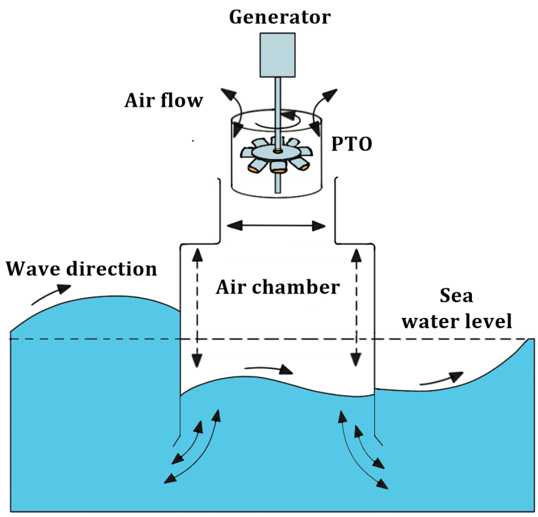

Figure 2.19: Basic principle of OWCWAEC technology.

Overtopping type
Wave movement has both kinetic and potential energy. The overtopping technology takes advantage of this by using a sloped wave-type surface to firstly block wave motion and then guide the waves to climb along the surface and into a reservoir. Then because of the difference between the internal and external water heads, the water in the reservoir flows along the outlet pipe driving the PTO, which in turn drives the generator to produce electricity. The overtopping WAEC (OWAEC) can also be divided into floating type and fixed type.[46] The principle can be seen in Figure 2.20.

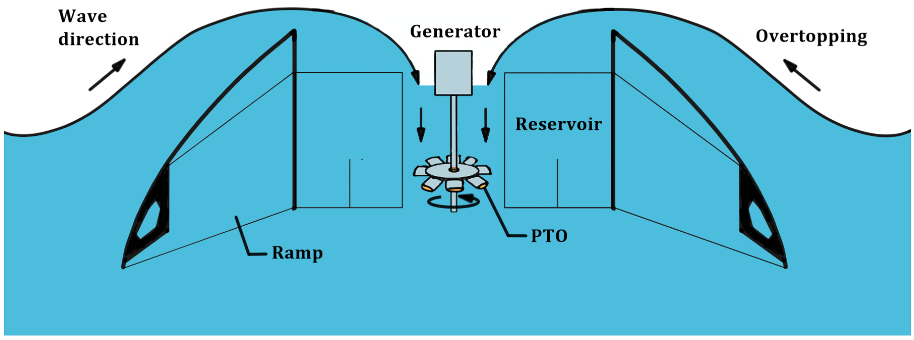

Figure 2.20: Basic principle of OWAEC technology.

2.3.2 Status and potential

As previously mentioned WAECs have a lot of potential to be a realistic alternative for renewable power generation. Ocean wave energy is one of the most reliable, powerful and attractive renewable energy sources. This because of the high accuracy in energy prediction and minimal energy loss because of waves propagating over a long distance, the high density of sea water compared to air and good availability and forecast-ability. The power intensity of wave energy is $2 - 3kW/m^2$ compared to wind and solar with $0.4 - 0.6kW/m^2$ and $0.1 - 0.2kW/m^2$ respectively. [47]

The installed capacity of WAECs from a few years back and planned capacity can be seen in Figure 2.21 and 2.22 respectively. A bunch reports have an optimistic view that wave energy could tackle a large amount of the electricity demand in different countries. It is estimated that wave energy could meet 15-22%, 33% and around 60% of the total electricity demands in UK, Denmark and the US respectively. Similar to this it is estimated that it could meet 15% of the total electricity demand in Europe. [47]

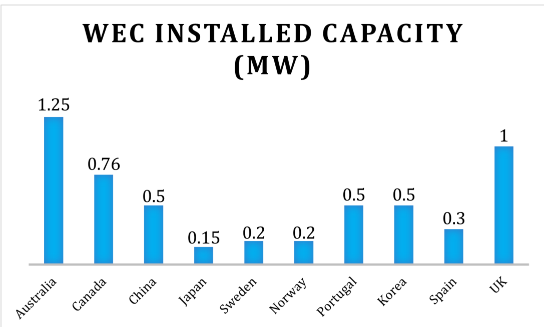

Figure 2.21: WAEC installed capacity as of 2016. Image taken from [47].

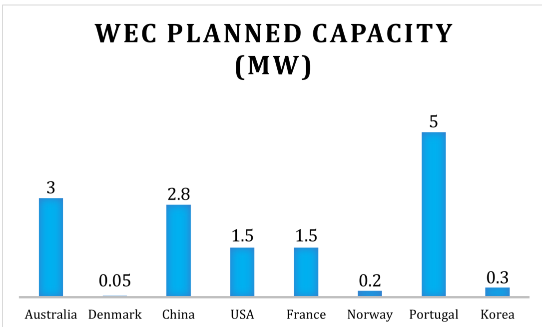

Figure 2.22: WAEC planned capacity as of 2016. Image taken from [47].

2.3.3 Challenges

With the potential of WAECs being high, there are still many different types of challenges when it comes to the technology. These challenges range from techno-economical problems to challenges with operation and maintenance in the unforgiving oceanic environment due to its salinity and extreme weather conditions. It is already a challenge to design, operate and install any type of structure, device or facility in the ocean. But WAEC makes it an even greater challenge by not only being located in the ocean, but also interacting with ocean waves to produce electricity. This means that the probably complex strategy of how to deal with these problems during operation and maintenance, have to be planned during the design stage of WAEC systems which will most likely increase the lifecycle cost. [45]

The biggest problem with WAEC technology today is that it is still in an early stage if you compare it to other forms of renewable power generation like solar and wind, which are both already matured and hard established. Because of this there is not a standard technology principle which means that as seen in Section 2.3.1, many different technologies are being considered for wave energy utilization to find out which is the best. Therefore it is difficult at a design stage to be able to predict and address the challenges ahead because of the scarce information of each technology. [45]

2.4 Battery storage system

To store energy a battery is often used. A battery consists of electrochemical cells that are made up of two electrodes with an electrolyte in between. The negative electrode (anode) reacts with the electrolyte and is oxidized, producing electrons. When the positive electrode (cathode) receives electrons during discharge of the battery, positive ions flow through the electrolyte, maintaining charge balance. To prevent the flowing ions from coating the surfaces of the electrodes there is a barrier or separator between the electrodes. Gaining electrons is called reduction, thus the chemical reactions in a battery are called reduction-oxidation reactions or redox reactions. These reduction and oxidation reactions have different standard potentials and the difference between them relates to the electrochemical cell's voltage. Connecting cells in series increases the battery's voltage additively. [48]

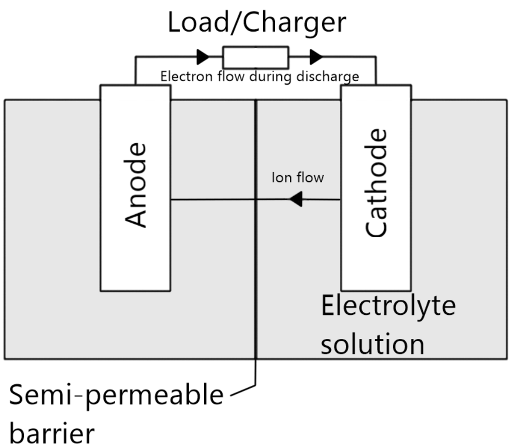

Figure 2.23: Schematic drawing of a battery.

During discharge of the battery chemical products are made that inhibit the redox reactions from continuing with the same efficiency. This eventually causes electrons to stop flowing and the battery is "empty". The reactions in the battery are generally reversible, and when connected to an external source of electricity the electrons and positive ions can flow back to the anode and cathode respectively, thus recharging the battery. This replacement of ions back onto the electrodes is not perfect and over many charge-discharge cycles the electrodes deteriorate, decreasing efficiency. Even when the battery is not connected, reactions can still occur and self-discharge the battery. [48]

There are many different battery technologies. Three of the most commonly used are lead-acid, lithium-ion and flow batteries.

Lead-acid

The lead-acid battery's cathode is made of lead dioxide and its anode is made of a metallic sponge lead. The electrolyte is a mixture of sulfuric acid and water. Some advantages of lead-acid batteries are their low cost, low self-discharge rate, technical maturity and fast response speed. These batteries do however have low life cycles and energy density as well as a noteworthy environmental impact. [49]

Lithium-ion

Lithium-ion batteries have an anode made of graphite and a cathode made from lithium. These are the most common battery on the market, making up 90% of batteries used today. Li-ion batteries have a long lifetime, high energy density, fast response and low self-discharge although they have a high cost. [49]

Flow battery

Flow batteries function differently from the other batteries. They utilize two electrolytes stored separately that get pumped into cells where they exchange ions through a separating membrane. A schematic of a flow battery can be seen in Figure 2.24. The most mature flow battery type is vanadium redox flow batteries (VRFB). These have high operational safety, long lifetime, high efficiency, low self-discharge but low energy density and high operating cost. [49] [50]

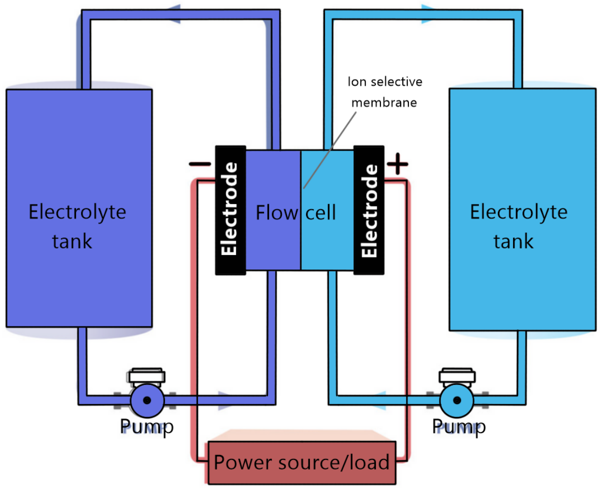

Figure 2.24: Schematic image of a flow battery.

Performance

Different battery technologies have different performance characteristics. For this thesis the important parameters are self discharge rate and lifespan. Based on the presented battery types a 0.1% self discharge per day and lifespan of 15 years is used. [49]

2.4.1 Battery energy storage systems

To utilize batteries for energy storage a battery energy storage system or BESS is used. The general layout of a BESS is depicted in Figure 2.25. Generally, these consist of three components: Batteries, a battery management system (BMS) and a power conversion system (PCS). The BMS monitors the batteries, keeping track of charge, performance and potential hazards. It prevents overcharging and optimizes the level of charge, all to prolong the system's lifetime. As the grid operates on alternating current and the batteries on direct current a PCS is required between the two. The PCS converts electrical power from DC to AC and vice versa. This bi-directionality of the PCS allows electricity to flow from the batteries during high load and to them during high production or off-peak hours. [51]

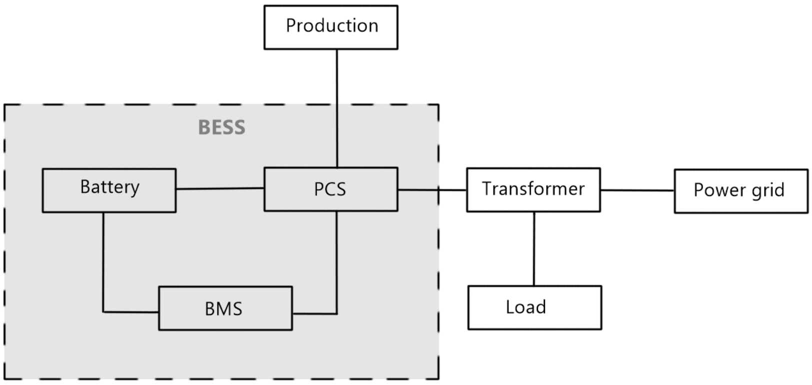

Figure 2.25: Simplified overview of a BESS and surrounding system components.

A battery energy storage system is often delivered as modules housed in containers. Along with the battery cells, the management systems and power conversion components are also mounted in the container. The modules are often customizable to fit the specific requirements of each project. The size of the containers are around 10 m^2/MWh. [52]

2.4.2 Status and potential

Historically there has been little installed battery energy storage. Most of the 28 GW total installed capacity at the end of 2022 was added in the last six years. However, installations are ramping up. The annual installed capacity in 2022 totalled 11 GW, a 75% increase from the previous year. [53] One projection using current policies predicts a total installed capacity of almost 600 GW at the end of 2030, with 110 GW having been added in 2030. [54]

2.4.3 Challenges

Further and accelerated deployment of battery storage is deemed necessary for a high penetration of renewable energy to be achievable. For this to be possible the cost of batteries have to be decreased. The amount of charge-discharge cycles that can be completed before the batteries lose performance, also called cycle life, also has to be improved. The self discharge of batteries mean that energy generally cannot be stored for more than a day. To make long duration storage with batteries viable technological advancements have to be made. If battery production is accelerated supply chain issues might arise. Availability of minerals and costs related to mining and processing might limit the growth in battery production. [55]

2.4.4 Economics

Battery costs vary widely from between technology types and projects, as can be seen in Table 2.3. [56] For this thesis an investment cost of 5000 SEK/kWh is used, based on a few sources. [55] [56] [57] [58] The currency conversions used are $1 = 10.47 SEK and €1 = 11.44 SEK.

Table 2.3: Economic costs for different battery technologies. [56]

Characteristics	Lead-acid	Li-ion	VRFB
Investment cost (SEK/kWh)	565-4188	3141-26175	1571-11360
O&M costs (SEK/kW/year)	73-524	63-126	73-733

2.5 Hydrogen storage system

Hydrogen can be produced from thermal, electrolytic or photolytic processes using different feedstocks like water, coal, natural gas, biomass, hydrogen sulfide, boron hydrides and others. The production route can be split into four different categories: biomass, fossil fuel, renewable and nuclear [59], which can be seen in Figure **??**. All of these add up to several different methods used for hydrogen production. The one relevant for this thesis is water electrolysis from renewable sources which will therefore be the only one covered.

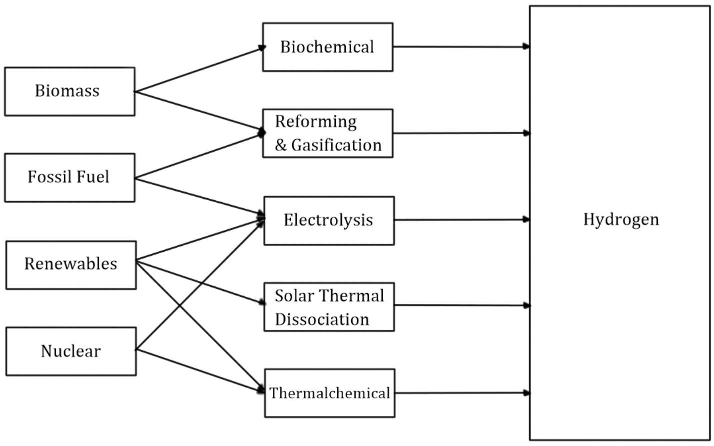

Figure 2.26: Production routes of hydrogen.

Water electrolysis
It is possible to decompose water into hydrogen and oxygen through redox reactions with the use of an electric current, which could come from a renewable source such as wind or PV. The unit that this reaction takes place in is called an electrolyser and the overall reaction is

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2.$$

There are three different types of electrolysers that are being used which are alkaline electrolysers, proton exchange membranes (PEM) and solid oxide electrolysers (SOE). The electrolyser stack consist of several cells which are linked in series. The design of this is either a monopolar design where the electrodes are positive or negative with parallel connection of the single cell or a bipolar design where the single cell are linked in series both geometrically and electrically. The bipolar design is more compact than the monopolar but is in return more expensive to manufacture. Furthermore there are three different types of electrolysis processes for splitting H_20. *Cold electrolysis* of liquid water at or close to ambient temperature, *high pressure electrolysis* with pressurised water and *high temperature steam electrolysis* where the water is converted to steam. [59]

2.5.1 Hydrogen energy storage systems

Hydrogen has a high gravimetric energy density but a low volumetric energy density. This means that the storage of hydrogen is an important factor to consider in a hydrogen energy storage system (HESS). There are typically three different approaches on how to store hydrogen, physical storage as compressed gas, physical storage as cryogenic liquid and materials-based storage. The most common and mature methods for hydrogen storage is the first two mentioned methods. Materials-based storage is still mostly under research and development and is depending on the advancements in the development of advanced materials. [59]

Physical storage as compressed gas
Hydrogen has the possibility to be stored as compressed gas with a pressure up to 700 bar in a cylinder that is capable of it. Pressurised hydrogen gas is the most popular and most used method of hydrogen storage. The big advantage of storing hydrogen as high pressured gas is the simplicity of the method and the fast rate that the gas can be stored and released. The drawback though is that the volumetric density does not increase proportionally with the pressure because of the real gas behaviour of hydrogen. [59]

Physical storage as cryogenic liquid
To get a better volumetric energy density the hydrogen can instead be stored as a cryogenic liquid which has higher energy stored per unit volume and also in the case of low pressure liquid hydrogen storage systems has a relatively low cost. The major drawback though is the high cost and energy consumption for liquefaction. Hydrogen needs to be cooled down to -252°C for liquefaction which means that the energy of over 30% of the lower heating value will be used for the process of liquefaction compared to only 15% for the process of compression. Another factor that plays a part is the boil-off phenomena which comes from the unavoidable heat input into the storage tanks that can evaporate 2-3% of the hydrogen every day. [59]

Material-based storage
A promising method for hydrogen storage is the material-based storage where hydrogen atoms or molecules are tightly bound with other elements. This method has the possibility to store a large amount of hydrogen in a relatively small volume which is solving the biggest drawback of hydrogen storage. There are two different bonding mechanisms for this type of storage, chemisorption and physisorption. In chemisorption, hydrogen molecules are dissociated into hydrogen atoms and integrated into the lattice of the materials. While in physisorption the hydrogen atoms or molecules are instead attached directly to the surface of the materials.[59]

Fuel cells
After the hydrogen has been produced and then stored the next step is to convert the hydrogen into electricity, for this a fuel cell can be used. A fuel cell manages electrochemical reactions to convert chemical potential energy into electricity and hydrogen is the normal fuel used for this. [59] The fuel cell is composed of three active components, a fuel electrode as the anode, an oxidant electrode as the cathode and an electrolyte in between. The simple operation of a fuel cell can be seen in Figure 2.27. Hydrogen is delivered to the anode from an outside gas flow stream and reacts with the anode with the reaction being

$$H_2 \rightarrow 2H^+ + 2e^-.$$

The proton then travels across the electrolyte while the electrons are forced trough an external circuit to get to the cathode. At the cathode the protons and electrons then react with oxygen also supplied from an outside gas flow stream to produce water. The reaction for this is

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

which completes the full reaction which is the two half reactions added together as

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + W + Waste\ heat$$

where W is the useful work. The electrons that travels trough the external circuit is doing work on an electric load therefore constituting the useful electrical energy output. As seen in the full reaction, waste heat is also generated from the electrochemical reactions. The waste heat and water need to be handled, which means that water and heat management plays an important part in the fuel cell design. [60]

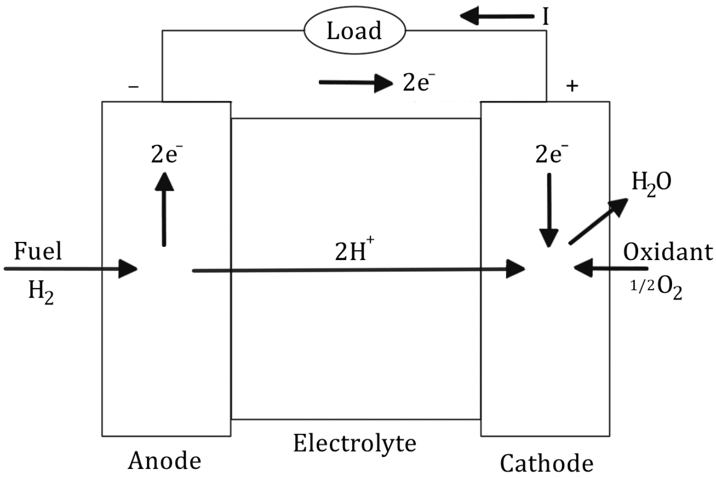

Figure 2.27: The simple operation of a fuel cell.

Power-to-gas

Another possibility for hydrogen instead of converting it to electricity is to directly use it in the gas grid or for methanation which then goes to the gas grid. [59] A schematic for this can be seen in Figure 2.28.

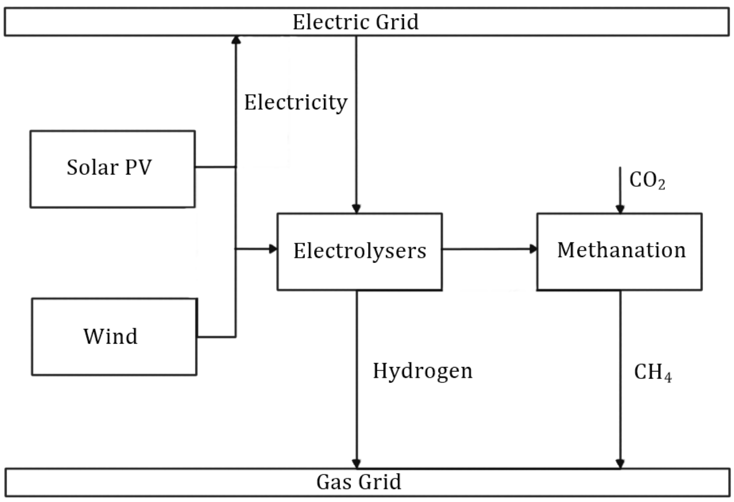

Figure 2.28: The principle of power-to-gas.

The easiest usage is to directly inject hydrogen into the natural gas grid. The advantages of this are that it is a one step process which reduces additional costs and energy losses and also that there is no need for storage of the hydrogen. But a potential drawback that has been researched is that this type of direct injection could influence the thermodynamic and transportation properties of the natural gas if significant quantities gets injected. It could also influence the natural pipeline and end use applications such as gas turbines and gas burners directly.
The other alternative is methanation where hydrogen reacts with carbon dioxide (CO_2) or carbon monoxide (CO) to produce methane. The reactions for this is

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

$$CO + 3H_2 \rightarrow CH_4 + H_2O.$$

The big advantages of this method is that the methane could directly be injected into the natural gas grid without any limitations. The CO_2 in the process could also come from existing sources which means that this system can become a way to recycle CO_2 emissions. The disadvantage however is that unlike the previous method, additional steps needs to be added with a methanation plant and hydrogen storage which will cause losses in both energy and efficiency. [59]

2.5.2 Status and potential

The round trip efficiency of hydrogen in a power-to-power system is nowhere near the efficiencies of other storage possibilities such as batteries. [61] But if we instead take a look at the power-to-gas scenario, hydrogen seems a lot more promising. Hydrogen that is produced through water electrolysis from renewable sources is often called green hydrogen. This type of hydrogen is a promising solution to be able to achieve the goals of decarbonization in industries by replacing the gray hydrogen that emits a lot of carbon dioxide. It can also contribute to increasing the development of renewable energy sources because more energy will be needed for the increased demand for green hydrogen. Lastly it can increase the energy system's flexibility because of electrolyzers' ability to rapidly increase or decrease power and have more secure energy for countries by having hydrogen as seasonal long term storage. [62]

Today, green hydrogen is only 0.1% of the total global hydrogen production but it is growing rapidly in recent years. [63] Europe has a three phase development strategy for hydrogen that extends from 2020 to 2050. This strategy can be seen in Table 2.4.

Table 2.4: European development strategy for hydrogen [62]

Period	Electrolyzers installed capacity (GW)	Green hydrogen production (Megaton)	Main target
Stage 1 (2020-2024)	6	1	Decarbonize the existing production of hydrogen in industries.
Stage 2 (2025-2030)	40	10 (1% of Europe's final energy demand)	Introduce hydrogen into new applications and industries.
Stage 3 (2031-2050)	Large-scale	Large-scale (10% of Europe's final energy demand)	Introduce hydrogen into sectors where it is hard to reduce emissions.

2.5.3 Challenges

Although green hydrogen is promising there is still a bunch of challenges that need to be addressed for it to be a realistic alternative. First of all green hydrogen is expensive to produce, convert, transport and store compared to other types of hydrogen production. There is also not a guaranteed future demand for green hydrogen, which the whole development is reliant on. Because of it being in a development stage it means that there is no technical and international standards which is a major obstacle affecting the development because of every country needing to develop their own standards and regulations. Hydrogen's safety and the public acceptance of this safety is also an important challenge. Hydrogen is very flammable in air and also tends to easily leak into the air from even the smallest gaps in pipes. This is something that needs to get addressed because of the important role of public acceptance for hydrogen's possibilities for expansion. [62]

2.6 Electricity market and prices

In this subsection theory on how the electricity market is built up both physically and how the financial trade works will be presented. Insight in how the electricity prices are set and which factors that influence the price will also be given.

2.6.1 Electricity market

The electricity market consist of two different parts, the physical transmission of electricity and the financial trade of electricity. [64]

The physical transmission of electricity takes place on different grids. The main power grid in Sweden is owned by the Swedish state and is managed by Svenska Kraftnät. The electricity produced by the generators will start its transportation route by going trough an electrical substation to increase the voltage to the right amount. When the electricity has the right voltage it will then travel on the main power grid at 400 kV or 220 kV to get to the regional switchgears. These have incoming and outgoing power lines at different voltages and transformers to adjust the voltage again. The electricity then travels on the regional power grid owned by local power grid companies at voltages between 130 kV - 40 kV. From the regional grid the electricity then travels to the local grid which has voltages below 40 kV. A transformation station located as close as possible to the subscriber is then used to finally get the electricity to usable three phase voltage at 400/230 V. [65]

The financial trade of electricity means that the generators sell electricity through the electricity market. Sweden, Norway, Denmark and Finland has, since the 90s, a common electricity market where prices are set at a special trading place, the energy exchange Nord Pool. The reason for this is to create an electricity market exposed to competition to get lower prices. [65] Nord Pool has a spot market for trading electricity per hour for delivery next day. [64] The spot prices that are set on Nord Pool are leading the prices the electricity suppliers pay when they buy electricity for their consumers. However, the end consumer is not a part of any common market and can only choose between electricity suppliers. [65] The end consumer also pays for two different services, the electricity consumed and for the ability to have the electricity transmitted on the grid.[64]

Sweden has four different bidding zones which can be seen in Figure 2.29. This division makes it easier to categorize where the main power grid needs to be built out and is also an indication on where in the country the electricity gets consumed. The production can then be adapted so it corresponds to the consumption in the same zone. Doing this can reduce the need to transport electricity large distances. Southern Sweden has the most consumers and less power generation while northern Sweden usually has overproduction which means that large amounts of electricity are transmitted from the northern parts to meet the needs of the southern parts of Sweden. The problem that arises from this is that the main power grid has a limited capacity which means that the large amount of electricity can not always physically be handled by the grid.[65]

Figure 2.29: Bidding zones in the Nordic region. Image taken from [66].

2.6.2 Electricity prices

The electricity prices are affected by several different factors that influence the value. The most common factor is the basic supply-demand factor, how much electricity that is produced and how big the demand for it is. The two biggest power generation resources in Sweden are hydro and nuclear which means that if the amount of water in the hydropower reservoirs is lower than usual or if any nuclear power plant is shut off during repair, it could lead to higher electricity prices. On the other hand the price could also get lower if, for example, the demand decreases because of a milder weather. There are also international factors that effect the electricity price, such as fuel prices and exchange rates. Electricity has the ability to be exported and imported between the Nordic countries and the rest of Europe. This means that the the electricity prices in the Nordic gets affected by the prices of the rest of Europe and vice versa. So for example if the oil and coal prices change, this affects the electricity prices of other countries with fossil power generation, and this in turn will affect the Nordic prices. [65]

The different costs that the consumer electricity price is divided up into is the cost for electricity trade, electricity grid, plus taxes and fees. The cost for electricity trade is the spot price from Nord Pool plus costs for risk management, annual fee and other administrative costs. Electricity grid costs come from the cost of transmitting electricity on the grid plus a subscription fee. The price fractions from the different costs can be seen in Figure 2.30. [67]

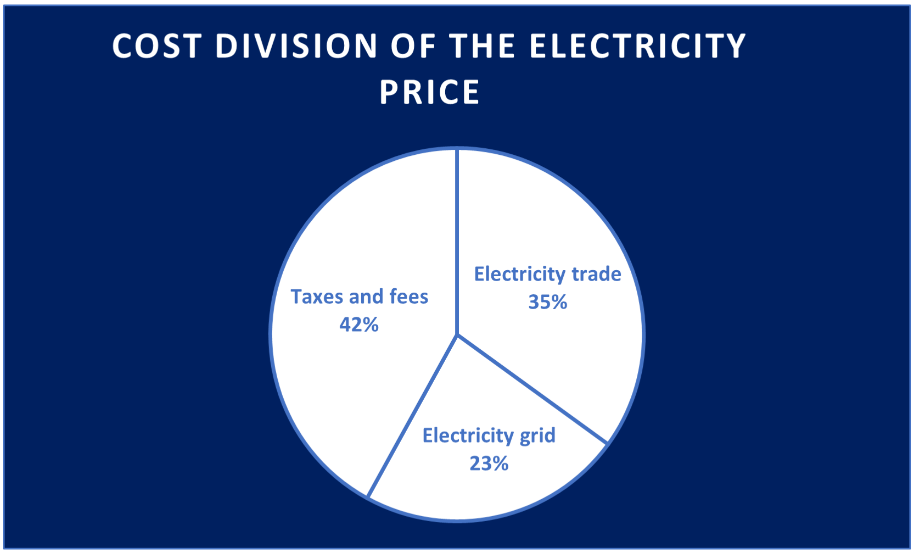

Figure 2.30: Cost division of the electricity price.

Selling electricity

It is possible to sell excess electricity to the grid if there is overproduction, which means that production is larger than the consumption. The sale has to go through an electricity supplier with the reason being that the supplier by law has to be responsible for the power balance, which means that they make sure that the energy supply and delivery is the same in the system. [68] Different suppliers pay different amounts of money for the electricity, but most suppliers demand that you also buy electricity from them so choosing the overall best deal is not always possible. [69]. The compensation however usually consists of two parts, compensation for the excess electricity and compensation for grid benefits. For example, E.ON, which is the electricity supplier used by CMP, compensates the excess electricity by an amount following their price list [68] and calculates the compensation for grid benefits from the formula:

*The gridareas gridlosses * their price for purchase of gridlosses + their costs for buying 1 kWh transferred electricity from the overlying grid = Compensation for grid benefits in öre/kWh* [70]

Approxmiate electricity prices

To approximate electricity prices two price scenarios may be regarded. One for low electricity costs based on spot prices between 2012 and 2020 and one for high electricity costs based on spot prices during 2021 and 2022. One price scenario approximation based on these years is presented in table 2.5. [22]

Table 2.5: Bought and sold energy prices for the two price scenarios. [22]

	Electricity price 1 (Low)	Electricity price 2 (High)
Bought energy (SEK/kWh)	1.07	1.72
Sold energy (SEK/kWh)	0.43	1.08

3 Methodology and theory

This section details which technologies are chosen for continued work in the thesis. The different consumption, production and battery scenarios that are considered are presented. The methodology used for the energy mapping, site study, simulations, optimizations and economic calculations are also described. A schematic figure of the workflow used in the methodology can be seen in Figure 3.1.

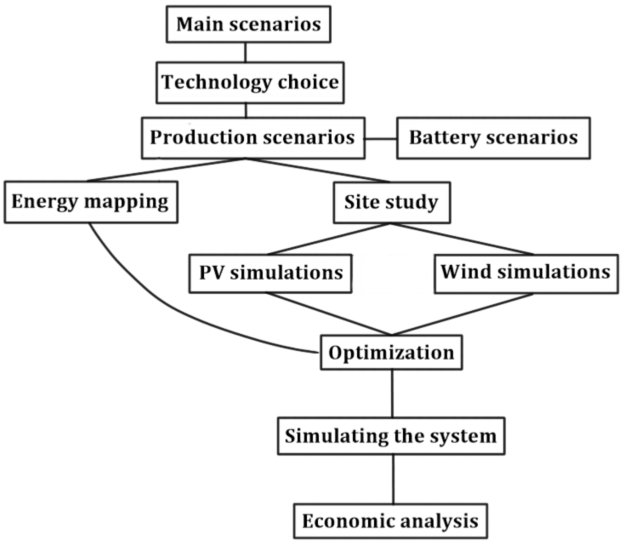

Figure 3.1: Schematic figure of the workflow.

3.1 Scenarios

In this subsection the main scenarios relating to maximum potential and energy requirements are first defined. The technologies to be further considered are then chosen to be able to finally define the production and battery scenarios.

3.1.1 Main scenarios

There are three main scenarios. One that looks at the maximum potential and two consumption scenarios that are based on the requirements that arise from different consumption profiles. The scenarios are chosen based on input and discussion with CMP about current and future needs and possibilities.

Maximum potential
In this scenario no specific consumption profile is be used. Instead, it evaluates all reasonable placements of electricity production to give an overview of the power generation possibilities in Malmö harbor. This scenario is presented first as the site study made for the area is used in the other scenarios.

Current consumption
This scenario is based on the current consumption of CMP's operations and aims to find if CMP's goal of being self-sufficient on energy can be fulfilled. The total yearly production is assumed to match the total yearly consumption.

Shore power
In 2024 a requirement to offer shore power will come into force which will lead to a higher consumption in CMP's operations. This scenario reflects that increase by approximating the additional consumption. The assumption that all ships will charge for the whole time they are docked is made. The total yearly production is assumed to match the increased total yearly consumption.

3.1.2 Technology choices

Not all the technologies presented in Section 2 are further considered in this thesis. In this section the reasoning behind which technologies to study is presented. This reasoning is largely based on the maturity of the technology and how easily it can be deployed in Malmö harbor.

PV
Photovoltaic power generation is a mature technology that has been present on the market for years. Although it does not constitute a large fraction of total global electricity production it is being rapidly deployed and is generally seen as one of the most important renewable energy sources moving forward. The technology is easily deployed on roof and land areas which makes it compatible with the area considered in this thesis. Also, CMP has an expressed interest in deploying PV. Therefore PV is chosen to be considered in the project.

Wind
Wind power is a mature technology that already accounts for a considerable fraction of the global energy supply. It has been present on the market for a long time and is still quickly being further built and developed. Like with PV, wind power is regarded as one of the most important renewable energy sources. Effects on residential areas and wildlife makes the planning of wind power more difficult. However, the current plans for wind power in Norra Hamnen have assessed that the environmental effects of potential turbines will be acceptable. Because of these reasons wind power is deemed suitable for the regarded area and is chosen to be considered in the project.

Wave
Although wave power has great potential it is still in development and is currently not a mature and easily deployed energy source. This, together with the lack of standardized technology and difficulties in planning and maintenance, means that wave power is chosen to be ignored in the project.

Battery energy storage
Battery energy storage is a mature technology with an accelerating deployment rate and presence on the market. There are still problems with cost and long-duration storage. Despite this BESS is chosen to be considered in the project as it is deemed the most relevant energy storage technology to the area and application of the thesis project.

Hydrogen
Hydrogen energy storage is limited as of now and largely still in development and testing. The poor round trip efficiency for power-to-power makes it better for production of hydrogen that is to be used directly or in the gas grid. Because of power-to-gas not being suitable for this thesis, hydrogen production and storage is chosen to be ignored in the project.

3.1.3 Production scenarios

For the two consumption-based scenarios[1], current consumption and shore power, a few different system compositions are used. They are based on the technology choices presented in Section 3.1.2 and CMP's expressed prioritization that PV will be built before wind. Thus, there are no scenarios with only wind power, but there are combinations of PV and wind power. Also, the production systems are studied with and without batteries. The chosen production scenarios can be seen in Table 3.1:

Table 3.1: Chosen production scenarios.

PV
PV and wind
PV and battery
PV, wind and battery

3.1.4 Battery scenarios

Four different battery sizes are analyzed in the scenarios that include batteries. They are based on different types of battery usage and are as follows:

Balance battery
This battery charges and discharges to ease over- and underproduction respectively. The sizing is made to try to maximize the increased utilization of the system while keeping the battery as small and, by extension, as cheap as possible. This battery is the basis for two of the other battery scenarios below and is referred to as the optimal or chosen battery.

Double balance battery
This battery functions identically to the balance battery. However, it has twice the capacity. This scenario is mostly meant to illustrate the effects of a larger balance battery.

Backup battery
During discussions with CMP they expressed interest in having a battery that could supply energy for one day in the case of grid problems such as blackouts. The size of this battery matches the day with the highest consumption. For the shore power scenario the battery is still only able to supply CMP's own operations and the size does not increase because of added power consumption. The battery is not used to supply energy during low production but is instead always kept fully charged.

Balance and backup battery
A battery system fulfilling both above mentioned functions is also modeled. This battery system always holds energy matching one day's consumption but also has capacity to charge and discharge to match over- and underproduction. The size of this battery equals the combined size of the balance and backup batteries.

3.2 Energy mapping

To find the energy requirements of CMP's operations the consumption is studied. Hourly consumption data for 2022 based on measurements by the electricity meters in the area is gathered from CMP's electricity supplier. The hourly data is then sorted into monthly data and plotted.

[1] For the maximum potential scenario the potential of all chosen types of electricity production and storage are described and no specific system compositions will be considered in regard to consumption. This as there is no consumption profile for this scenario.

3.2.1 Shore power

To calculate the increased energy demand for providing shore power to all docking vessels data given by CMP is used. Firstly, the required power needed for each vessel is approximated from their weight by using the table from reference [71]. The energy consumption is then calculated from this multiplied by the docking duration and distributed over the year based on the time and date each ship docked.

3.3 Site study

In the site study suitable locations are determined for placement of power generation.

3.3.1 Locations for PV

To determine which locations were suitable for PV, firstly a map over CMPs areas in Malmö port is studied. From this map each roof and possible ground area is highlighted as potential places to put PV panels on. For the ground areas, each unused and well aligned green area is marked as a possible area. For the roofs a delimitation is set that only roofs with a capacity over 1000 square meter worth of PV panels is going to be used. This because the installation of PV panels on smaller roofs would be to much work for the minimal effect it would have compared to the other roofs and the whole consumption. To now figure out which roofs that would fit with this delimitation, Google Earth is used. Google Earth is a program that renders 3D representation of Earth based on satellite imagery. This program has a measurement function which is used to measure the area of each roof where it was possible to put PV while taking account for ventilation. An example of how the measurements are made can be seen in Figure 3.2. From this process six different roofs are chosen as possible roofs. These roofs and all the possible ground areas can be seen in Figure 3.3.

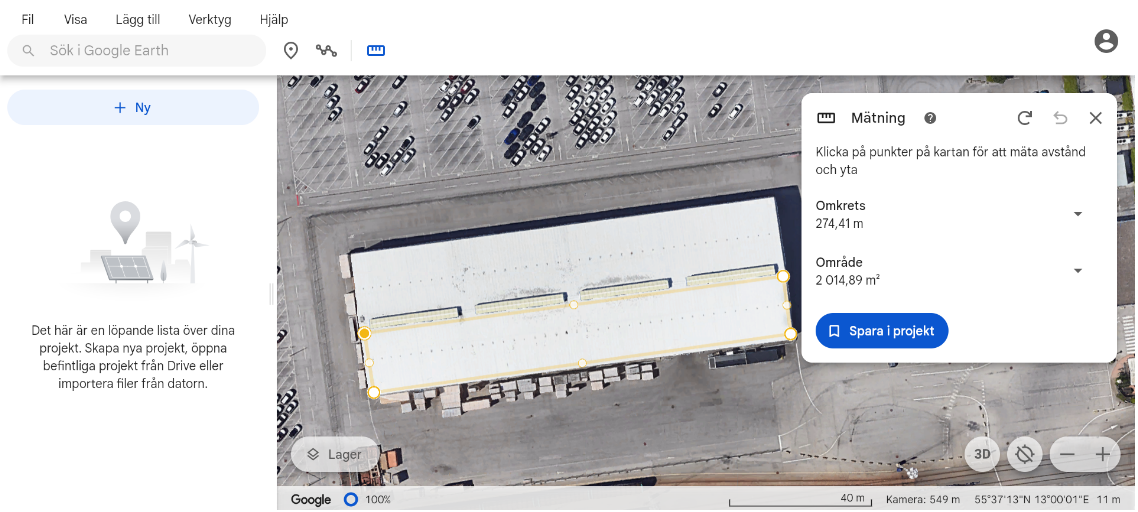

Figure 3.2: Example of measurement technique used in Google Earth.

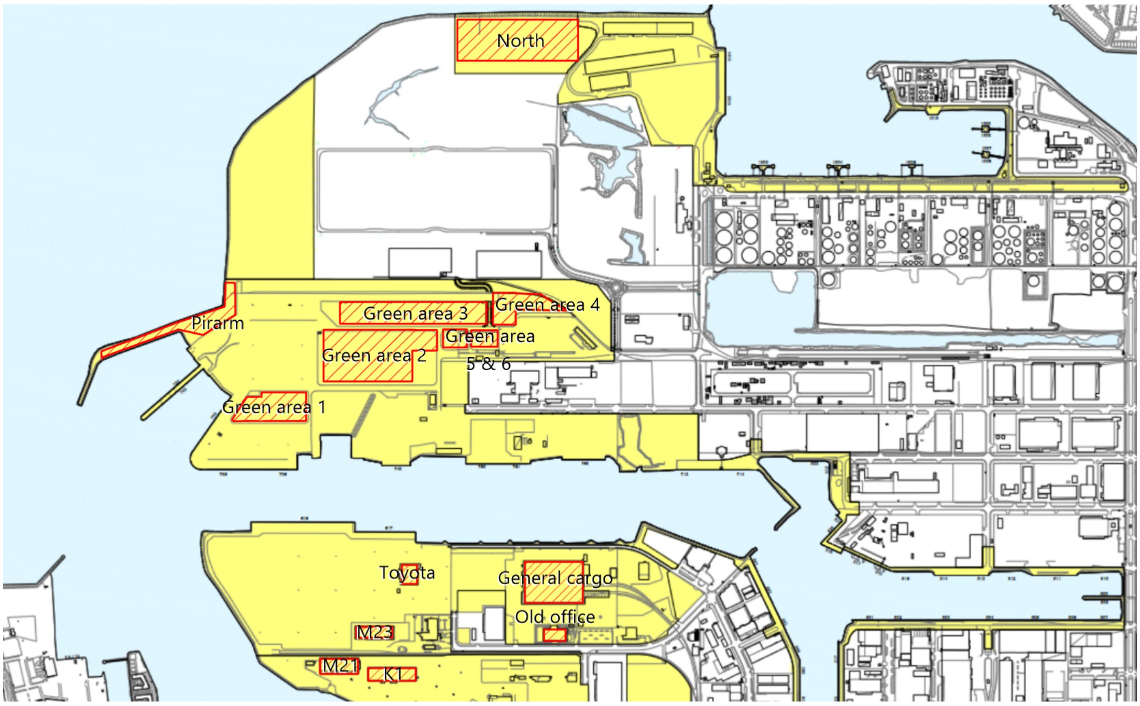

Figure 3.3: Possible areas for PV panels with belonging names.

Calculation for the PV panel area of each possible area is now made. For the roofs the calculation had already been made when figuring out which roof fit the delimitation. For the ground areas shading had to be considered. To avoid this as much as possible, firstly the panels had to be at a distance of three times the height from the nearest covering object which is a rule of thumb typically used [22]. The rows of PV panels also had to have a certain distance in between them. To calculate this the program SAM is used. SAM is a program where different renewable energy systems can be modelled, such as PV systems. In the program a PV panel and a ground coverage ratio (GCR) had to be chosen to get the row distance. The chosen panel is the LONGi LR5-54HPH-415M which is chosen because it is a panel used by EON. For the GCR, which is the ratio of the PV array area to the total ground area, a GCR of 0.3 is chosen because of it being a typical used value for PV modelling and installation. With these two parameters the row distance is acquired. Using the row distance and measurements of the ground area, the area of PV panels could now be calculated by seeing how many rows that would fit in each area and how long each row could be.

The tilt is how the panel is tilted from the ground where 0°=horizontal and 90°=vertical. The azimuth is the orientation of the panel where 0°=south, 90°=west and -90°=east. These parameters are now estimated for each roof and ground area by using Google Earth and choosing the tilt of ground mounted PV panels as 40° because this tilt is in tilt range resulting in the best performance for the location. A ground reflectance, which is the fraction of solar radiation incident on the ground that is reflected, is also estimated. This is estimated from looking at the roofs and ground areas from Google Earth and matching with a table for ground reflectance in [72]. The tilt, azimuth, panel area and ground reflectance for each roof and ground area can be seen in Table 3.2. The roofs and one ground area (Pirarm) are divided into either north/south side or east/west side. This because the different sides of the roof have different azimuths and Pirarm also has two different azimuths for its system so this division then makes it easier for calculations.

Table 3.2: Data for roof and ground areas where:(S)=South side, (N)=North side, (E)=East side, (W)=West side.

Name	Tilt (°)	Azimuth (°)	Panel area (m^2)	Ground reflectance
K1	12	-7(S), 173(N)	2200	0.15
M21	12	-7(S), 173(N)	2000 (S), 2100 (N)	0.15
M23	12	-7(S), 173(N)	2200 (S), 1800 (N)	0.125
Toyota	12	83(W), -97(E)	1130 (W), 1670 (E)	0.5
General cargo	12	-7(S), 173(N)	10700 (S), 9100 (N)	0.15
Old office	12	-7(S), 173(N)	1380 (S), 750 (N)	0.2
Green area 1	40	-7	5280	0.3
Green area 2	40	-7	14590	0.3
Green area 3	40	-7	10420	0.3
Green area 4	40	-7	3520	0.3
Green area 5	40	-7	1200	0.3
Green area 6	40	-7	1400	0.3
North	40	-7	11860	0.3
Pirarm	40	0(E), -26(W)	1920 (E), 900 (W)	0.3

3.3.2 Locations for wind

The process for determining suitable locations for wind turbines is largely based on the existing plans for Norra Hamnen. The plans and the results of the environmental impact assessment (EIA) were evaluated and the findings were applied to the whole area considered in this thesis.

The EIA is used as a basis for determining necessary distances to residential areas and Natura 2000-areas. Effects on wildlife mentioned in the assessment are considered, both for the areas the EIA analyzes and the surrounding areas of relevance. The EIA's description of possible visual impacts on the cityscape is used to limit the amount of turbines and their placement. The proposed height limits in the detail plan as well as turbines used in the EIA are used to determine suitable turbine sizes and thereby also rated power. Distance requirements between turbines due to wake effects are considered together with waterways for ships and prevailing wind directions to find possible placements of the turbines. Rotors standing downwind from another rotor in the prevailing wind directions are separated with 7 rotor diameters (7D). A spacing of 5D was used for crosswind turbine spacing.

3.4 Simulating the production

In this subsection the methodology and theory behind the PV and wind simulation will be presented.

3.4.1 PV simulations

To simulate the production from the PV panels the program Excel is used. Excel is a software program were the user can create spreadsheets to organize data with formulas and functions. This is used to easily construct a calculation program for the production based on hourly values of all data.

First the weather data, taken from [73], for the area is gathered from a weather station located in Malmö. The data gathered is in the form of global horizontal radiation, G_h, direct normal radiation, $G_{b,n}$, and diffuse horizontal radiation, $G_{d,h}$, for every hour in a typical meteorological year (TMY). The TMY format uses data over several years and selects the data for each month based on a year that had data considered to be "typical" for that month. In this case the following months and years was used: January 1957, February 2004, Mars 2004, April 2012, May 2005, June 2017, July 2002, August 2007, September 2019, October 2004, November 2018 and December 1956.

To be able to calculate the rest of the needed radiations the incidence angle, θ, needed to be calculated. For this, firstly the declination angle, δ, is calculated. The declination angle can be seen in Figure 3.4 and is defined as the angle between the sun and the equator plane. The equation for this is

$$\delta = 23.45 sin(360(284 + n)/365)$$

where n is the day of the year.

So if we for example take the date December 11th which is the 345th day of the year the declination would be $\delta = 23.45 sin(360(284 + 345)/365) = -23.12°$.

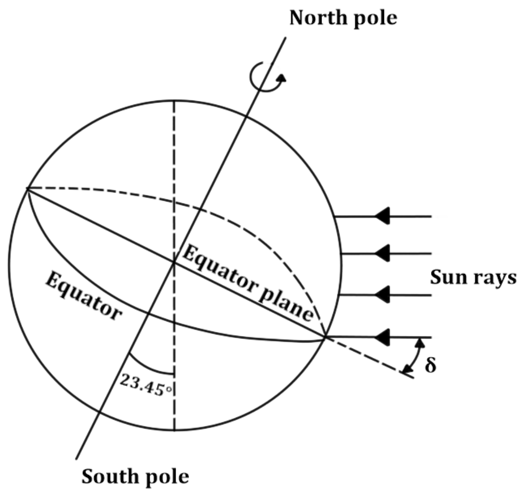

Figure 3.4: Definition of declination angle

Solar time, which is time measured by Earth's rotation relative to the Sun, is then calculated from

$$Solar\ time = Standard\ time + 4(L_{st} - L_l) + E$$

where:
L_{st} is the time zone standard meridian
L_l is the local meridian
E is the "equation of time".

E is due to that the orbit around the sun is slightly elliptical and is a function of the time of year. It is calculated by

$$E = 229.2(0.000075 + 0.001868 cos(B) - 0.032077 sin(B) - 0.014615 cos(2B) - 0.04089 sin(2B))$$

where $B = 360(n - 1)/365$.

If we once again take December 11th as an example and add that the time is 9:00 and we are located in Malmö which means that local meridian is -13.071 and standard meridian -15 we get:

$B = 360(345 - 1)/365 = 339.29$

$E = 229.2(0.000075 + 0.001868 cos(339.29) - 0.032077 sin(339.29) - 0.014615 cos(2 * 339.29) - 0.04089 sin(2 * 339.29)) = 6.71$

$Solar\ time = 9:00 + 4(-15 - (-13.071)) + 6.71 = 8:59$

Next the hour angle, ω, is calculated, which is defined as the angular displacement of the sun, east or west from the local meridian due to the rotation of the earth which can be seen in Figure 3.5. The equation for this is

$$\omega = ((HH - 12) + MM/60) * 15$$

where:
HH = hours in solar time
MM = minutes in solar time.

Continuing the example we now get an hour angle of $\omega = ((7 - 12) + 59/60) * 15 = -45.25°$.

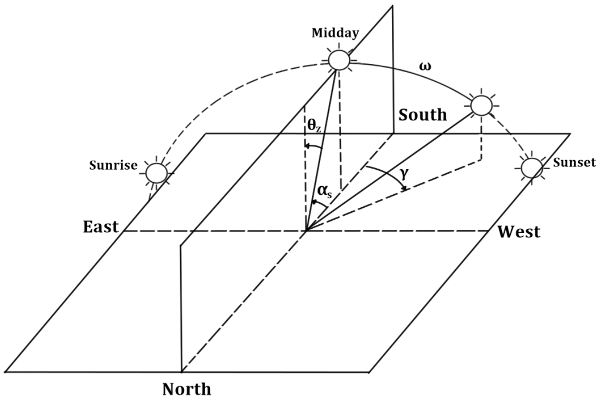

Figure 3.5: Definition of hour angle, solar altitude and solar azimuth angle

The solar altitude, α_s can also be seen in Figure 3.5 and is defined as the angle between the suns rays and a horizontal plane and is calculated from

$$\alpha_s = arcsin(cos(\delta)cos(\omega)cos(\lambda) + sin(\delta)sin(\lambda))$$

where λ is the latitude of the site.

Malmö has the latitude 55.5715, so if we continue our example we now get a solar altitude of $\alpha_s = arcsin(cos(-23.12)cos(-45.25)cos(55.5715) + sin(-23.12)sin(55.5715)) = 2.42°$.

The solar azimuth angle, γ, can also be seen in Figure 3.5 and is defined as the azimuth of the suns position and is calculated from:

$$\gamma_s = arccos((cos(\delta)cos(\omega)sin(\lambda) - sin(\delta)cos(\lambda))/cos(\alpha_s)) * \omega/|\omega| \qquad (\omega \neq 0)$$

$$\gamma_s = arccos((cos(\delta)sin(\lambda) - sin(\delta)cos(\lambda))/cos(\alpha_s)) \qquad (\omega = 0)$$

The solar azimuth angle for our example is then
$\gamma_s = arccos((cos(-23.12)cos(-45.25)sin(55.5715) - sin(-23.12)cos(55.5715))/cos(2.42)) * -45.25/|-45.25| = -40.83°$.

The angle of incidence seen in Figure 3.6 could now be calculated. It is defined as the angle between the sun rays and the normal on a surface and has the equation

$$\theta = arccos(cos(\delta)sin(\omega)sin(\beta)sin(\gamma) + cos(\delta)cos(\omega)sin(\lambda)sin(\beta)cos(\gamma) - sin(\delta)cos(\lambda)sin(\beta)cos(\gamma)$$

$$+ cos(\delta)cos(\omega)cos(\lambda)cos(\beta) + sin(\delta)sin(\lambda)cos(\beta)),$$

where β is the surface tilt.

If we say we have a surface tilt of 40° we now get an angle of incidence for our example as $\theta = arccos(cos(-23.12)sin(-45.25)sin(40)sin(-40.83) + cos(-23.12)cos(-45.25)sin(55.5715)$ $sin(40)cos(-40.83) - sin(-23.12)cos(55.5715)sin(40)cos(-40.83) + cos(-23.12)cos(-45.25)cos$ $(55.5715)cos(40) + sin(-23.12)sin(55.5715)cos(40)) = 55.54°$

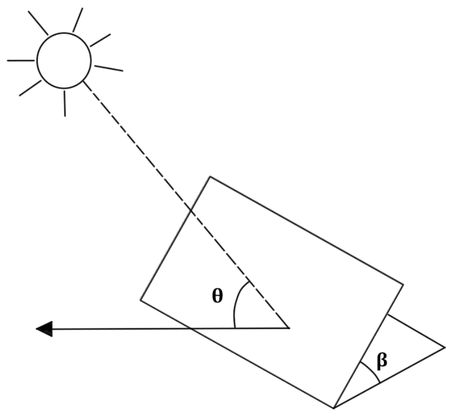

Figure 3.6: Definition angle of incidence

With the angle of incidence the radiations is now be calculated. Firstly the direct radiation on a tilted surface, G_b, diffuse radiation on a tilted surface, G_d, and ground reflected radiation, G_g, is calculated in order from the equations

$$G_b = G_{b,n}cos(\theta)$$

$$G_d = G_{d,h}(1 + cos(\beta))/2$$

$$G_g = \rho_g G_h(1 - cos(\beta))/2$$

where:
ρ_g is the ground reflectance.

With a ground reflectance of 0.3 and the given radiations from the weather data as $G_h = 18Wh/m^2$, $G_{b,n} = 57Wh/m^2$, $G_{d,h} = 12Wh/m^2$, our example continues with the different radiations as

$G_b = G_{b,n}cos(55.54) = 32.25Wh/m^2$

$G_d = G_{d,h}(1 + cos(40))/2 = 10.59Wh/m^2$

$G_g = 0.3 * G_h(1 - cos(40))/2 = 0.63Wh/m^2$

With these the total radiation on the surface, G_{tot}, is now calculated from the equation

$$G_{tot} = G_b + G_d + G_g$$

Which in our example is $G_{tot} = 32.25 + 10.59 + 0.63 = 43.47$

The hourly production over the year is now calculated from the equation

$$Production = G_{tot} * \eta * A$$

where:
η is the efficiency of the PV panel
A is the PV area.

If we have a efficiency of 0.2 and an area of $50m^2$ we get a production with our example of $Production = 43.47 * 0.2 * 50 = 435Wh$.

To include the temperature effects the cell temperature, T_{cell}, is calculated using the equation

$$T_{cell} = T_{amb} + (\alpha * G_{tot} * (1 - \eta))/U$$

where:
α is the absorbtance
U is a temperature dependent set value depending on the circulation around the PV panels.

If we use $U = 20$, $\alpha = 0.9$ and an ambient temperature from the weather data $T_{amb} = 7.2°$ we get in our example $T_{cell} = 7.2 + (0.9 * 43.47 * (1 - 0.2))/20 = 8.76°$

Inverter efficiency is dependent on the power in (DC) from the PV panels. To estimate this, values from the PV simulations program Pvsyst is used. From the program different efficiencies at different powers are given. To then get an average value from this the European efficiency method is used given by

$$\eta_{EURO} = 0.03\eta_{5\%} + 0.06\eta_{10\%} + 0.13\eta_{20\%} + 0.10\eta_{30\%} + 0.48\eta_{50\%} + 0.2\eta_{100\%}$$

The values given in Pvsyst are not following the exact efficiency values in the above equation. To fix this interpolation is used. With this the inverter efficiency is calculated to 0.96.

To now include the temperature effects and the inverter losses the following equation ia instead now used to calculate the hourly production

$$Production = G_{tot} * \eta * A * (1 - (T_{cell} - 25°) * 0.004) * \eta_{inv}$$

where:
η_{inv} is the inverter efficiency.

This means that we get a final production of our example of an $50m^2$ PV system located in Malmö at 9:00 December 11th as $Production = 43.47 * 0.2 * 50 * (1 - (8.76 - 25) * 0.004) * 0.96 = 444Wh$.

3.4.2 Wind simulations

To handle the wind data and simulate electricity production from a wind turbine Matlab is used. Matlab is a programming language for numerical calculations using matrices.

To get wind data for the location, wind measurements from the weather station at Kastrup airport are used, taken from [73]. The weather station took hourly measurements at 5.2 m height. The data used is for a typical meteorological year (TMY) and consists of the following months and years: January 1961, February 1977, March 1978, April 1983, May 1960, June 1957, July 2016, August 1971, September 2004, October 1971, November 1961 and December 1985.

To extrapolate the wind data to different heights the vertical profile of the wind is approximated using the power law, Equation 2. The shear index is approximated by considering table values related to terrain characteristics matching Kastrup and Malmö harbour as well as wind resource databases for Malmö harbour. The chosen shear index is 0.09.

Next, a power curve detailing the power output of a specific turbine as a function of wind speed is chosen. The hourly wind data is then matched to each value's closest power curve data point and the power output for every hour is acquired. The power output is multiplied by 1 to get the energy, in Wh, produced each hour. No losses, internal or grid related, are included in the calculations.

To get an approximation of prevailing wind directions at the location, wind data from the weather station Oskarsgrundet from 1985 to 1999, taken from [73], is used to make a wind rose. A wind rose shows the frequency of wind from different directions as well as wind speed ranges for each direction.

3.5 Optimization

To simulate the different energy systems and find optimal sizing of parameters a simple model is created in Matlab. The system model consists of hourly consumption data from the energy mapping and hourly production data from the production simulations. An overview of the optimization process is depicted in Figure 3.7.

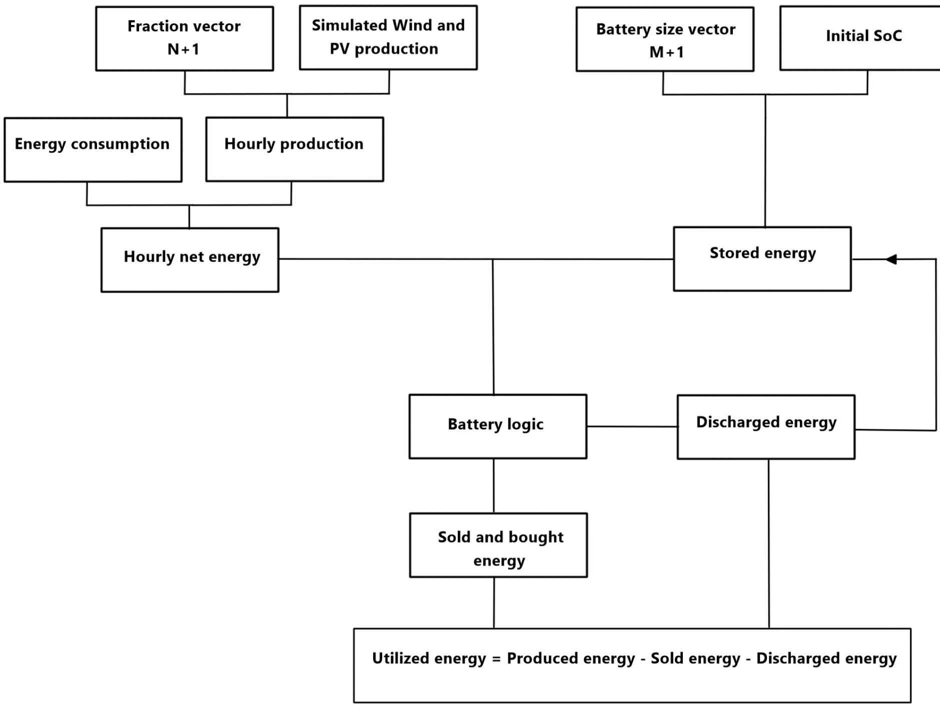

Figure 3.7: An overview of the optimization process. This diagram represents the optimization of PV, wind and battery presented in Section 3.5.3. For the PV and wind optimization the hourly net energy is directly used to calculate the sold and bought energy (discharged energy is not used).

A simple battery model is also created. The battery model consists of an energy storage capacity, an hourly self discharge rate and an initial state of charge. State of charge (SoC) represents how much energy is currently stored in the battery, often presented as a percentage of the total capacity. The initial SoC describes the fraction of the total energy, i.e. the SoC, of the battery at the start of the simulated year. Each simulated hour the stored energy decreases according to the self discharge rate. This simple model uses a round trip efficiency of 100%.

For the optimization, the power curve for a 1 MW turbine is used to simulate the production data. A PV panel with $-7\,\text{deg}$ azimuth and $12\,\text{deg}$ tilt is used to simulate the production data.

3.5.1 PV and wind

The PV and wind production data are both scaled to, when summed, equal the total yearly consumption. A fraction vector is then created with N+1 evenly spaced elements from 0 to 1. Here N is a measure of the resolution of the simulation. A N of 100 gives 101 (N+1) simulations with an evenly spaced fraction vector, in this case: [0 0.01 0.02 ... 0.99 1]. The simulation cases are then represented by a loop from 1 to N+1. For each simulation the corresponding value is taken from the fraction vector and the scaled wind data is multiplied by the fraction. The scaled solar data is multiplied by 1 minus the fraction to complement the amount of wind power. In each simulation case the total produced electricity equals the total energy consumption over a year but different amounts of energy come from PV and wind respectively.

For each simulation case a loop from 1 to 8760 represents each hour in the simulated year. For each hour the energy balance, *produced electricity* - *energy consumption*, is calculated. A negative energy balance meant that energy had to be bought whilst a positive energy balance meant energy would be sold. Then the amount of utilized energy that hour is calculated by subtracting any sold energy from the production. After every hour is simulated, the total utilization for that simulation case is saved in a vector.

A plot of the utilized energy as a function of the fraction is then made. The maximum value is then found and the corresponding optimal fraction is noted. Using the rated power of turbine used for production simulation, the original wind production data and the optimal fraction the optimal rated power for a wind turbine is found. The closest realistic rated power is then chosen by studying available and historical wind turbine models and their rated power.

3.5.2 PV and battery

The PV production data is scaled so the sum of it equals the total yearly consumption. A battery size vector is then created with M+1 evenly spaced elements from 0 to a chosen maximum battery size. Just like N above, M is a measure of the resolution of the simulations. A M of 100 gives 101 (M+1) simulations with an evenly spaced battery vector, with a maximum battery size of for example 50 kWh: [0 0.5 1 ... 49.5 50]. The initial state of charge is then defined as well as the hourly self discharge rate. The simulation cases are represented by a loop from 1 to M+1. For each simulation the current battery size is chosen as the corresponding value from the battery size vector.

At the start of each simulation case the current stored energy is set to the chosen initial state of charge multiplied by the battery size for this simulation. This value is then divided by the hourly self discharge rate so that the current stored energy matches the chosen initial state of charge after the self discharge is calculated for the first hour. A loop from 1 to 8760 is then started to go through each hour in the simulated year. For each hour the self discharge is accounted for and the net energy is calculated: *produced electricity* - *energy consumption*.

Using the net energy as a starting point the logic presented in Figure 3.8 is then used to determine whether the battery is charged or not and if energy has to be bought or sold. The logic is as follows: If the net energy is positive a check is performed to see if this addition of energy would be more than is required to fill the battery. If that is the case the battery becomes fully charged and the excess energy is noted as sold. Otherwise the battery only gets charged. If the net energy is negative it is supplied from the battery. If the stored energy in the battery is less than is required the stored energy is used and the rest of the required energy is noted as having to be bought. The utilized energy is then calculated by subtracting any sold energy and the self discharge from the produced energy. The utilized energy for each simulation case is stored in a vector.

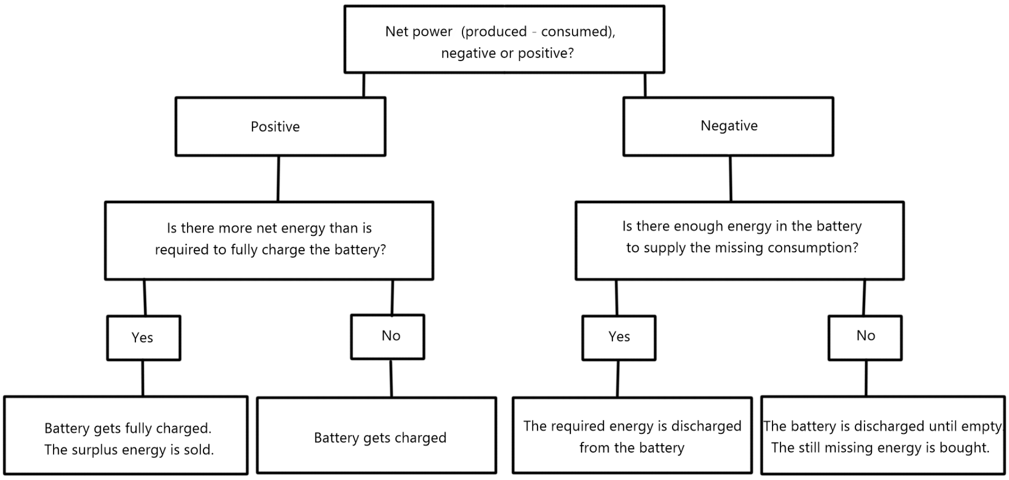

Figure 3.8: Sketch of the logic used when determining charge and discharge from the battery as well as when to buy and sell energy.

A plot of the utilized energy as a function of battery size is then made. The approximate point where the positive incline of the graph started decreasing is noted as the chosen battery size.

3.5.3 PV, wind and battery

The simulations for PV, wind and battery are a combination of the two simulations described in Section 3.5.1 and Section 3.5.2. The wind and PV production data are scaled to, when summed, equal the total yearly consumption. A fraction vector is created with N+1 evenly spaced elements from 0 to 1. A battery size vector is created with M+1 elements from 0 to a chosen maximum battery size. For each of the N+1 cases for the fraction vector all M+1 cases of the battery size vector will be simulated, resulting in a total of $(N+1)\cdot(M+1)$ simulations.

For each simulation the corresponding values are taken from the fraction vector and the battery size vector. The scaled wind and PV production data are multiplied by the fraction and 1 minus the fraction respectively. Thus, in every simulation case the total production equals the total yearly consumption, but different amounts of energy come from wind and PV. The current battery size is set to the value from the battery size vector. At the start of each simulation the current stored energy is set to: $battery\ size \cdot initial\ state\ of\ charge / hourly\ self\ discharge\ rate$. Dividing by the hourly self discharge rate ensures the current charge matches the chosen initial state of charge after the self discharge is calculated for the first hour. A loop from 1 to 8760 is then started to go through each hour in the simulated year. For each hour the self discharge is accounted for and the net energy is calculated: *produced electricity* - *energy consumption*.

Just as in Section 3.5.2, the net energy is used together with the logic presented in Figure 3.8 to determine whether the battery is charged or not and if energy has to be bought or sold. The logic is as follows: If the net energy is positive a check is performed to see if this addition of energy is more than is required to fill the battery. If that is the case the battery becomes fully charged and the excess energy is noted as sold. Otherwise the battery only gets charged. If the net energy is negative it is supplied from the battery. If the stored energy in the battery is less than is required the stored energy is used and the rest of the required energy is noted as having to be bought. The utilized energy is then calculated by subtracting any sold energy and the self discharge from the produced energy. The utilized energy for each simulation case is stored in a matrix.

Next, the highest utilization and corresponding fraction is found for each battery size. The highest utilization is plotted as a function of battery size. The approximate point where the positive incline started decreasing is noted as the chosen battery size. A plot of the fraction yielding the highest utilization for each battery size is made. The fraction corresponding to the chosen battery size is noted. Using the rated power of the turbine used for production simulation, the original wind production data and the noted fraction the optimal rated power for a wind turbine is found. The closest realistic rated power is then chosen by studying available and historical wind turbine models and their rated power.

3.6 Simulating the system

Simulations of the system are done in Excel. Hourly production, consumption and in some of the cases, battery parameters, are used to get three different comparable parameters: Monthly production, monthly energy balance and monthly utilized electricity. Where production is the total production, energy balance is how much electricity goes in and out the system (bought and sold) and utilized electricity how much of the produced electricity was used to meet the consumption in the system. A schematic drawing of all the system components and possible energy flows can be seen in Figure 3.9

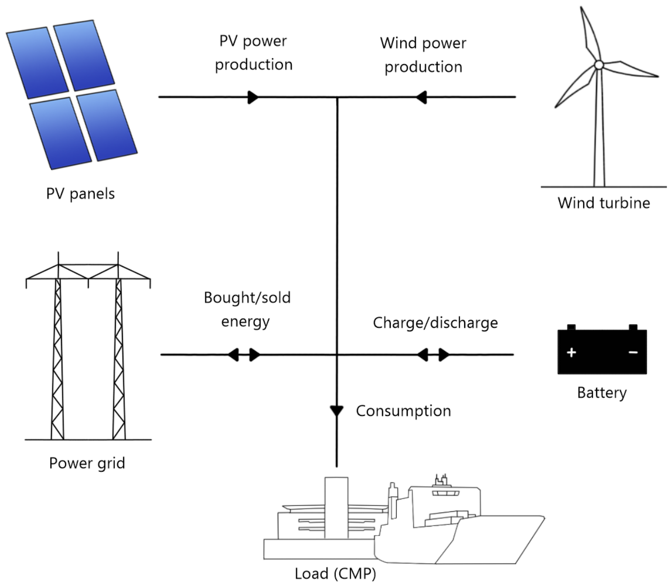

Figure 3.9: Overview of the energy flows in the complete system. Arrows represent energy flow directions.

3.6.1 Using only production

From the different roofs and ground areas for PV presented in Section 3.3.1 a priority list is made in which the areas are prioritized after highest annual production per area with roofs being prioritized over ground areas as this is preferred by CMP. Using this list, which can be seen in Table 3.3, the annual production from each area is subtracted from the annual consumption in succession until the consumption is satisfied. The percentage needed of the latest area used to exactly satisfy the consumption is then calculated to know which areas and how much of them are needed. When the production from wind is also taken into account the wind production is put into the priority list as well using the optimized PV-Wind fraction found in Section 3.5.1.

Table 3.3: Priority list for placement of PV.

Area	Priority
K1 S	1
M21 S	2
M23 S	3
General Cargo S	4
Old Office S	5
Toyota L	6
Toyota R	7
Old office N	8
K1 N	9
M21 N	10
M23 N	11
General Cargo N	12
Pirarm E	13
Pirarm W	14
North	15
Green areas	16

The comparable parameters could now be calculated. Firstly the hourly production numbers from each PV area and, if present, wind is summarized to get the total hourly production. To get the energy balance the hourly production is subtracted by the hourly consumption. The utilized electricity is calculated by checking, for each hour, if the energy balance is positive or negative. If it is positive, only the consumption for that hour is added to the utilized electricity. If it is negative, the whole production is instead added to the utilized electricity, because this means that the production is less than consumption and therefore all production can be useful. To get the monthly values the hourly values is summed together for each of the hours that corresponds to each month.

3.6.2 Using production with battery

Adding a battery to the system means two more parameters to take into account. State of charge and the discharge of the battery. The state of charge just managed how much of the electricity went in and out of the battery as well as checking if the battery was empty or full. A sketch of the logic used for this in Excel can be seen in Figure 3.10.

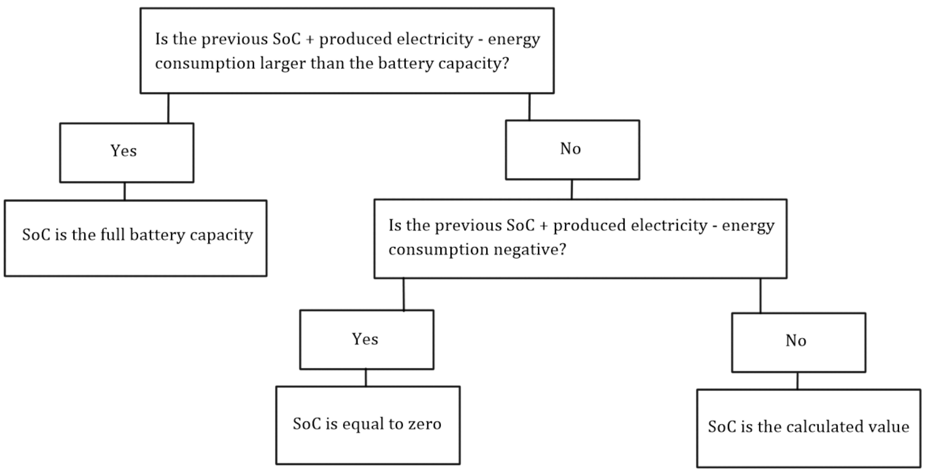

Figure 3.10: Sketch of the logic used for state of charge in Excel.

The discharge is how much of the electricity that is discharged from the battery each hour depending on the state of charge of the battery. This is calculated each hour by just multiplying the discharge rate with the the current state of charge. The production is calculated in the same way as in the previous section but the energy balance and utilized electricity is calculated differently depending on the different battery scenarios presented in Section 3.1.4. For each scenario the amount of time that the state of charge is either max or min is also calculated. For the balance batteries minimum is an empty battery, while for the backup batteries minimum means lowest allowed charge.

Balance battery

For the balance battery the energy balance each hour is calculated by first checking if the absolute value of the production subtracted by the consumption and difference in state of charge from previous hour is equal to zero. If it is, it means that the battery is either charging or discharging the full amount and the energy balance should then be zero because there is no electricity going in or out from the system. If it is not equal to zero, the energy balance is instead just the value from taking the production subtracted by the consumption and difference in state of charge from previous hour. Which is the electricity that goes in and out of the system. A sketch of the logic used for this in Excel can be seen in Figure 3.11.

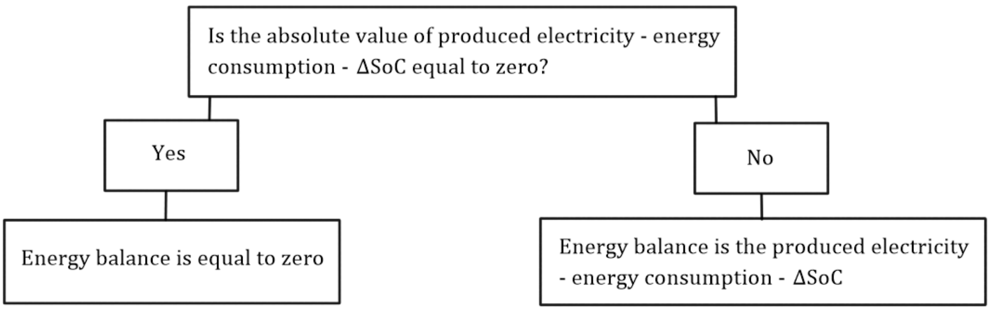

Figure 3.11: Sketch of the logic used for energy balance in Excel.

The utilized electricity is calculated by first checking if the energy balance for that hour is negative or equal to zero. If it is, then the utilized electricity is equal to all of the production for that hour because it is either used to cover a bit of the consumption or to cover the consumption and also charge the battery. But if the energy balance is positive it means that we have an overproduction and that the battery is either full or going to be full. If that is the case, the consumption for that hour is first added to the utilized electricity because this will always be satisfied. The battery is then checked to see if it is full. If it is, then the consumption is the only thing that is added, but if the battery will become fully charged with this addition of energy, we check how much we can fit in the battery and add that to the utilized electricity as well. A sketch of the logic used for this in Excel can be seen in Figure 3.12.

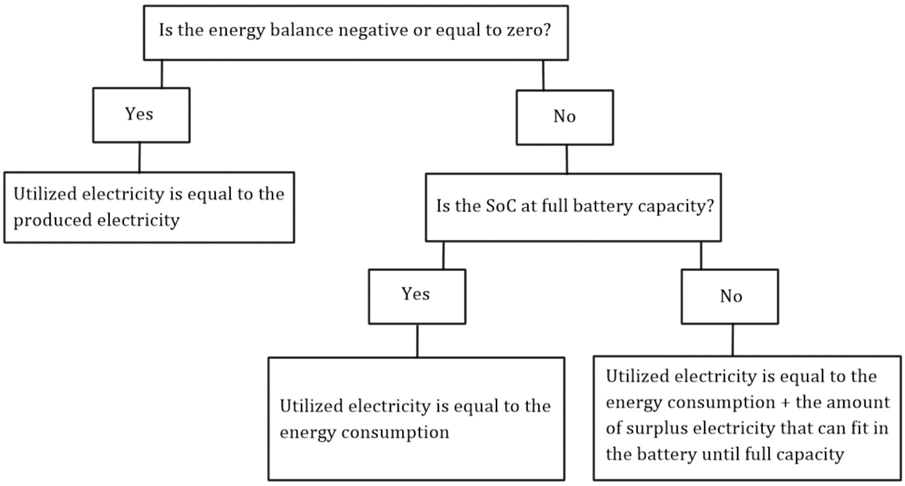

Figure 3.12: Sketch of the logic used for utilized electricity in Excel.

The discharge every hour is handled by being subtracted from the energy balance when the battery is full because it is reducing how much electricity that is going out from the system. When the battery is either charging or discharging the hourly discharge is subtracted from the utilized electricity because it is electricity from the production that will not meet the consumption of the system. Finally when the battery is empty there is no discharge to handle so nothing differs.

The double balance battery is calculated in the same way.

Balance and backup battery
For the balance and backup battery the energy balance and utilized electricity is calculated in the same way. The difference here is how the discharge every hour is taken care of. Because the battery always needs to have a full day worth of charge, there will always be a discharge every hour because the battery is never empty. So if we have an under production and the battery is not over its lowest allowed charge, then the discharge is subtracted from the energy balance because it is electricity that needs to be bought into the system. If the battery is full, the discharge is still subtracted from the energy balance because it is reducing how much electricity that is going out from the system. When the battery is charging or discharging it is also still taken care of by subtracting the discharge from the utilized electricity.

Backup battery
The backup battery is essentially just the case of not having the balance functions of a battery but just dealing with the constant self discharging. This means that the energy balance and utilized electricity is calculated in the same way as it was when there was no battery present. But for this case, a discharge will now always be subtracted from the energy balance because we either need to get that electricity in to system, or it is reducing how much electricity that is going out from the system. If we have under production the discharge is also subtracted from the utilized electricity because that the production will focus on charging the battery to its lowest allowed charge over satisfying the consumption. The reason that it is still subtracted from the energy balance for this case is that the production will have less of its electricity satisfying the consumption so that electricity will have to be bought into the system.

3.7 Economics

To be able to construct viable electricity production and energy storage they have to be cost effective. To determine cost effectiveness the cost of the system must be compared to the revenue. Costs consist of manufacturing, installation, financing, maintenance and operation.

The value of money is not constant, it changes due to inflation and interest rates. Regarding only interest, the value of invested money annually increases by a factor of $1+r$, where r is the discount rate. The value of r describes how the time value for money changes and how risky an investment might be. The future value after N years can be described as

$$FV = PRV(1+r)^N \tag{3}$$

where PRV is the present value of money.

To express one-off or irregular costs and incomes as yearly payments one can use levelizing. A sum of money of present value PRV can be described as

$$PRV = \frac{A}{1+r} + \frac{A}{(1+r)^2} + ... + \frac{A}{(1+r)^N} = A\sum_{j=1}^{N} \frac{1}{(1+r)^j},$$

where A is the annual payment during N years. This equation is a geometric series and can be simplified to

$$PRV = A[1-(1+r)^{-N}]/r. \tag{4}$$

The ratio between annual payments and present value is called the capital recovery factor (CRF) and determines the annual payment required for a given PRV, N and r. The CRF relates to the inverse of the relation in Equation 4 and is described by

$$A = PRV \cdot CRF = PRV \cdot \frac{r}{(1-(1+r)^{-N})}. \tag{5}$$

The sum of all relevant present values is called the net present value (NPV). From Equation 3 the present value of a future cost, C, in year j can be described as $PRV = C/(1+r)^j$. The net present value of a cost C that will be paid each year is therefore

$$NPV = \sum_{j=1}^{N} PRV_j = \sum_{j=1}^{N} \frac{C}{(1+r)^j}.$$

If inflation is accounted for the cost will increase annually as $C_j = C(1+i)^j$, where i is the inflation rate. The net present value then becomes

$$NPV = \sum_{j=1}^{N} \frac{C(1+i)^j}{(1+r)^j}.$$

For an energy system the net present value of costs can be described as

$$NPV_C = P_d + P_a Y(\frac{1}{1+r}, N) + C_c f_{OM} Y(\frac{1+i}{1+r}, L), \tag{6}$$

where:
P_d is the downpayment on system costs,
P_a is the annual payment on system costs which equals $(C_C - P_d) \cdot CRF$,
N is the period of the loan,
L is the lifetime of the system,
C_c is the capital cost of the system,

f_{OM} is the annual operation and maintenance cost described as a fraction of capital cost.

The function $Y(k,l)$ is described by

$$Y(k,l) = \sum_{j=1}^{l} k^j = \begin{cases} \frac{k-k^{l+1}}{1-k}, & \text{if } k \neq 1 \\ l, & \text{if } k = 1 \end{cases}$$

and is used in Equation 6 to get the present value of a series of payments.

From these concepts the levelized cost of energy (LCOE) can be determined. The LCOE describes the cost per produced kWh and is calculated by dividing all levelized annual costs by the annual electricity production. The levelized annual costs can be calculated using the total net present value of all costs in Equation 5 resulting in the formula

$$LCOE = \frac{NPV_C \cdot CRF}{\text{Annual electricity production}} \tag{7}$$

where the CRF is based on system lifetime, L, and discount rate.

Average annual return, AAR, is the revenue from produced electricity. It can be calculated from the annual produced energy multiplied by the price of electricity. In a system with energy consumption where electricity production is added the AAR can instead be calculated as the yearly difference in costs between a year without the system and one when the system is operational. The formula can be written as

$$AAR = E_0 \cdot C_{bought} - (E_b \cdot C_{bought} - E_s \cdot C_{sold}), \tag{8}$$

where:
E_0 is the annual consumed energy, this also equals the amount of energy that has to be bought during the year where the productions system is not installed.
C_{bought} is the energy price for bought electricity.
C_{sold} is the energy price for sold electricity.
E_b is the amount of energy needed to be bought during the year where the production system is installed.
E_s is the amount of energy that is sold during the year where the production system is installed.

A simple estimate of the payback time can be acquired by dividing the capital cost of the system with the AAR. [24] To calculate the discounted payback time, first find the annual net cash flow for each year during the lifetime. Then discount the cash flow of each year according to equation 3. Finally, using these discounted cash flows, find how many years it takes to pay off the investment cost. [74]

Internal rate of return (IRR) is the value of discount rate required for NPV of costs to equal NPV of income (NPV_I). NPV_I can be described by

$$NPV_I = AAR * Y(1/(1+r), N). \tag{9}$$

A higher IRR means better economic performance as the electricity production can match a higher interest rate on investment loans. [24]

3.7.1 Economic analysis

Simple economic calculations were performed for each scenario. The calculation process is described here. In addition to being presented below, the relevant parameters and their chosen values are summarized in Table 3.4.

Table 3.4: Summary of chosen parameters for economic calculations.

Parameter	Chosen value
Discount rate (%)	7
Inflation (%)	0
Bought energy, low (SEK/kWh)	1.07
Sold energy, low (SEK/kWh)	0.43
Bought energy, high (SEK/kWh)	1.72
Sold energy, high (SEK/kWh)	1.08
O&M of battery (SEK/year)	0
Lifetime of battery (years)	15
Lifetime of system (years)	30
Period of loan (years)	30

Using the sizing of PV, wind and battery for each scenario the total capital investment cost and annual operations and maintenance (O&M) costs for each scenario is calculated. Different investment cost per kW installed capacity is used for PV built on roof and on ground. For all economic calculations, onshore wind turbine prices are used. The batteries have a 15 year lifetime, so a reinvestment equaling the initial investment cost done after 15 years is included in the investment cost. This reinvestment is assumed to have a future value equal to the investment cost of the present but is then discounted to present value, using Equation 3 and a discount rate of 7%. Operation and maintenance costs of the batteries are set to 0.

Two different electricity price scenarios are considered, each reflecting the high and low electricity prices scenarios described in Section 2.6.2. The prices are presented in Table 2.5. Both price scenarios are considered for each production and battery scenario in both the current consumption and shore power scenarios. For both energy price scenarios the AAR is calculated using simulated data for bought and sold energy using Equation 8. The capital cost is then divided by the AAR to get a simple estimate of the payback time.

The NPV of costs is calculated according to Equation 6. The downpayment is assumed to equal the capital cost and therefore the annual payment was set to 0. The period of the loan, N, is set to equal the lifetime of the whole system, L= 30 years, and inflation is disregarded ($i = 0$). These assumptions hold for all calculations moving forward. The NPV of income is calculated according to Equation 9, using the AAR. The net NPV is then calculated as the difference between the NPV for costs and the NPV for income. To find the LCOE the CRF is first calculated using Equation 5. The simulated annual production is then used in Equation 7 to get the LCOE.

To find the IRR, different discount rates are applied to the NPV calculations above until the discount rate resulting in the net NPV equaling 0. Finally the annual net cash flow for each year during the lifetime is found using the AAR and O&M costs. These are then each discounted to present value. The discounted payback time can then be found by examining how many years of discounted net cash flow were required to equal the investment cost.

4 Results

In this section all the results are presented. These results are divided into their respective scenarios. An overview and description of the different scenarios can be seen in Table 4.1.

Table 4.1: An overview of the different scenarios. PV and wind capacity is given in MW whilst battery capacity is given in MWh.

Scenarios	**Description**	**Installed capacity (MW, MWh)**
Maximum potential	PV,wind	PV: 12.5, Wind: 12.0
Current consumption		
Scenario 1	PV	PV: 5.7
Scenario 2	PV, wind	PV: 1.1, Wind: 1.3
Scenario 3	PV, balance battery	PV: 5.7, Battery: 5
Scenario 3.0.5	PV, double balance battery	PV: 5.7, Battery: 10
Scenario 3.1	PV, balance and backup battery	PV: 5.7, Battery: 29
Scenario 3.2	PV, backup battery	PV: 5.7, Battery: 24
Scenario 4	PV, wind, balance battery	PV: 2.1, Wind: 1.0, Battery: 4
Scenario 4.0.5	PV, wind, double balance battery	PV: 2.1, Wind: 1.0, Battery: 8
Scenario 4.1	PV, wind, balance and backup battery	PV: 2.1, Wind: 1.0, Battery: 28
Scenario 4.2	PV, wind, backup battery	PV: 2.1, Wind: 1.0, Battery: 24
Shore power		
Scenario 5	PV	PV: 16.3
Scenario 6	PV, wind	PV: 4.6, Wind: 3.0
Scenario 7	PV, balance battery	PV: 16.3, Battery: 10
Scenario 7.0.5	PV, double balance battery	PV: 16.3, Battery: 20
Scenario 7.1	PV, balance, backup battery	PV: 16.3, Battery: 34
Scenario 7.2	PV, backup battery	PV: 16.3, Battery: 24
Scenario 8	PV, wind, balance battery	PV: 4.6, Wind: 3.0, Battery: 7
Scenario 8.0.5	PV, wind, double balance battery	PV: 4.6, Wind: 3.0, Battery: 14
Scenario 8.1	PV, wind, balance and backup battery	PV: 4.6, Wind: 3.0, Battery: 31
Scenario 8.2	PV, wind, backup battery	PV: 4.6, Wind: 3.0, Battery: 24

4.1 Maximum potential

Three possible wind turbine sitings are presented in Figure 4.1. One array of three turbines, including the two turbines within the red area that are proposed by the detail plan from Malmö stad. One array of four offshore turbines loosely following the coastline of Norra Hamnen. One array of four offshore turbines going straight out into the water. The maximum amount of 3 MW turbines deemed realistic to build in Malmö harbour is four.

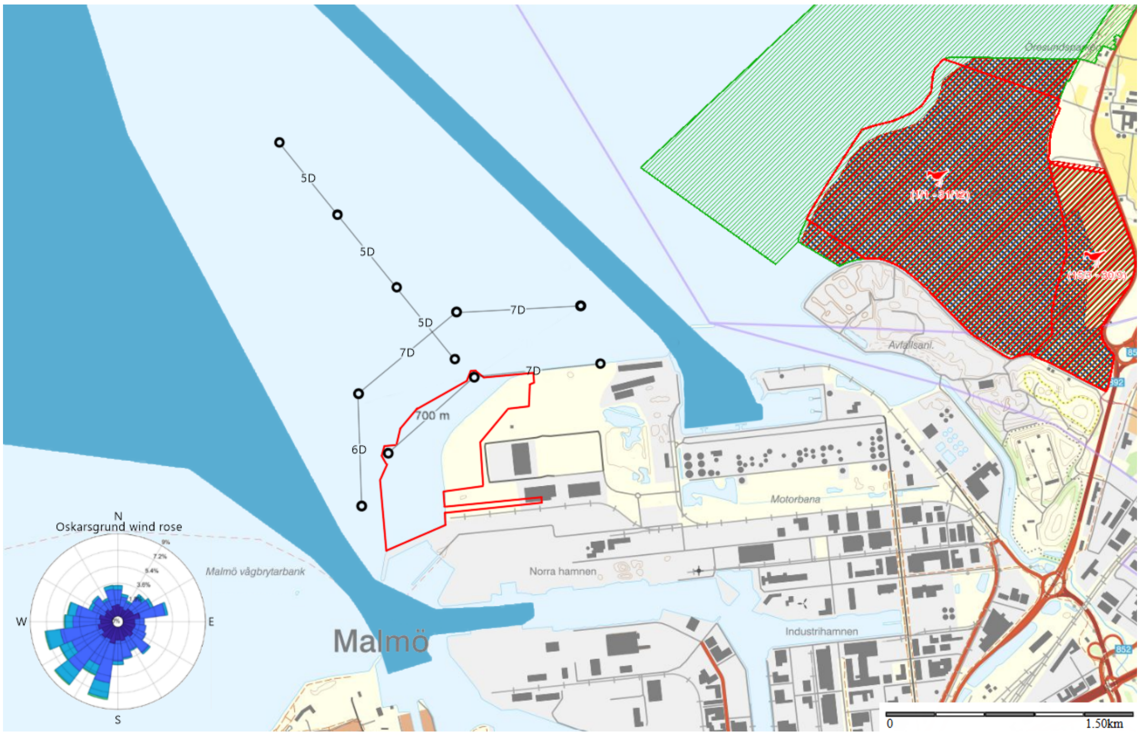

Figure 4.1: Some possible siting layouts for 3 MW wind turbines. Hatch marks nature protection areas. Red outline marks the proposed expansion of the harbor. Darker blue is sea lanes. Distances given in meters or rotor diameters, D=112 m. The wind rose for Oskarsgrund is presented as well. Map taken from [39].

For PV all the areas from Figure 3.3 are used. In talks with CMP we have discussed the likelihood that the surfaces labeled Green areas can be utilized for PV during the whole lifetime. From this discussion we have made the assumption that only 30% of the area is possible to utilize for PV panels. This means a total PV capacity of 12.5 MW.

The monthly production from the maximum potential with a capacity of 12 MW wind and 12.5 MW PV can be seen in Figure 4.2. The production from wind and PV can be seen separately in Figure 4.3. The total annual production is 61.4 GWh, of which 48.8 GWh comes from wind and 12.6 GWh from PV.

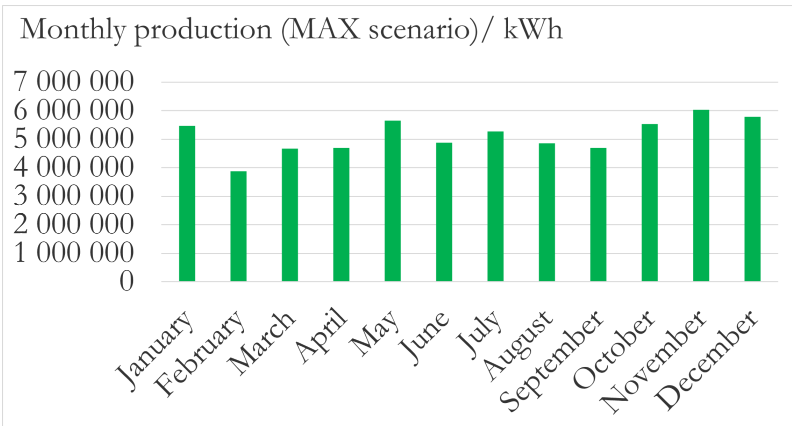

Figure 4.2: Total production in the maximum potential scenario.

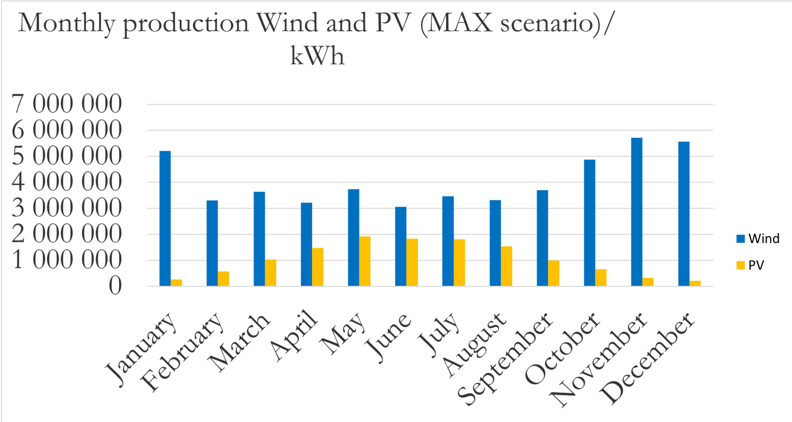

Figure 4.3: Production from wind and PV in the maximum potential scenario.

4.2 Scenario: Current consumption

The monthly consumption in the current consumption scenario is presented in Figure 4.4. The total yearly consumption is 5.5 GWh. The highest daily consumption during the year is 24 MWh. The figure shows a monthly consumption varying between about 350 and 600 MWh with consumption going from highest in winter to lowest in summer.

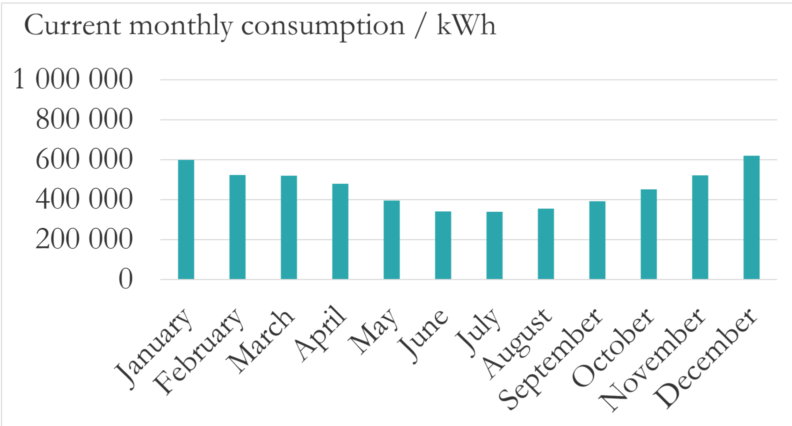

Figure 4.4: Monthly consumption in the current consumption scenario.

4.2.1 Scenario 1: PV

For this scenario only production from PV is present, the areas being used is K1, M21, M23, Toyota, Old Office, General Cargo S and 7% of General Cargo N. These areas add up to a total capacity of 5.7 MW. Figures for the monthly production, consumption compared to production, energy balance, utilized electricity compared to the monthly production and tables for investment costs and calculation can be seen in Figures 4.5-4.8 and Tables 4.2 and 4.3. The utilization for this scenario is 35%, bought electricity is 3.62 GWh and sold electricity is 3.62 GWh.

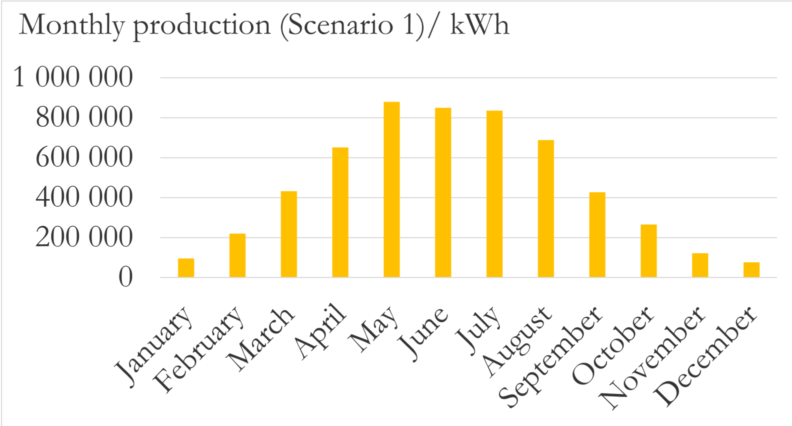

Figure 4.5: Monthly production for Scenario 1: Current consumption with 5.7 MW PV.

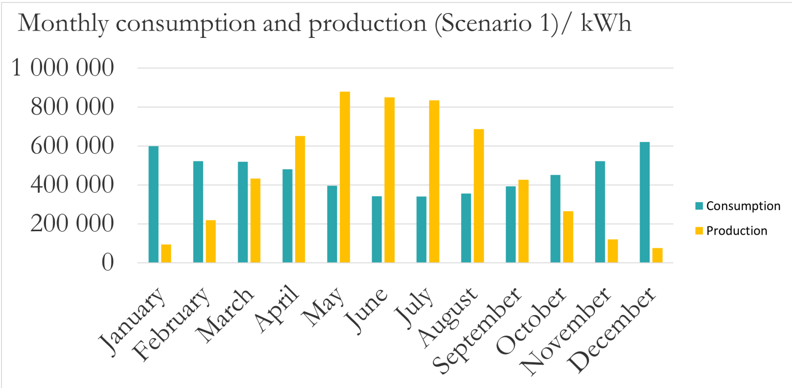

Figure 4.6: Monthly production and consumption for Scenario 1: Current consumption with 5.7 MW PV.

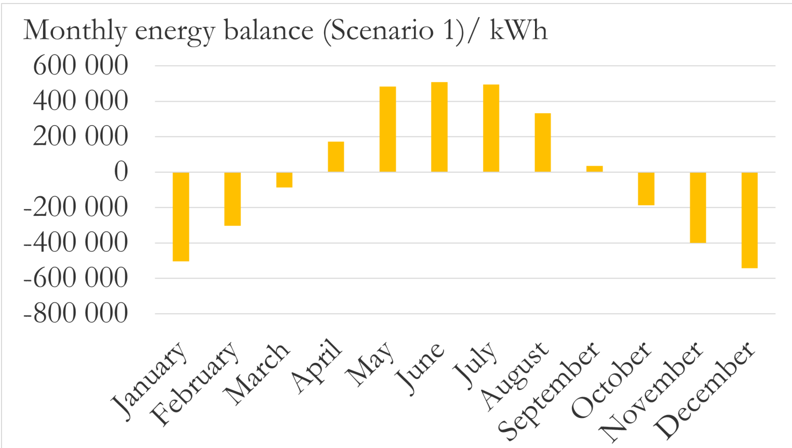

Figure 4.7: Monthly energy balance for Scenario 1: Current consumption with 5.7 MW PV.

The production profile in Figure 4.5 shows that production is high in summer and very low in winter. There is about a factor 10 between the summer months and winter months. Figure 4.6 shows a large overproduction in the summer and underproduction in the winter. The effect of this is seen in the energy balance, Figure 4.7, which shows that a lot of energy is sold in summer and bought during winter. During the year, 3.62 GWh of energy is both bought and sold. The amount of bought and sold energy is equal as the total produced energy equals the total consumed energy. So all produced energy that cannot be utilized in the system will have to be bought at some other time of year.

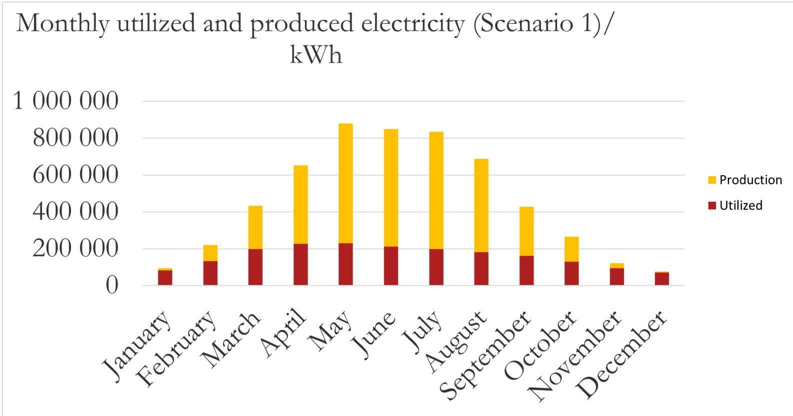

Figure 4.8: Monthly production with the amount of utilized electricity of the production for Scenario 1: Current consumption with 5.7 MW PV.

Figure 4.8 shows that the utilized energy is low year round and varies less between months than the production and consumption profiles. During winter, a majority of the production is utilized whilst only a small fraction is utilized in summer. Total utilization is 35%, meaning also that 35% of the consumption is met with production from the PV panels. The production is oversized for the summer months and will, due to the lack of sun, not cover the energy requirement in winter unless severely oversized compared to the total yearly consumption.

Table 4.2: Investment cost, O&M cost and LCOE for Scenario 1.

Investment cost (SEK)	59 101 400
O&M cost (SEK/year)	1 801 732
LCOE (SEK/kWh)	1.18

Table 4.3: Investment calculation with electricity price 1 (low) and 2 (high) for Scenario 1.

	Electricity price 1	**Electricity price 2**
NPV (SEK)	-36 590 398	8 112 709
IRR (%)	-1	8
Simple payback (Year)	17	9
Discounted payback (Year)	>30	22

The LCOE for Scenario 1 is 1.18 SEK/kWh. As the annual return is not only based on selling energy, but also on reducing the energy that needs to be bought, the LCOE does not tell us everything about the required energy price for profitability. Both the buy and sell price of electricity affects the profitability of the system. Table 4.3 shows that for electricity price 1 the NPV is negative and the IRR is lower than 7%. Both of these facts tell us that the system will not be profitable. With the higher electricity price 2 the NPV is positive, indicating a net profit. The IRR is 8% and the discounted payback time 22 years. For this electricity price the project would be profitable.

4.2.2 Scenario 2: PV and wind

The result of the optimization of PV and wind sizing can be seen in Figure 4.9. The optimal wind turbine size is 1.24 MW and based on this a 1.3 MW turbine is chosen as a realistic turbine sizing. The figure also shows that higher fractions of wind energy lead to higher utilization, up to the maximum found around 75% energy from wind. Notably, 100% wind power results in a higher utilization than 100% PV.

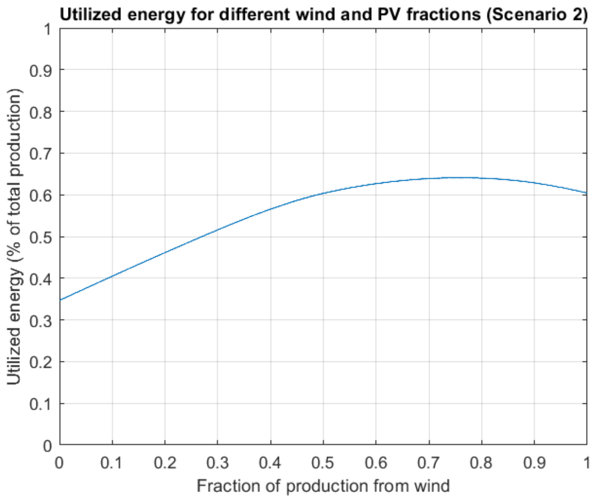

Figure 4.9: Utilized energy as a function of the fraction of electricity produced by wind. 100% wind energy corresponds to wind power producing energy equaling the yearly consumption. Solar power produces the fraction that wind doesn't produce.

The 1.3 MW turbine produces 80% of the required yearly energy. The areas being used for PV to provide the remaining 20% of the total production is K1 S, M21 S and 64% of M23 S. These areas add up to a total capacity of 1.1 MW. Figures for the monthly production, consumption compared to production, energy balance, utilized electricity compared to the monthly production and tables for investment costs and calculation for the production system as a whole can be seen in Figures 4.10-4.13 and Tables 4.4 and 4.5. The utilization for this scenario is 64%, bought electricity is 1.99 GWh and sold electricity is 1.99 GWh.

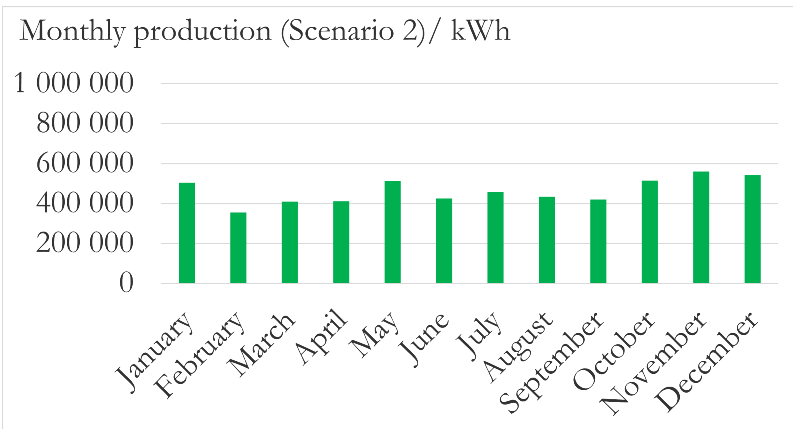

Figure 4.10: Monthly production for Scenario 2: Current consumption with 1.1 MW PV and 1.3 MW Wind.

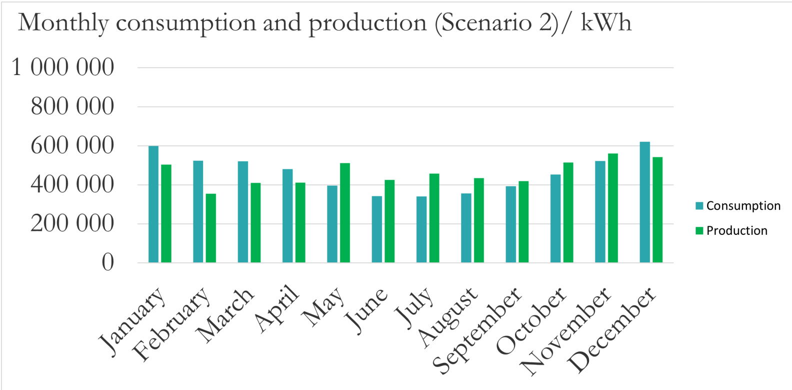

Figure 4.11: Monthly production and consumption for Scenario 2: Current consumption with 1.1 MW PV and 1.3 MW Wind.

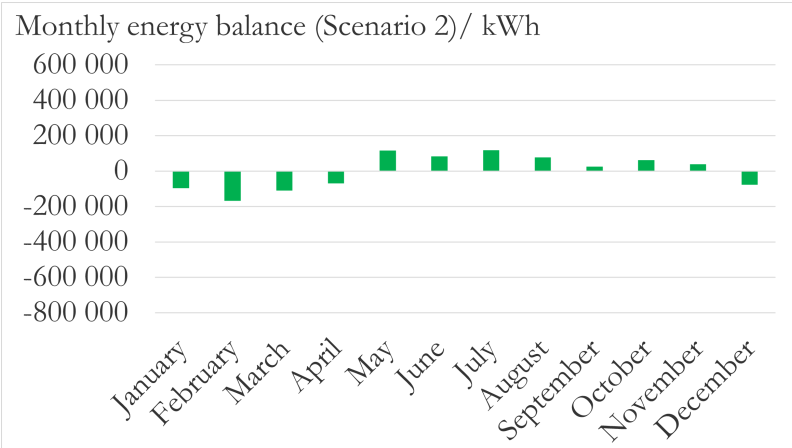

Figure 4.12: Monthly energy balance for Scenario 2: Current consumption with 1.1 MW PV and 1.3 MW Wind.

The production profile in Figure 4.10 shows that production is relatively even over the year. Production is highest during winter, apart from in February which has the lowest production of all the months. Figure 4.11 shows that the production profile follows the consumption profile quite well. There is still a slight underproduction during winter as well as over production during summer, as can also be seen in Figure 4.12. During the year 1.99 GWh of energy is both bought and sold.

Figure 4.13 shows that the utilized energy varies between about 50% and 75% between months. More energy is utilized during winter. Total utilization is 64%, meaning that 64% of the consumption is met with production from the PV and wind system.

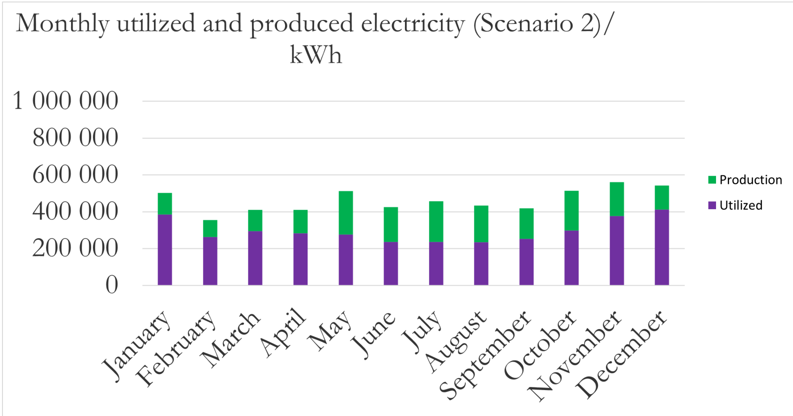

Figure 4.13: Monthly production with the amount of utilized electricity of the production for Scenario 2: Current consumption with 1.1 MW PV and 1.3 MW Wind.

Table 4.4: Investment cost, O&M cost and LCOE for Scenario 2.

Investment cost (SEK)	28 702 400
O&M cost (SEK/year)	866 612
LCOE (SEK/kWh)	0.57

Table 4.5: Investment calculation with electricity price 1 (low) and 2 (high) for Scenario 2.

	Electricity price 1	**Electricity price 2**
NPV (SEK)	18 302 180	63 011 020
IRR (%)	13	26
Simple payback (Year)	7	4
Discounted payback (Year)	12	5

The LCOE for Scenario 2 is 0.57 SEK/kWh. Table 4.5 shows that the NPV is positive for both electricity price 1 and 2. The system is profitable for both energy prices. The IRR is 13% for the first electricity price and the discounted payback is 12 years. For the second electricity price the IRR is 26% and the discounted payback time is 5 years.

4.2.3 Scenario 3: PV and battery

The utilized energy as a function of battery size is presented in Figure 4.14. It can be observed that adding a battery increases the utilization. Further, the utilization increases with increasing battery size. Notably the increase in utilization per MWh is largest for smaller batteries and increasing the battery above 10 MWh barely has any further effect on utilization. This observation is used in the balancing battery sizing choice where a 5 MWh balance battery is chosen as that is where the large positive gradient of the utilization-battery size curve starts decreasing.

The 5 MWh balance battery choice means a 10 MWh double balance battery is chosen. The backup battery size is chosen as 24 MWh and for the balance and backup battery a 29 MWh size is chosen based on the battery definitions made in Section 3.1.4.

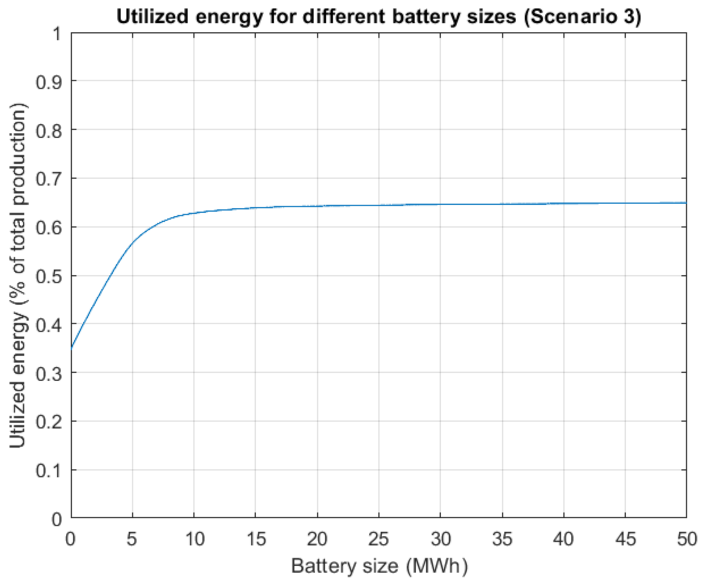

Figure 4.14: Utilized energy as a function of battery size.

This scenario uses the same PV production as Scenario 1 which means that it is the same areas that are being used again which are, K1, M21, M23, Toyota, Old Office, General Cargo S and 7% of General Cargo N. These areas add up to a total capacity of 5.7 MW. Figures for the monthly production, consumption compared to production, energy balance, utilized electricity compared to the monthly production and tables for investment costs and calculation for the different types of batteries can be seen in Figures 4.15-4.18 and Tables 4.7 and 4.8. The utilization, amount of bought and sold electricity and amount of time in max and min SoC in each battery scenario is presented in Table 4.6.

Table 4.6: Bought energy, sold energy, utilization, time in max SoC and time in min SoC for the different battery scenarios in Scenario 3.

Battery	Bought (GWh)	Sold (GWh)	Utilization (%)	MAX SoC (h)	MIN SoC (h)
5 MWh	2.43	2.40	55	1573	3745
10 MWh	2.13	2.08	60	1290	3113
29 MWh	2.81	2.25	52	1573	3745
24 MWh	4.21	3.34	32	8760	0

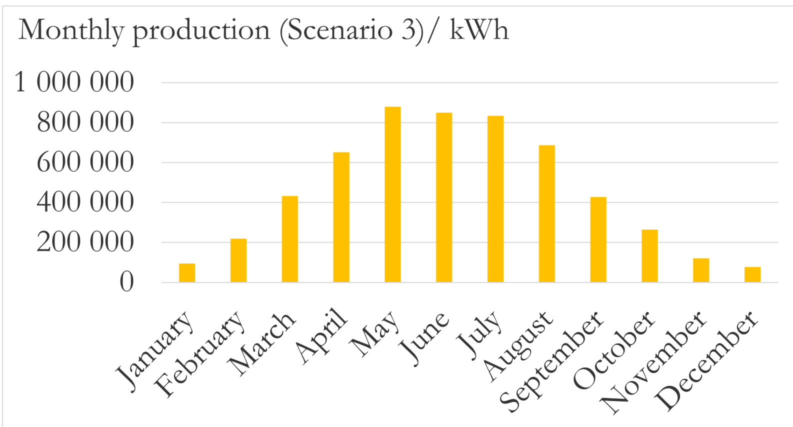

Figure 4.15: Monthly production for Scenario 3/3.0.5/3.1/3.2: Current consumption with 5.7 MW PV with a battery.

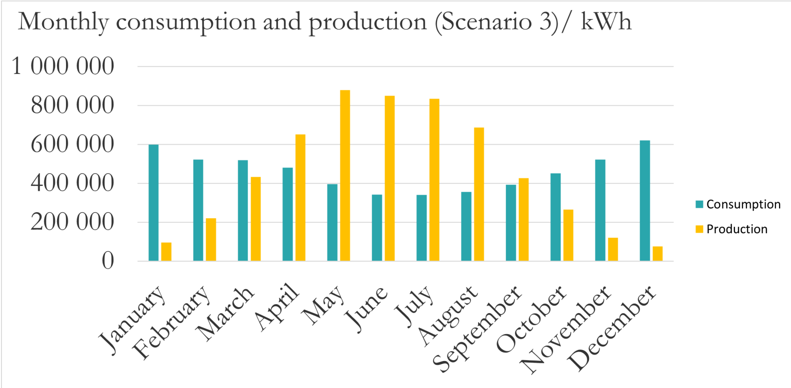

Figure 4.16: Monthly production and consumption for Scenario 3/3.0.5/3.1/3.2: Current consumption with 5.7 MW PV with a battery.

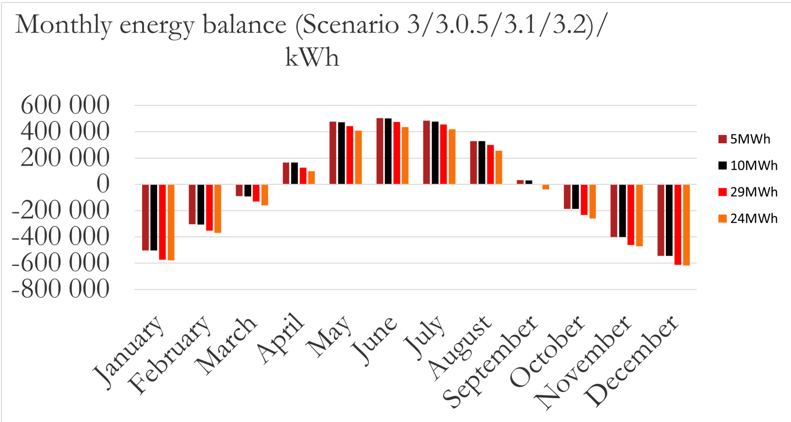

Figure 4.17: Monthly energy balance for Scenario 3/3.0.5/3.1/3.2: Current consumption with 5.7 MW PV with 5 MWh, 10 MWh, 29 MWh and 24 MWh battery.

The production profile in Figure 4.15 is equal to the one in Scenario 1 with high production in summer and low production in winter. Like in Scenario 1 Figure 4.16 shows a large overproduction in the summer and underproduction in the winter. The energy balance profiles for all four battery scenarios, seen in Figure 4.17, resemble the energy balance in Scenario 1, where a lot of energy is sold during summer and bought during winter. Table 4.6 shows that the 5 MWh balance and 10 MWh double balance scenarios have similar amounts of bought and sold energy. The double balance battery requires less energy to be sold and bought, which is expected as the utilization is higher for this battery. The two batteries with backup functionality need more bought and less sold energy. The 24 MWh backup battery requires noticeably more energy to be bought and sold, a comparable amount to Scenario 1. This because there is no balance function and the utilization therefore is low, like in Scenario 1.

Regarding the SoC for the different batteries, Table 4.6 shows that the double balance battery has fewer hours with a full or empty battery than the 5 MWh and 29 MWh batteries. This is a result of the higher utilization in the 10 MWh double balance battery scenario. The 5 MWh and 29 MWh batteries have the same number of MAX and MIN SoC hours. This is likely due to the fact that the balance part (which is the only one considered for the SoC) is of equal size in the two scenarios. The 24 MWh backup battery has no balance function, which is why the SoC is always MAX and MIN for this battery.

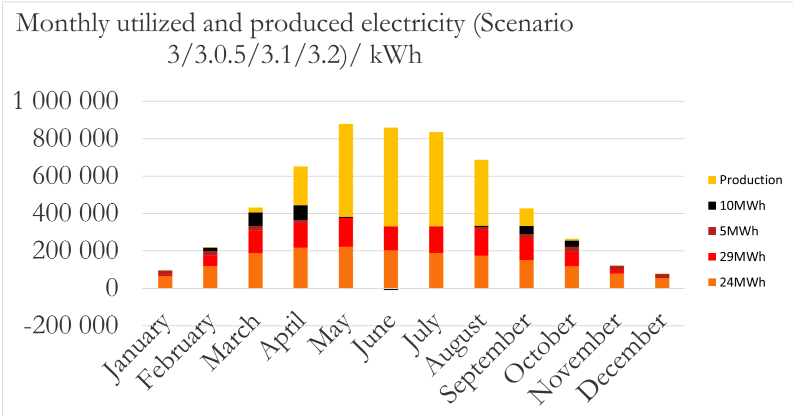

Figure 4.18: Monthly production with the amount of utilized electricity of the production for Scenario 3/3.0.5/3.1/3.2: Current consumption with 5.7 MW PV with 5 MWh, 10 MWh, 29 MWh and 24 MWh battery.

Figure 4.18 shows that the utilized energy varies between close to 100% in winter and just below 50% in summer for the 5 MWh, 10 MWh and 29 MWh batteries. The utilization is lower for the 24 MWh backup battery, ranging between 75% in winter and 25% in summer. The most noticeable difference between the three batteries with balance function is seen in the spring and autumn months. Where the double balance battery results in a noticeably larger utilization. The large difference between the three balancing batteries and the 24 MWh backup battery is also clearly seen in the total utilization in Table 4.6 of 55%, 60%, 52% and 32% respectively. As in Scenario 1 the production is oversized in summer and cannot meet the consumption in winter. The three balance batteries do however increase the utilization during the summer months.

Table 4.7: Investment cost, O&M cost and LCOE for Scenario 3/3.0.5/3.1/3.2.

	5 MWh	**10 MWh**	**29 MWh**	**24 MWh**
Investment cost (SEK)	93 162 550	127 223 701	256 656 073	222 594 922
O&M cost (SEK/year)	1 801 732	1 801 732	1 801 732	1 801 732
LCOE (SEK/kWh)	1.68	2.17	4.06	3.56

Table 4.8: Investment calculation with electricity price 1 (low) and 2 (high) for Scenario 3/3.0.5/3.1/3.2.

Electricity price 1	**5 MWh**	**10 MWh**	**29 MWh**	**24 MWh**
NPV (SEK)	-61 433 873	-93 163 180	-230 771 720	-209 490 081
IRR (%)	-3	-6	-15	-19
Simple payback (Year)	20	28	>30	>30
Discounted payback (Year)	>30	>30	>30	>30
Electricity price 2	**5 MWh**	**10 MWh**	**29 MWh**	**24 MWh**
NPV (SEK)	-16 978 583	-48 878 193	-190 605 855	-171 842 682
IRR (%)	5	2	-8	-8
Simple payback (Year)	11	16	29	>30
Discounted payback (Year)	>30	>30	>30	>30

In Table 4.7 it can be seen that the LCOE is lowest for the 5 MWh battery, at 1.68 SEK/kWh, followed by 2.17 SEK/kWh for the 10 MWh battery and notably higher for the two larger batteries. The 29 MWh balance and backup battery has the highest LCOE of 4.06 SEK/kWh followed by 3.56 SEK/kWh for the 24 MWh one. Even though the utilization is better for the 10 MWh battery the increase in utilization is much smaller for the same increase in investment cost compared to going from no battery to the 5 MWh balance battery. The increase in utilization means increase in AAR, but the higher investment cost still results in a higher LCOE than for the 5 MWh battery. The same can be said for the 29 MWh and 24 MWh batteries, where the 29 MWh battery has higher utilization but also higher LCOE. Regarding profitability, Table 4.8 shows that no battery scenario is profitable regardless of electricity price. It can be seen that the 5 MWh balance battery performs best economically. For the higher energy price the IRR is positive at 5%.

4.2.4 Scenario 4: PV, wind and battery

The optimization of battery size and PV-Wind production fraction is presented in Figures 4.19 and 4.20. A balancing battery size of 4 MWh is chosen. This corresponds to an optimal wind turbine size of 1.1 MW and based on this a 1 MW wind turbine is chosen as a realistic turbine sizing. The double balance battery is chosen as 8 MWh, which follows from the balance battery size. The backup battery size is chosen as 24 MWh and for the balance and backup battery a 28 MWh size is chosen based on the battery definitions made in Section 3.1.4.

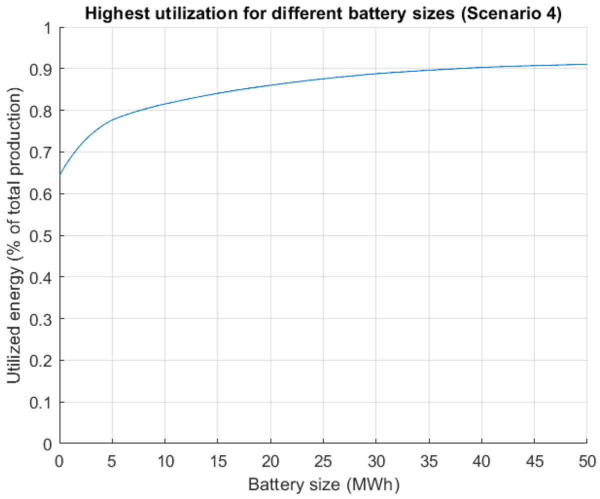

Figure 4.19: Highest utilization for each battery size.

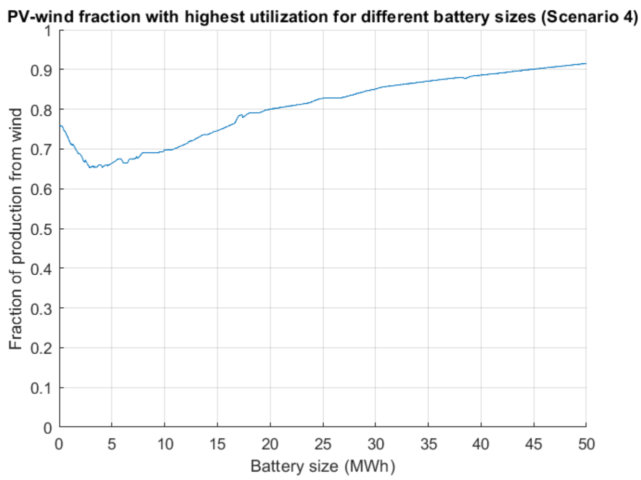

Figure 4.20: Fraction of production from wind resulting in the highest utilization as a function of battery size.

Figures 4.19 and 4.20 are two different views of the same 3-dimensional graph. The three dimensions are *Battery size*, *Fraction of production from wind* and *Utilization*. The curve depicted in the two figures shows the highest utilization and corresponding wind production fraction for each simulated battery size.

Observing Figure 4.19 it can be noted that, as in Scenario 3, adding a battery increases the utilization. The utilization also increases as the battery size increases. This increase is rapid up to about 4 MWh but decreases for larger battery sizes. This observation was used in the battery sizing choice where a 4 MWh balance battery was chosen. Figure 4.20 presents the relation between battery size and optimal fraction of PV and wind production. It can be seen that the addition of a battery first decreases the amount of wind power in the highest utilization energy mix. For batteries larger than about 3 MWh the optimal fraction starts shifting towards more wind. This behaviour generally continues for the rest of the plotted battery sizes.

The 1 MW wind turbine produces 61% of the required yearly energy. The areas being used for PV to provide the remaining 39% of the total production is K1 S, M21 S, M23 S and 39% of General Cargo S. These areas add up to a total capacity of 2.1 MW. Figures for the monthly production, consumption compared to production, energy balance, utilized electricity compared to the monthly production and tables for investment costs and calculation for the production system as a whole for the different batteries can be seen in Figures 4.21-4.24 and Tables 4.10 and 4.11. The utilization, amount of bought and sold electricity and amount of time in max and min SoC in each battery scenario is presented in Table 4.9.

Table 4.9: Bought energy, sold energy, utilization, time in max SoC and time in min SoC for the different battery scenarios in Scenario 4.

Battery	Bought (GWh)	Sold (GWh)	Utilization (%)	MAX SoC (h)	MIN SoC (h)
4 MWh	1.33	1.30	75	2057	2729
8 MWh	1.12	1.06	78	1642	2212
28 MWh	1.62	1.10	66	2057	2729
24 MWh	2.56	1.69	56	8760	0

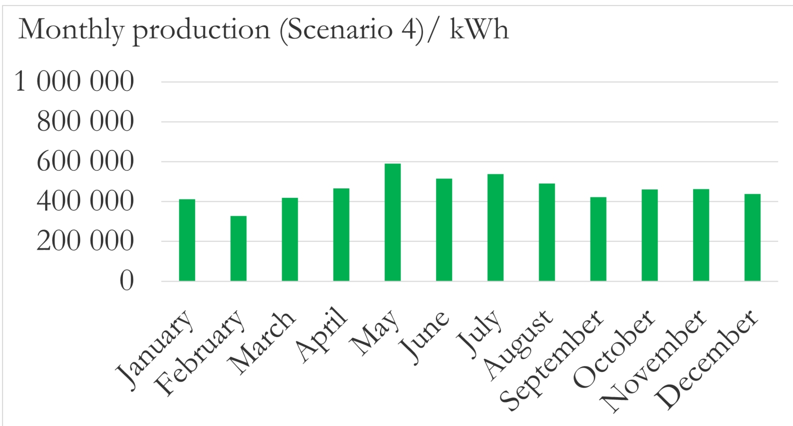

Figure 4.21: Monthly production for Scenario 4/4.0.5/4.1/4.2: Current consumption with 2.1 MW PV and 1.0MW Wind with a battery.

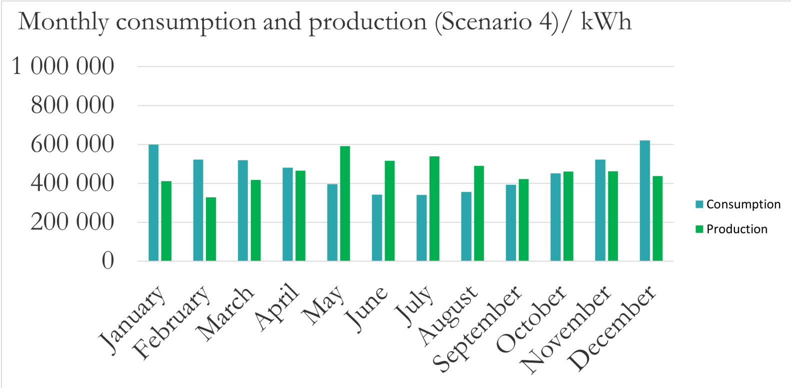

Figure 4.22: Monthly production and consumption for Scenario 4/4.0.5/4.1/4.2: Current consumption with 2.1 MW PV and 1.0MW Wind with a battery.

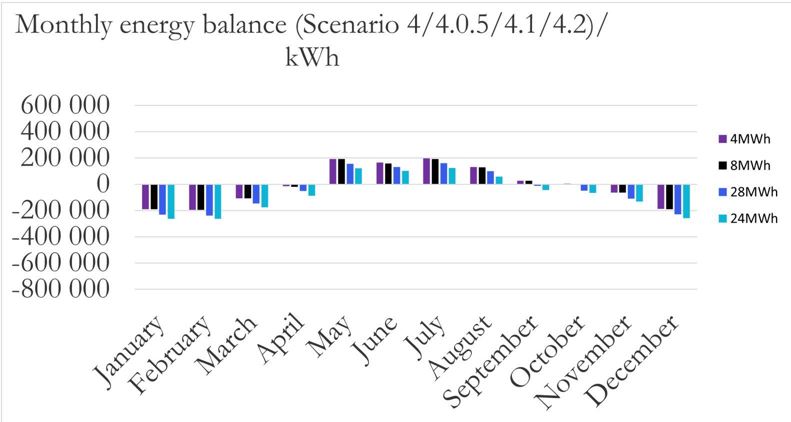

Figure 4.23: Monthly energy balance for Scenario 4/4.0.5/4.1/4.2: Current consumption with 2.1 MW PV and 1.0MW Wind with 4 MWh, 8 MWh, 28 MWh and 24 MWh battery.

The production profile in Figure 4.21 shows that production is relatively even from August to March and up to 50% higher in summer. Figure 4.22 shows that there is underproduction in winter and overproduction in summer. Still, the production profile follows the consumption profile quite well, especially during autumn. Figure 4.23 shows the energy balance for the four different battery scenarios. The profiles of all batteries are similar to the energy balance profile in Scenario 2. Noticeably the energy balance is lower during September to March. This is likely caused by the smaller installed capacity of wind power, which leads to less production during the winter. The energy balance is also higher during summer, probably for the same reason as there is more PV and thus more production in summer. The total amount of bought and sold energy as well as the utilization for the different batteries, seen in Table 4.9, follows the same pattern as in Scenario 3. However, in this scenario the total amounts of bought and sold energy are lower. The utilization is also higher than in Scenario 3, which explains the lowered need to buy and sell energy. The SoC for the batteries follows the same pattern as in Scenario 3.

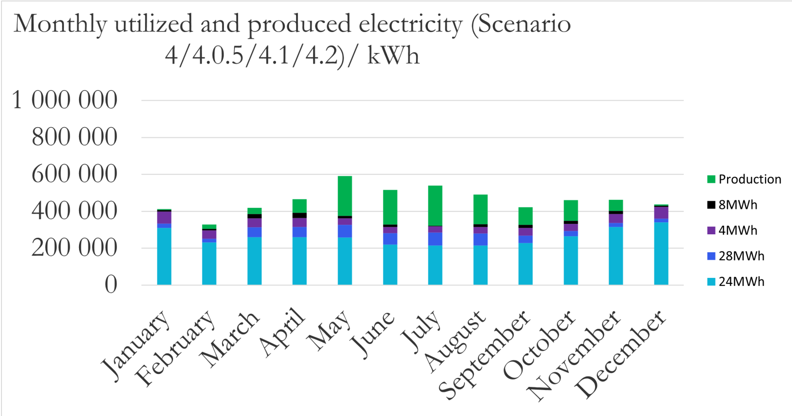

Figure 4.24: Monthly production with the amount of utilized electricity of the production for Scenario 4/4.0.5/4.1/4.2: Current consumption with 2.1 MW PV and 1.0 MW Wind with 4 MWh, 8 MWh, 28 MWh and 24 MWh battery.

Figure 4.24 shows that the utilized energy varies between close to 100% in winter and about 60% in summer for the 4 MWh, 8 MWh and 28 MWh batteries. The utilization is lower for the 24 MWh backup battery, but the difference is not as big as in Scenario 3. The amount of utilized energy is quite even for all months. A notable comparison to Scenario 3 is that the amount of utilized energy in the summer months is similar in both scenarios. The difference, that is also reflected in the higher utilization percentages in this scenario, is that there is more production, and therefore also higher utilization, in winter. The utilization in the battery scenarios are, in order, 75%, 78%, 66% and 56%. The differences between these numbers are smaller than in Scenario 3.

Table 4.10: Investment cost, O&M cost and LCOE for Scenario 4/4.0.5/4.1/4.2.

	4 MWh	**8 MWh**	**28 MWh**	**24 MWh**
Investment cost (SEK)	62 199 520	89 448 441	225 693 043	198 444 122
O&M cost (SEK/year)	1 059 028	1 059 028	1 059 028	1 059 028
LCOE (SEK/kWh)	1.10	1.49	3.47	3.08

Table 4.11: Investment calculation with electricity price 1 (low) and 2 (high) for Scenario 4/4.0.5/4.1/4.2.

Electricity price 1	**4 MWh**	**8 MWh**	**28 MWh**	**24 MWh**
NPV (SEK)	-12 539 759	-38 206 276	-180 837 249	-163 012 092
IRR (%)	4	1	-10	-11
Simple payback (Year)	11	18	>30	>30
Discounted payback (Year)	>30	>30	>30	>30
Electricity price 2	**4 MWh**	**8 MWh**	**28 MWh**	**24 MWh**
NPV (SEK)	31 867 304	6 022 782	-140 291 321	-125 364 693
IRR (%)	13	8	-4	-5
Simple payback (Year)	7	11	23	23
Discounted payback (Year)	13	25	>30	>30

In Table 4.10 we see that the LCOE is lowest for the 4 MWh battery, at 1.10 SEK/kWh, followed by 1.49 SEK/kWh for the 8 MWH battery and notably higher for the two larger batteries. The 28 MWh balance and backup battery has the highest LCOE of 3.47 SEK/kWh followed by 3.08 SEK/kWh for the 24 MWh one. The same arguments for increase in utilization versus increase in investment cost and therefore LCOE as in Scenario 3 can be made here. Regarding profitability,

Table 4.11 shows that both the 4 MWh and 8 MWh balance battery scenarios are profitable with the higher electricity price.

4.2.5 Comparison

To get a better overview of the different scenarios for current consumption a comparison of capacity, production and utilization can be seen below in Table 4.12. An economic comparison for the current consumption scenarios can be seen in Tables 4.13 and 4.14.

Table 4.12: Comparison of the different scenarios for current consumption.

Scenario	Capacity	Production distribution	Utilization
PV	PV: 5.7 MW	PV: 100%	35%
PV and wind	PV: 1.1 MW, Wind: 1.3 MW	PV: 20%, Wind: 80%	64%
PV and battery	PV: 5.7 MW	PV: 100%	5 MWh: 55% 10 MWh: 60% 29 MWh: 52% 24 MWh: 32%
PV, wind and battery	PV: 2.1 MW, Wind: 1.0 MW	PV: 39%, Wind: 61%	4 MWh: 75% 8 MWh: 78% 28 MWh: 66% 24 MWh: 56%

Table 4.13: Economic comparison of the different scenarios for current consumption (electricity price 1).

Electricity price 1			
Scenario	**LCOE (SEK/kWh)**	**IRR (%)**	**Discounted payback (years)**
PV	1.18	-1	> 30
PV and wind	0.57	13	12
PV and battery	5 MWh: 1.68 10 MWh: 2.17 29 MWh: 4.06 24 MWh: 3.56	5 MWh: -3 10 MWh: -6 29 MWh: -15 24 MWh: -19	5 MWh: > 30 10 MWh: > 30 29 MWh: > 30 24 MWh: > 30
PV, wind and battery	4 MWh: 1.10 8 MWh: 1.49 28 MWh: 3.47 24 MWh: 3.08	4 MWh: 4 8 MWh: 1 28 MWh: -10 24 MWh: -11	4 MWh: > 30 8 MWh: > 30 28 MWh: > 30 24 MWh: > 30

Table 4.14: Economic comparison of the different scenarios for current consumption (electricity price 2).

Electricity price 2			
Scenario	**LCOE (SEK/kWh)**	**IRR (%)**	**Discounted payback (years)**
PV	1.18	8	22
PV and wind	0.57	26	5
PV and battery	5 MWh: 1.68 10 MWh: 2.17 29 MWh: 4.06 24 MWh: 3.56	5 MWh: 5 10 MWh: 2 29 MWh: -8 24 MWh: -8	5 MWh: > 30 10 MWh: > 30 29 MWh: > 30 24 MWh: > 30
PV, wind and battery	4 MWh: 1.10 8 MWh: 1.49 28 MWh: 3.47 24 MWh: 3.08	4 MWh: 13 8 MWh: 8 28 MWh: -4 24 MWh: -5	4 MWh: 13 8 MWh: 25 28 MWh: > 30 24 MWh: > 30

4.3 Scenario: Shore power

The monthly consumption in the shore power consumption scenario is presented in Figure 4.25. The total yearly consumption is 16.8 GWh. This consumption profile is similar in shape to the current consumption profile: consumption is higher in winter than summer. This is probably because the work load and therefore electricity demand of CMP's own operations increases with vessels docking. The consumption varies between about 1100 MWh and 1600 MWh, a slightly larger percent difference compared to the current consumption scenario.

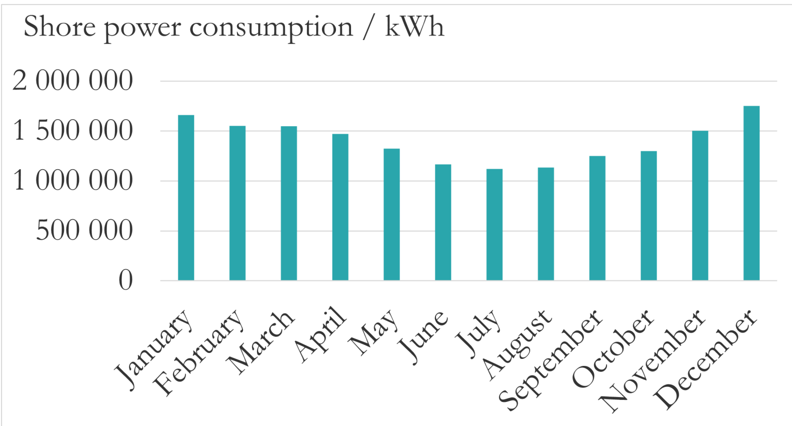

Figure 4.25: Monthly consumption in the shore power scenario.

4.3.1 Scenario 5: PV

For this scenario only production from PV is present, the areas being used is K1, M21, M23, Toyota, Old Office, General Cargo, Pirarm, North and 82% of the Green areas. In the max scenario we only allowed a usage of 30% of the labeled Green areas which means that to meet the consumption with shore power, production from only PV will not be enough. However, results with usage of 82% of the Green areas will still be presented. These areas add up to a total capacity of 16.3 MW. Figures for the monthly production, consumption compared to production, energy balance, utilized electricity compared to the monthly production and tables for investment costs and calculation can be seen in Figures 4.26-4.29 and Tables 4.15 and 4.16. The utilization for this scenario is 41%, bought electricity is 9.85 GWh and sold electricity is 9.85 GWh.

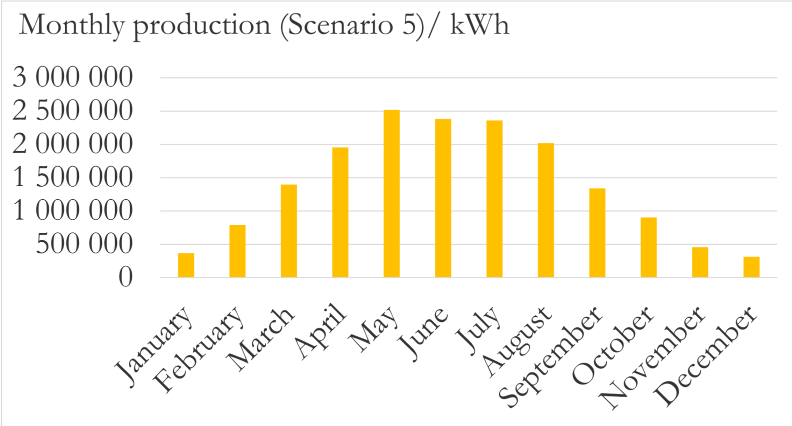

Figure 4.26: Monthly production for Scenario 5: Shore power with 16.3 MW PV.

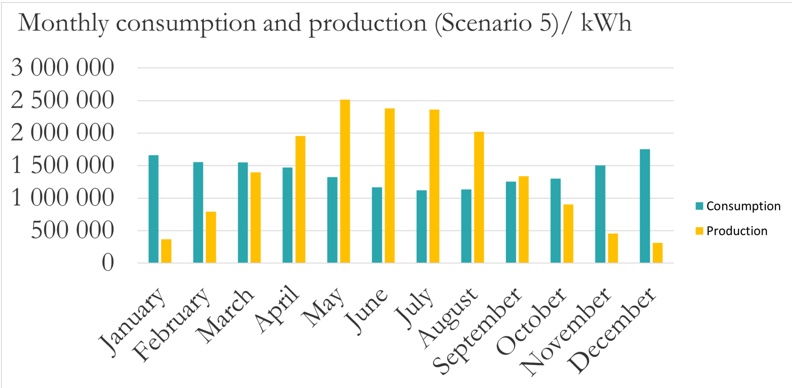

Figure 4.27: Monthly production and consumption for Scenario 5: Shore power with 16.3 MW PV.

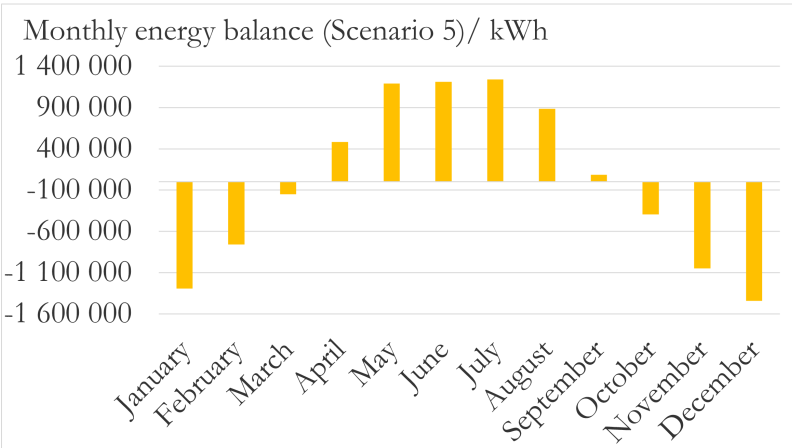

Figure 4.28: Monthly energy balance for Scenario 5: Shore power with 16.3 MW PV.

The production profile in Figure 4.26 is very similar to that in Scenario 1 and 3. Production is high in summer and very low in winter. Figure 4.27 shows a large overproduction in the summer and underproduction in the winter. The effect of this is seen in the energy balance, figure 4.28, which shows that a lot of energy has to be sold in summer and bought during winter. During the year 9.85 GWh of energy is both bought and sold.

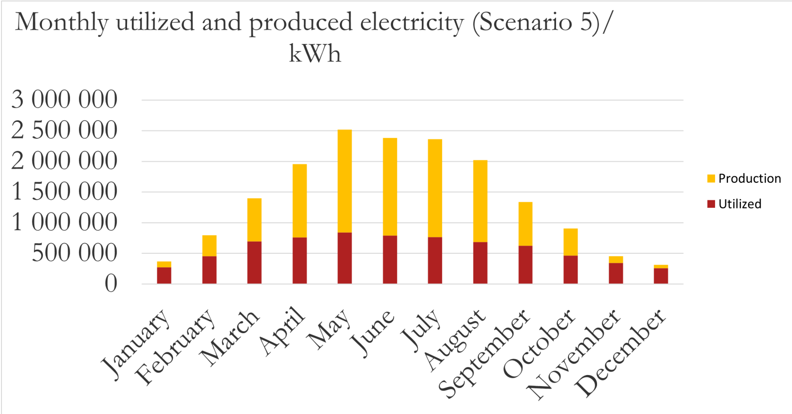

Figure 4.29: Monthly production with the amount of utilized electricity of the production for Scenario 5: Shore power with 16.3 MW PV.

Figure 4.29 shows that the utilized energy is low year round and varies less between months than the production and consumption profiles. During winter, a majority of the production is utilized whilst only a fraction is utilized in summer. Total utilization is 41%. The production is oversized for the summer months and will, due to the lack of sun, not cover the energy requirement in winter unless severely oversized compared to the total yearly consumption.

Table 4.15: Investment cost, O&M cost and LCOE for Scenario 5.

Investment cost (SEK)	194 152 600
O&M cost (SEK/year)	5 130 760
LCOE (SEK/kWh)	1.24

Table 4.16: Investment calculation with electricity price 1 (low) and 2 (high) for Scenario 5.

	Electricity price 1	**Electricity price 2**
NPV (SEK)	-113 054 480	22 390 498
IRR (%)	0	8
Simple payback (Year)	17	9
Discounted payback (Year)	>30	23

The LCOE for Scenario 1 is 1.24 SEK/kWh. This is similar to the LCOE in the corresponding current consumption scenario, Scenario 1. Table 4.16 shows that for electricity price 1 the system will not be profitable. With the higher electricity price 2 however the NPV is positive, the IRR is 8% and the discounted payback time 23 years. For this electricity price the project would be profitable.

4.3.2 Scenario 6: PV and wind

The result of the optimization of PV and wind sizing can be seen in Figure 4.30. The figure shows that higher fractions of wind energy lead to higher utilization, up to the maximum found around 70% energy from wind. As in Scenario 2, 100% wind power results in a higher utilization than 100% PV. The optimal wind turbine size is 3.43 MW and based on this a 3 MW turbine is chosen as a realistic turbine sizing.

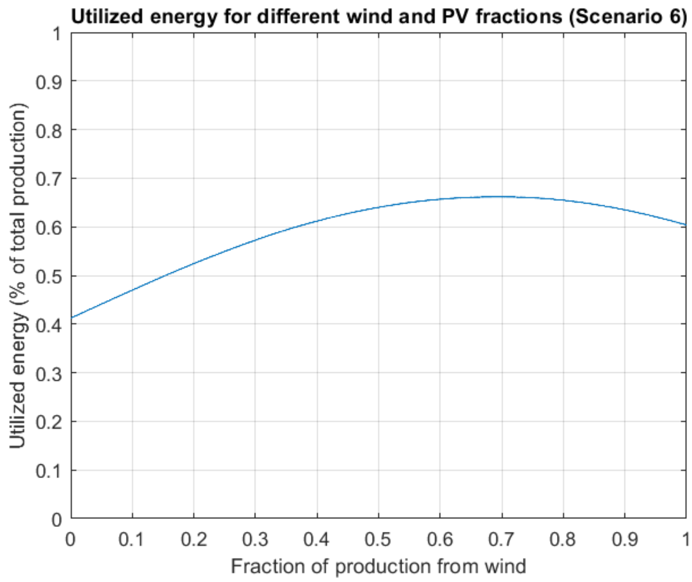

Figure 4.30: Utilized energy as a function of the fraction of electricity produced by wind. 100% wind energy corresponds to wind power producing energy equaling the yearly consumption. Solar power produces the fraction that wind doesn't produce.

The 3 MW wind turbine produces 77% of the required yearly energy. The areas being used for PV to provide the remaining 23% of the total production is K1 S, M21 S, M23 S, General Cargo S, Old office, Toyota and 64% of K1 N. These areas add up to a total capacity of 4.6 MW. Figures for the monthly production, consumption compared to production, energy balance, utilized electricity compared to the monthly production and tables for investment costs and calculation for the production system as a whole can be seen in Figures 4.31-4.34 and Tables 4.17 and 4.18. The utilization for this scenario is 68%, bought electricity is 5.44 GWh and sold electricity is 5.44 GWh.

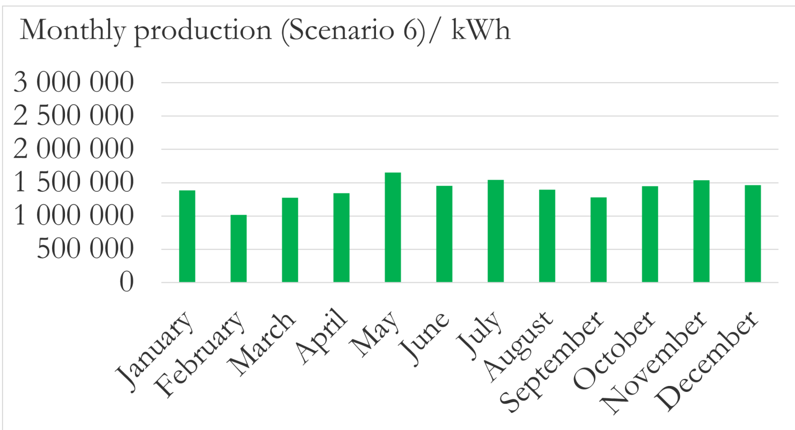

Figure 4.31: Monthly production for Scenario 6: Shore power with 4.6 MW PV and 3 MW Wind.

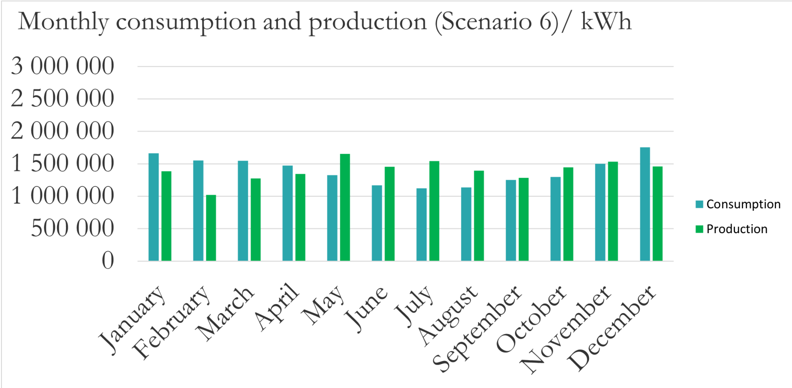

Figure 4.32: Monthly production and consumption for Scenario 6: Shore power with 4.6 MW PV and 3 MW Wind.

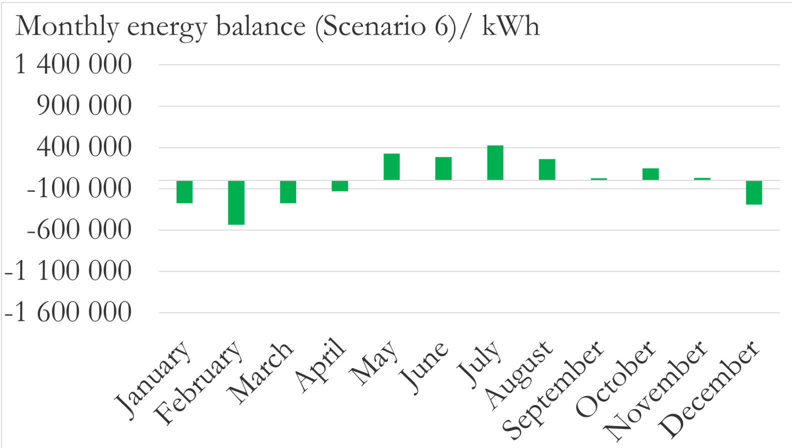

Figure 4.33: Monthly energy balance for Scenario 6: Shore power with 4.6 MW PV and 3 MW Wind.

The production profile in Figure 4.31 shows that production is relatively even over the year with a minimum in spring. Figure 4.32 shows that the production profile follows the consumption profile quite well. There is a slight underproduction during winter as well as overproduction during summer, as can also be seen in figure 4.33. During the year 5.44 GWh of energy is both bought and sold.

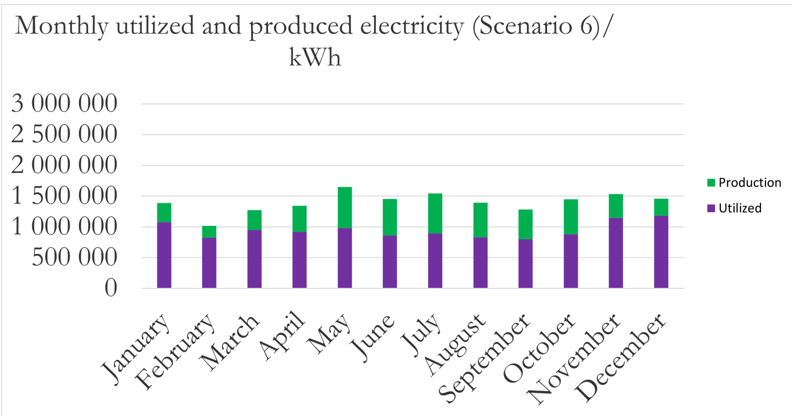

Figure 4.34: Monthly production with the amount of utilized electricity of the production for Scenario 6: Shore power with 4.6 MW PV and 3 MW Wind.

Table 4.17: Investment cost, O&M cost and LCOE for Scenario 6.

Investment cost (SEK)	87 290 300
O&M cost (SEK/year)	2 641 714
LCOE (SEK/kWh)	0.58

Table 4.18: Investment calculation with electricity price 1 (low) and 2 (high) for Scenario 6.

	Electricity price 1	Electricity price 2
NPV (SEK)	59 712 181	195 157 159
IRR (%)	13	26
Simple payback (Year)	7	4
Discounted payback (Year)	11	5

The LCOE for scenario 6 is 0.58 SEK/kWh, as seen in Table 4.17. Table 4.18 shows that the NPV is positive for both electricity price 1 and 2. The system is profitable for both energy prices. The IRR is 13% for the first electricity price and the discounted payback is 11 years. For the second electricity price the IRR is 26% and the discounted payback time is 5 years. These economic results are very similar to the ones in Scenario 2.

4.3.3 Scenario 7: PV and battery

The utilized energy as a function of battery size is presented in Figure 4.35. The relation is similar to the one described in Scenario 3. A balance battery of 10 MWh was chosen by observing where the gradient started decreasing. This means 20 MWh is chosen for the double balance battery. The backup battery size is chosen as 24 MWh and for the balance and backup battery a 34 MWh size is chosen.

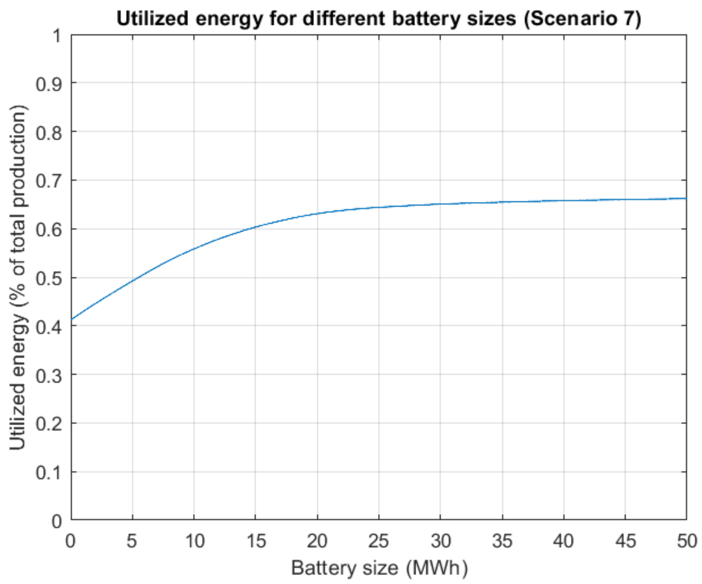

Figure 4.35: Utilized energy as a function of battery size.

This scenario uses the same PV production as Scenario 5 which means that only production from PV is still not enough. The results will however still be presented with the excess use of the Green areas. The areas being used are the following, K1, M21, M23, Toyota, Old Office, General Cargo, Pirarm, North and 82% of the Green areas. These areas add up to a total capacity of 16.3 MW. Figures for the monthly production, consumption compared to production, energy balance, utilized electricity compared to the monthly production and tables for investment costs and calculation for the different types of batteries can be seen in Figures 4.36-4.40 and Tables 4.20 and 4.21. The utilization, amount of bought and sold electricity and amount of time in max and min SoC in each battery scenario is presented in Table 4.19.

Table 4.19: Bought energy, sold energy, utilization, time in max SoC and time in min SoC for the different battery scenarios in Scenario 7.

Battery	Bought (GWh)	Sold (GWh)	Utilization (%)	MAX SoC (h)	MIN SoC (h)
10 MWh	7.33	7.26	56	1649	4211
20 MWh	6.03	5.92	63	1350	3235
34 MWh	7.75	7.10	56	1649	4211
24 MWh	10.45	9.58	40	8760	0

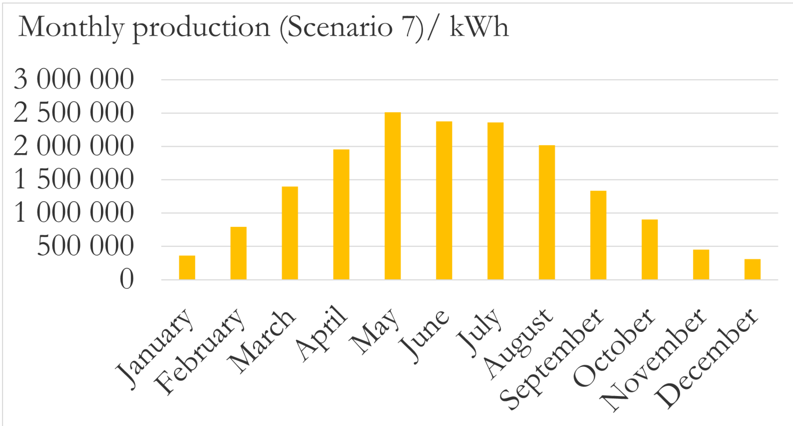

Figure 4.36: Monthly production for Scenario 7/7.0.5/7.1/7.2: Shore power with 16.3 MW PV with a battery.

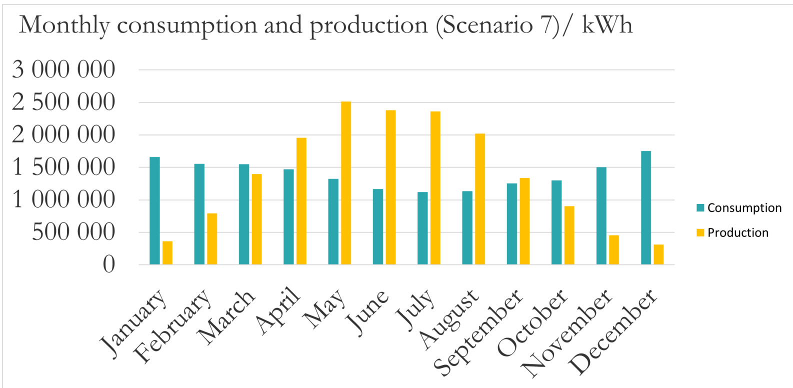

Figure 4.37: Monthly production and consumption for Scenario 7/7.0.5/7.1/7.2: Shore power with 16.3 MW PV with a battery.

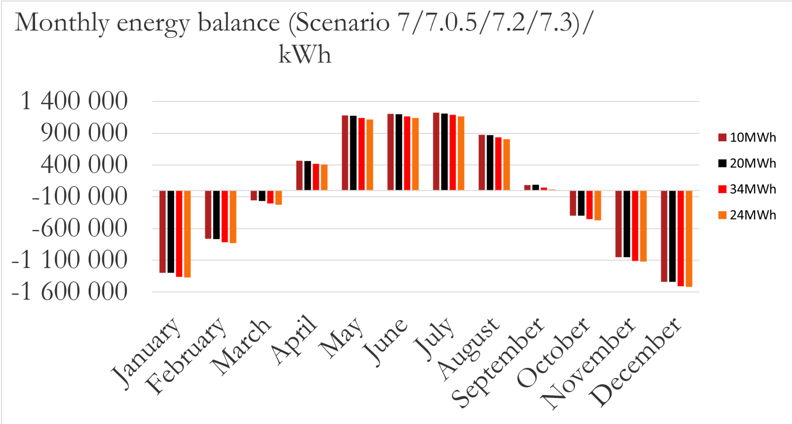

Figure 4.38: Monthly energy balance for Scenario 7/7.0.5/7.1/7.2: Shore power with 16.3 MW PV with 10 MWh, 20 MWh, 34 MWh and 24 MWh battery.

The production profile in Figure 4.36 is equal to the one in Scenario 5 with high production in summer and low production in winter. Like in Scenario 5 Figure 4.37 shows a large overproduction in the summer and underproduction in the winter. Figure 4.38 shows the energy balance for the four different battery scenarios. The profile for all four battery scenarios resemble the energy balance in the other PV scenarios, where a lot of energy is sold during summer and bought during winter. Table 4.19 shows that the 10 MWh balance, 20 MWh double balance and 34 MWh balance and backup scenarios have similar amounts of bought and sold energy. The double balance battery requires less energy to be sold and bought, which is expected as the utilization is higher for this battery. The 34 MWh battery requires more energy to be bought and less to be sold than the 10 MWh one. The 24 MWh backup battery requires noticeably more energy to be bought and sold, a comparable amount to Scenario 5. This because there is no balance function and the utilization therefore is low, like in Scenario 5. The SoC for the batteries follows the same pattern as in Scenario 3.

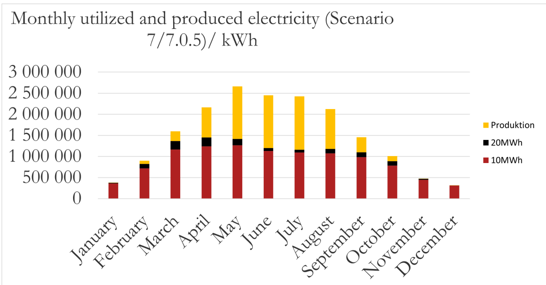

Figure 4.39: Monthly production with the amount of utilized electricity of the production for Scenario 7/7.0.5: Shore power with 16.3 MW PV with 10 MWh and 20 MWh battery.

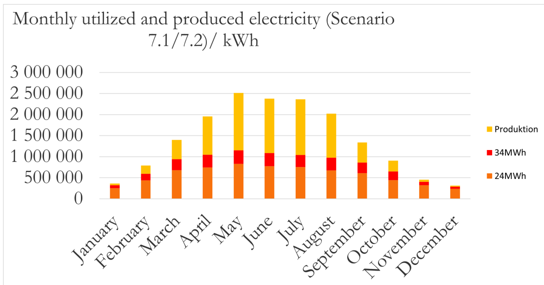

Figure 4.40: Monthly production with the amount of utilized electricity of the production for Scenario 7.1/7.2: Shore power with 16.3 MW PV with 34 MWh and 24 MWh battery.

Figures 4.39 and 4.40 show that the utilized energy varies between close to 100% in winter and just below 50% in summer for the 10 MWh, 20 MWh and 34 MWh batteries. The utilization is lower for the 24 MWh backup battery, ranging between 75% in winter and 30% in summer. The most noticeable difference between the three batteries with balance function is seen primarily in the spring but also the summer and autumn months. Where the double balance battery results in a noticeably larger utilization. The difference between the three batteries with balance function and the one without is also clearly seen in the total utilization in Table 4.19 of 56%, 63%, 56% and 40% respectively. Compared to Scenario 3 the utilization was not noticeably better for the 10 MWh battery compared to the 34 MWh battery. This is also why the utilization is presented in two figures for this scenario, as the utilization for the 10 MWh battery was not higher for every month. As in Scenario 5 the production is oversized in summer and cannot meet the consumption in winter. The two balance batteries do however increase the utilization during the summer months.

Table 4.20: Investment cost, O&M cost and LCOE for Scenario 7/7.0.5/7.1/7.2.

	10 MWh	**20 MWh**	**34 MWh**	**24 MWh**
Investment cost (SEK)	262 274 901	330 397 202	425 768 423	357 646 122
O&M cost (SEK/year)	5 130 760	5 130 760	5 130 760	5 130 760
LCOE (SEK/kWh)	1.56	1.89	2.35	2.02

Table 4.21: Investment calculation with electricity price 1 (low) and 2 (high) for Scenario 7/7.0.5/7.1/7.2.

Electricity price 1	**10 MWh**	**20 MWh**	**34 MWh**	**24 MWh**
NPV (SEK)	-161 528 638	-219 597 634	-331 530 178	-286 036 741
IRR (%)	-1	-3	-7	-7
Simple payback (Year)	20	24	>30	>30
Discounted payback (Year)	>30	>30	>30	>30
Electricity price 2	**10 MWh**	**20 MWh**	**34 MWh**	**24 MWh**
NPV (SEK)	-26 633 641	-85 042 025	-201 398 081	-157 657 472
IRR (%)	6	4	0	0
Simple payback (Year)	11	13	18	17
Discounted payback (Year)	>30	>30	>30	>30

In Table 4.20 we see that the LCOE is lowest for the 10 MWh battery, at 1.56 SEK/kWh, followed by 1.89 SEK/kWh for the 20 MWh battery and notably higher for the two larger batteries. The 34 MWh balance and backup battery has the highest LCOE of 2.35 SEK/kWh followed by 2.02 SEK/kWh for the 24 MWh one. The same arguments for increase in utilization versus increase in investment cost and therefore LCOE as in Scenario 3 can be made here. Regarding profitability, Table 4.21 shows that no battery scenario is profitable regardless of electricity price. It can be seen that the 10 MWh balance battery performs best economically. For the higher energy price the IRR is positive at 6%. The economical results are slightly better for this scenario compared to the corresponding current consumption scenario, Scenario 3.

4.3.4 Scenario 8: PV, wind and battery

The optimization of battery size and PV-Wind production fraction is presented in Figures 4.41 and 4.42. A balancing battery size of 7 MWh is chosen. This corresponds to an optimal wind turbine size of 3.13 MW and based on this a 3 MW wind turbine is chosen as a realistic turbine sizing. The double balance battery is chosen as 14 MWh, which follows from the balance battery size. The backup battery size is chosen as 24 MWh and for the balance and backup battery a 31 MWh size is chosen.

Figures 4.41 and 4.42 are two different views of the same 3-dimensional graph. The three dimensions are *Battery size*, *Fraction of production from wind* and *Utilization*. The curve depicted in the two figures shows the highest utilization and corresponding wind production fraction for each simulated battery size.

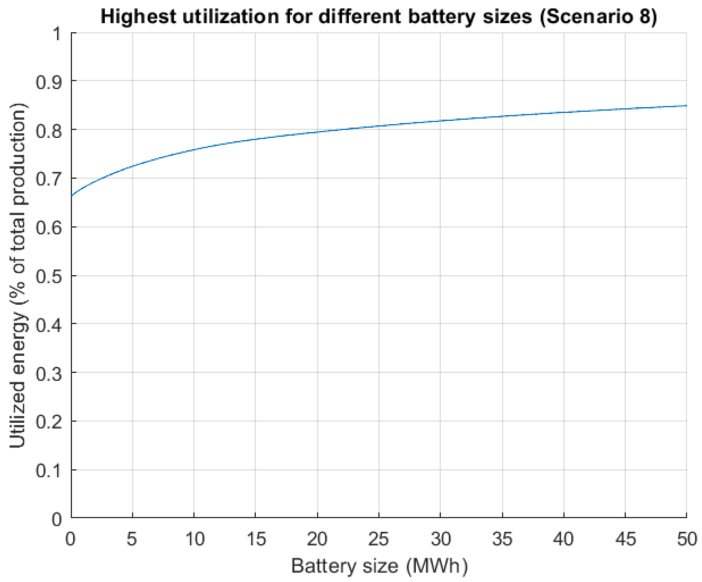

Figure 4.41: Highest utilization for each battery size.

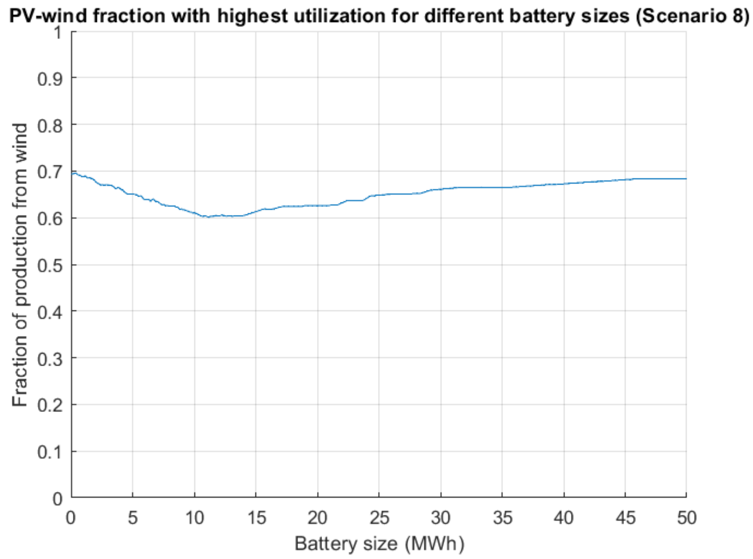

Figure 4.42: Fraction of production from wind resulting in the highest utilization as a function of battery size.

Observing Figure 4.41 it can be noted that, as in Scenario 7, adding a battery increases the utilization. The utilization also increases as the battery size increases. The gradient has a more even decrease than seen before. Observing the graph a 7 MWh battery sizing is deemed suitable. Figure 4.42 presents the relation between the battery sizes in Figure 4.41 and optimal fraction of PV and wind production. As in Scenario 4, it can be seen that the addition of a battery first decreases the amount of wind power in the highest utilization energy mix. For batteries larger than about 11 MWh the optimal fraction starts shifting towards more wind. This behaviour generally continues for the rest of the plotted battery sizes.

The 3 MW turbine produces 77% of the required yearly energy. The areas being used for PV to provide the remaining 23% of the total production is K1 S, M21 S, M23 S, General Cargo S, Old office, Toyota and 64% of K1 N. These areas add up to a total capacity of 4.6 MW.

Figures for the monthly production, consumption compared to production, energy balance, utilized electricity compared to the monthly production and tables for investment costs and calculation for the production system as a whole for the different batteries can be seen in Figures 4.43-4.46 and Tables 4.23 and 4.24. The utilization, amount of bought and sold electricity and amount of time in max and min SoC in each battery scenario is presented in Table 4.22.

Table 4.22: Bought energy, sold energy, utilization, time in max SoC and time in min SoC for the different battery scenarios in Scenario 8.

Battery	Bought (GWh)	Sold (GWh)	Utilization (%)	MAX SoC (h)	MIN SoC (h)
7 MWh	4.22	4.14	75	2687	3091
14 MWh	3.67	3.53	78	2261	2547
31 MWh	4.54	3.88	72	2687	3091
24 MWh	5.91	5.04	65	8760	0

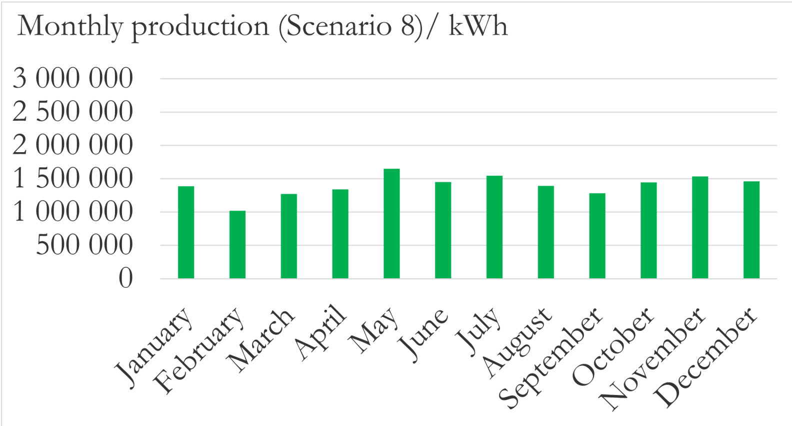

Figure 4.43: Monthly production for Scenario 8/8.0.5/8.1/8.2: Shore power with 4.6 MW PV and 3 MW Wind with a battery.

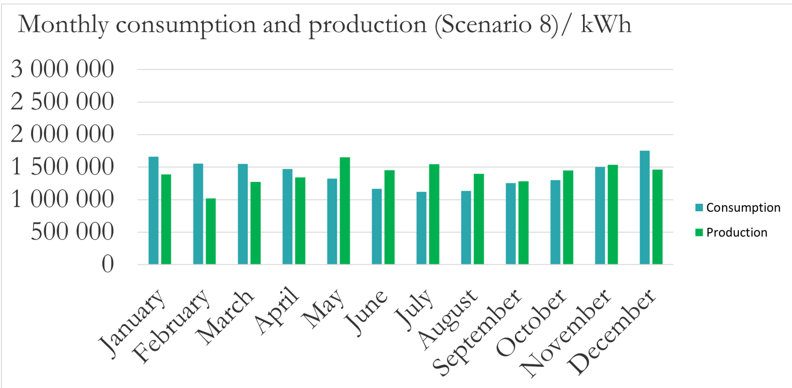

Figure 4.44: Monthly production and consumption for Scenario 8/8.0.5/8.1/8.2: Shore power with 4.6 MW PV and 3 MW Wind with a battery.

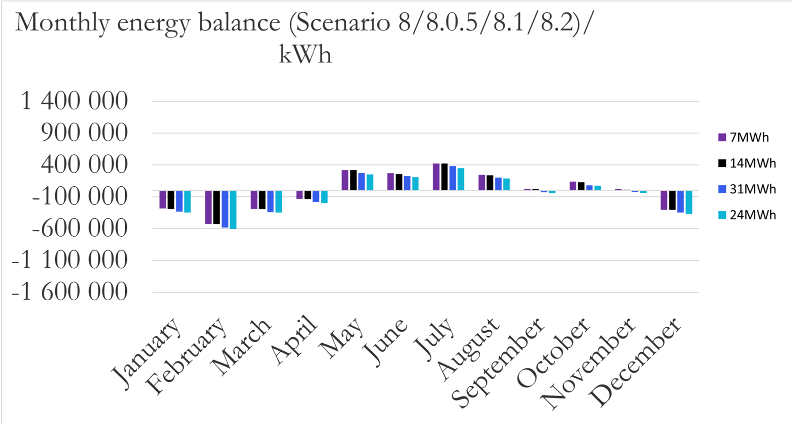

Figure 4.45: Monthly energy balance for Scenario 8/8.0.5/8.1/8.2: Shore power with 4.6 MW PV and 3 MW Wind with 7 MWh, 14 MWh, 31 MWh and 24 MWh battery.

The production profile in Figure 4.43 shows that production is relatively even during the year. The production dips in spring and autumn and is highest in summer. Figure 4.44 shows that there is underproduction in winter and overproduction in summer. Still, the production profile follows the consumption profile quite well, especially during autumn. Figure 4.45 shows the energy balance for the four different battery scenarios. The profiles of all batteries are very similar to the energy balance profile in Scenario 6. This is expected as the sizing of wind power and PV is the same in Scenario 6 and 8. The total amount of bought and sold energy as well as the utilization for the different batteries, seen in Table 4.22 follows the same pattern as in Scenario 7. However, in this scenario the total amounts of bought and sold energy are lower. The utilization is also higher than in Scenario 7, which explains the lowered need to buy and sell energy. The SoC for the batteries follows the same pattern as in Scenario 3.

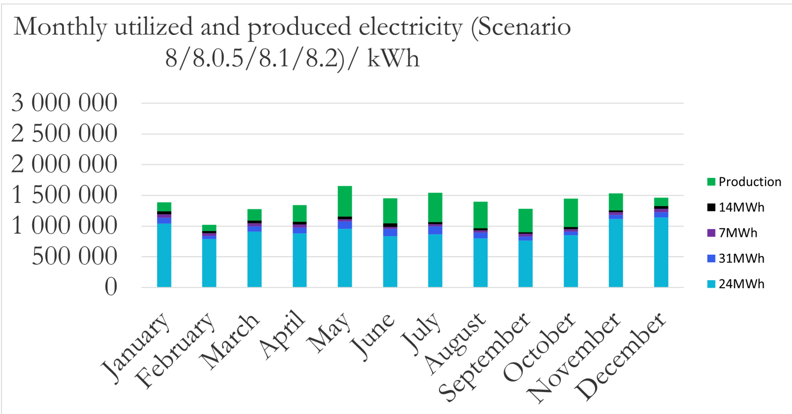

Figure 4.46: Monthly production with the amount of utilized electricity of the production for Scenario 8/8.0.5/8.1/8.2: Shore power with 4.6 MW PV and 3 MW Wind with 7 MWh, 14 MWh, 31 MWh and 24 MWh battery.

Figure 4.46 shows that the utilized energy varies between close to 100% in winter and about 60% in summer for the 7 MWh, 14 MWh and 31 MWh batteries. The utilization is lower for the 24 MWh backup battery, but the difference is not as big as in Scenario 7. The amount of utilized energy is quite even for all months. The utilization in the battery scenarios are, in order, 75%, 78%, 72% and 65%. The difference between these numbers is smaller than in the other scenarios with batteries.

Table 4.23: Investment cost, O&M cost and LCOE for Scenario 8/8.0.5/8.1/8.2.

	7 MWh	**14 MWh**	**31 MWh**	**24 MWh**
Investment cost (SEK)	134 975 911	182 661 521	298 469 433	250 783 822
O&M cost (SEK/year)	2 641 714	2 641 714	2 641 714	2 641 714
LCOE (SEK/kWh)	0.81	1.03	1.59	1.36

Table 4.24: Investment calculation with electricity price 1 (low) and 2 (high) for Scenario 8/8.0.5/8.1/8.2.

Electricity price 1	**7 MWh**	**14 MWh**	**31 MWh**	**24 MWh**
NPV (SEK)	21 218 416	-22 426 154	-147 857 991	-112 240 022
IRR (%)	9	5	-1	0
Simple payback (Year)	9	12	21	19
Discounted payback (Year)	21	>30	>30	>30
Electricity price 2	**7 MWh**	**14 MWh**	**31 MWh**	**24 MWh**
NPV (SEK)	155 980 052	111 846 779	-17 757 616	16 139 247
IRR (%)	19	14	6	8
Simple payback (Year)	6	7	12	11
Discounted payback (Year)	8	12	>30	25

In Table 4.23 we see that the LCOE is lowest for the 7 MWh battery at 0.81 SEK/kWh, followed by 1.03 SEK/kWh for the 14 MWh battery and notably higher for the two larger batteries. The 31 MWh balance and backup battery has the highest LCOE of 1.59 SEK/kWh followed by 1.36 SEK/kWh for the 24 MWh one. The same arguments for increase in utilization versus increase in investment cost and therefore LCOE as in Scenario 3 can be made here. Regarding profitability, Table 4.24 shows that the 7 MWh battery is profitable for both electricity prices. The 14 MWh double balance and 24 MWh backup batteries are also profitable for the higher energy price. We see that the profitability of this scenario is the best out of all the scenarios with batteries. Also this scenario has the best overall utilization out of all the scenarios. The good profitability is likely an effect of the high utilization.

4.3.5 Comparison

To get a better overview of the different scenarios for shore power a comparison of capacity, production and utilization can be seen below in Table 4.25. An economic comparison for the shore power scenarios can be seen in Table 4.26.

Table 4.25: Comparison of the different scenarios for shore power.

Scenario	Capacity	Production distribution	Utilization
PV	PV: 16.3 MW	PV: 100%	41%
PV and wind	PV: 4.6 MW, Wind: 3 MW	PV: 23%, Wind: 77%	68%
PV and battery	PV: 16.3 MW	PV: 100%	10 MWh: 56% 20 MWh: 63% 34 MWh: 56% 24 MWh: 40%
PV, wind and battery	PV: 4.6 MW, Wind: 3 MW	PV: 23%, Wind: 77%	7 MWh: 75% 14 MWh: 78% 31 MWh: 72% 24 MWh: 65%

Table 4.26: Economic comparison of the different scenarios for shore power.

Electricity price 1

Scenario	LCOE (SEK/kWh)	IRR (%)	Discounted payback (years)
PV	1.24	0	> 30
PV and wind	0.58	13	11
PV and battery	10 MWh: 1.56 20 MWh: 1.89 35 MWh: 2.35 24 MWh: 2.02	10 MWh: -1 20 MWh: -3 34 MWh: -7 24 MWh: -7	10 MWh: > 30 20 MWh: > 30 34 MWh: > 30 24 MWh: > 30
PV, wind and battery	7 MWh: 0.81 14 MWh: 1.03 31 MWh: 1.59 24 MWh: 1.36	7 MWh: 9 14 MWh: 5 31 MWh: -1 24 MWh: 0	7 MWh: 21 14 MWh: > 30 31 MWh: > 30 24 MWh: > 30

Electricity price 2

Scenario	LCOE (SEK/kWh)	IRR (%)	Discounted payback (years)
PV	1.24	8	23
PV and wind	0.58	26	5
PV and battery	10 MWh: 1.56 20 MWh: 1.89 35 MWh: 2.35 24 MWh: 2.02	10 MWh: 6 20 MWh: 4 34 MWh: 0 24 MWh: 0	10 MWh: > 30 20 MWh: > 30 34 MWh: > 30 24 MWh: > 30
PV, wind and battery	7 MWh: 0.81 14 MWh: 1.03 31 MWh: 1.59 24 MWh: 1.36	7 MWh: 19 14 MWh: 14 31 MWh: 6 24 MWh: 8	7 MWh: 8 14 MWh: 12 31 MWh: > 30 24 MWh: 25

5 Discussion

In this section the thesis will be discussed. The discussion are divided into a result discussion where the results are discussed and analysed, a method discussion where the methodology used as well as what uncertainties that are present in the study are discussed.

5.1 Result discussion

Our results generally show that a high fraction of production from wind increases the utilization. This is due to wind power having a more even distribution over the year, even matching the slightly higher demand in winter. However, also having some production from PV gives the absolute best results. The reason for this could be that PV supplies energy during the day when there is most activity in the harbor, thus perhaps complementing the short-term intermittency of wind. It is important to also note that for the shore power scenario, there is not deemed to be enough available area to construct PV to cover the energy requirements. Meaning a combination of the two technologies would be required for self-sufficiency.

Regarding batteries it is seen that the double balance battery gives the best utilization. Comparing the balance battery with the balance and backup battery we see that the utilization is lower for the balance and backup battery. A similar effect is seen if the backup battery is compared to a scenario without a battery all together (for example Scenario 6 and Scenario 7.2, which both have the same amount of PV production but the latter also has a backup battery). This reduction in utilization is due to the self discharge of the battery. Adding a battery or increasing the size of the battery increases the self discharge and reduces the amount of energy that can be utilized for consumption.

Next, we will discuss the profitability of the scenarios. The perhaps most noticeable thing is that few of the scenarios are profitable. Out of the 20 scenarios only 9 can be profitable. Considering electricity price, there are 40 total economic calculations, of which only 12 are profitable. Only 3 scenarios are profitable for the lower electricity price, all of which are PV and wind scenarios. PV and battery scenarios are never profitable. The two PV scenarios are profitable for the higher electricity price.

Overall, having a mix of PV and wind power is more profitable. This is due to the utilization being higher when using a mix as well as the investment cost per kWh being lower for wind power than PV, mainly due to more electricity being produced per installed MW. Regarding batteries, even though the balance batteries increase the utilization (compared to a system without batteries) their expensive cost outweighs the improved utilization in all of the scenarios. The scenarios that are still profitable when batteries are added are those who had a high profitability without batteries.

The scenarios with highest utilization that were also profitable are Scenario 4.0.5 and 8.0.5 for current consumption and shore power respectively. Both scenarios have the same utilization of 78% but the profitability is better in Scenario 8.0.5. This is likely caused by the battery sizing since, as established, in our models batteries generally have a negative impact on profitability. In Scenario 8.0.5, the battery is smaller in relation to the overall system size. The battery is only 57% larger than in Scenario 4.0.5, whilst the total energy requirement (and approximately the system as a whole) is 3 times larger than in Scenario 4.0.5.

5.2 Method discussion and uncertainties in the study

In this thesis different assumptions, simplifications and method choices was made as well as having some uncertainties in the gathered data which all affects the results. In this section these will be mentioned and discussed.

Firstly the results are based on the premise that the total yearly production will match the total yearly consumption. Because of this the scenarios ended up with a lot of overproduction because of the need to oversize the system. If we instead had optimized the production as well we could maybe have gotten similar overall utilization of electricity for a smaller system which means a higher utilization percentage of the production. In this thesis we only focus on operations that are self-sufficient on a yearly basis and not totally off grid self-sufficient. The argument for this that can be made here is the realism in if CMPs operations actually need to be able to be off grid self-sufficient. In Scenario 3.1/3.2/7.1 and 7.2 we have a more realistic view with being able to be sufficient only for a day to cover up for unexpected events such as blackouts. But as seen in the result and discussed in the previous section this means worse economical numbers so here you have to weigh this against the benefit with being able to be one day self-sufficient.

Regarding the additional energy requirements from shore power, some assumptions were made. It is assumed that all vessels that dock are equipped for shore power and that they consume power at full effect during the whole time they are docked. In reality all vessels will likely not be equipped for shore power, especially initially. Charging will probably also not occur during a ship's whole stay. The additional consumption from shore power will therefore likely be smaller than what is presented in this thesis. As these assumptions effect all ships the distribution over the year will likely look similar apart from being scaled down.

The electricity prices used were yearly fixed to get more simplified calculations. However in a realistic case the prices is instead most likely to be variable by the hour. As seen in Section 2.6.2 the electricity prices changes depending on demand. The demand of electricity is higher during the cold and dark winter months when a lot of electricity is needed for lights and heating and lower during the warm and bright summer months when this is not needed in the same extent. This means that electricity prices are higher during the winter months because of higher demand and lower in the summer months because of less demand. So if we would not have used a fixed yearly electricity price the scenarios with higher production in the summer and lower production in the winter would probably have been less profitable. This because as seen in the result, a lower electricity price will affect the profitability negatively.

In all of the calculations and build ups of the scenarios, no regards have been taken to all the additional infrastructure needed for a power generating system connected to the grid. Taking the infrastructure into consideration would probably have changed up the placement of the different system and most certainly add additional losses such as transmission losses to the system, as well as affect the profitability negatively both from the reduced production with additional losses and increased cost for the infrastructure. But with this it would have added more realism to if the different systems in the scenarios was actually going to be able to be made which now without it stands at a more hypothetically stage, even though adding infrastructure still would have the scenarios being hypothetical.

Some simplifications were made in the calculations for PV production. There are a lot of different losses attached to the power generation from PV. In this thesis the only losses present was inverter and temperature losses. These losses is although the two most important losses to consider, but they were also a bit simplified in the calculations. This means that the production numbers is in the high end of what a real PV system of the same size would actually produce. PV panels also degrade over time which is also not considered in either the production calculations or investment calculations which means that the system over time would not produce as much electricity as presented in the results which also would affect the economical profitability. There is also an uncertainty with the method used to estimate the panel area, tilt and azimuth. Using Google Earth and not real construction drawings means that all the estimations for these parameters are roughly made which could affect the production in both ways. The data used for cost calculations is also a bit uncertain. The investment cost is taken from a site for price comparisons of PV system installations in Sweden and not a scientific report because of the difficulty in finding a report that is telling for the Swedish market. The cost also do not consider economy of scale which means that our different systems might actually have a lower cost because of their size.

If we also look at the O&M costs they differ a lot from report to report depending on different parameters. The one used in this report comes from a Swiss study on their domestic market, due to a lack of useful Swedish sources. This means that it is not for certain that this is applicable for a Swedish market. In Switzerland most things are more expensive than it is in Sweden. It is not a problem in Switzerland because they also have higher incomes [75], but when the Swiss expenses gets translated directly to Swedish currency as was made in this thesis, the numbers might be higher than they should because of the lower general income in Sweden.

For the wind production calculations there were also some simplifications and error causes. First, the wind data used is not taken from Malmö, instead it is from Kastrup airport. This means both wind directions and more importantly wind speeds and variations may differ significantly from Malmö. The extrapolation of the wind data uses an approximation of the ground conditions in Malmö harbour, which means the roughness length used might be somewhat incorrect. Adding the fact that the wind data isn't from Malmö means the uncertainties increase even more. When calculating the power generation wind speeds were grouped into bins, meaning the resolution of the simulation is decreased. Further, no wake effects from the buildings in Malmö harbour were studied and for the maximum scenario no wake from the multiple wind turbines were considered. Losses from the mechanical components and converters are also not considered. This means that in reality the amount of delivered energy would be smaller than simulated. Regarding investment costs, they are based on a global average installation cost for wind turbines. The actual price for this location may therefore differ somewhat.

The method used to model the batteries are also simplified to ease calculations. We only account for self discharge and ignore things such as round-trip losses, depth of discharge and batteries not being able to store energy over longer periods. Round-trip losses would decrease the batteries efficiency and therefore for every scenario making the bought electricity higher and the utilized electricity lower which would decrease the profitability. Accounting for depth of discharge would mean the batteries have to be larger to be able to provide the same capacity and service to the system. This would increase investment costs and self discharge, meaning worse economic performance and slightly worse utilization. Because no consideration is taken to batteries not being able to store energy over longer periods the model used might not even work in a real scenario because the energy might be stored over longer periods than is physically possible for the batteries. In the investment calculations for batteries the used investment cost per kWh was approximated and based on general battery prices. It is likely that the actual price may be higher. Also, O&M costs were disregarded as meaning that in reality the lifetime cost of a battery system would be higher than shown here, reducing profitability of scenarios with battery systems. However, with all these additional things negatively affecting the profitability we should also consider that in the model we have chosen to optimize the batteries for utilization and not for profitability. So if we would have instead optimized them after profitability we might have had more profitable numbers for those battery scenarios. Svenska Kraftnät also has two markets for reserve capacity. A capacity market where volumes are put in and then ordered a day before the operational day with having a compensation always given to the ordered volumes even if the capacity is not used. And an energy activation market where volumes are put in then ordered during the operational hour with having a compensation given only for the activated energy. [76] If the batteries used in the scenarios, especially the backup batteries, was used in these markets the batteries would have had an increase in profitability which would have made having a backup battery being a lot more attractive from an economical point of view then it has in our results.

6 Conclusions and future work

In this section the conclusions for the thesis as well as an discussion about future work will be presented.

6.1 Conclusions

The technologies that are relevant for the operation of CMP is PV, wind and battery. PV and wind are the only relevant forms of renewable power generation because of wave power being too immature for commercial usage for the nearest future. Batteries are the only relevant form of energy storage because of HESS also being to immature for commercial usage in the nearest future for the power-to-power system needed for CMP. Using PV and wind, the maximum potential for power generation at CMP's areas in Malmö harbor is 61.4 GWh.

For the current consumption scenario the annual energy requirement is 5.5 GWh. This is less than the maximum potential electricity production which means that the current consumption can be met with production in Malmö harbour. It could be seen that the presence of wind power in the system always increases the utilization and the utilization finds its maximum at a wind electricity production fraction of around 75% of the total consumption. The presence of battery also always increases the utilization, more so the larger the battery. However the increase per added MWh of battery size levels out rapidly so consideration was instead taken of where the increase was no longer as steep because of profitability reasons for the balance scenario. This could be seen with the results from the double balance battery which showed a smaller increase in utilization with the same increase in investment cost compared to when going from no battery to the balance battery. Although this, the studied electricity production and energy storage systems with 2.1 MW PV, 1 MW wind and 8 MWh balance battery system (Scenario 4.0.5) still resulted in the highest utilization of 78%. An overview of this system can be seen in Figure 6.1. For profitability, PV and wind (Scenario 2) is the only scenario that is profitable with both the low and high electricity price, but for the high electricity price PV (Scenario 1), PV and wind with balance battery (Scenario 4) and PV and wind with double balance battery (Scenario 4.0.5) is also profitable. This because it could be seen that the addition of wind increases the profitability and the addition of battery decreases the profitability.

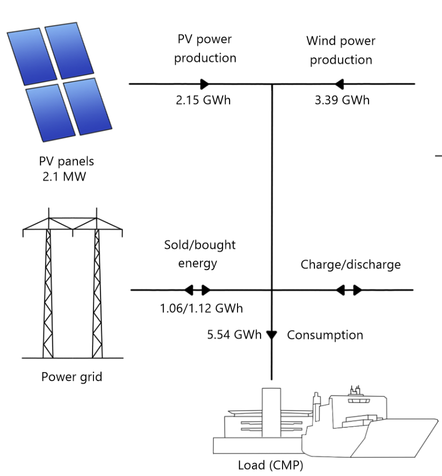

Figure 6.1: Overview of the system with the highest utilization for the current consumption scenario (Scenario 4.0.5). Energy flows and capacity are presented with arrows representing energy flow directions.

For the shore power scenario the annual energy requirement is 16.8 GWh. This is still less than the maximum potential electricity production which means that the addition of shore power can also be met with production in Malmö harbour. However, it could not be met by only PV production unless more usage of the labeled Green areas was allowed. In this scenario wind power still always increased the utilization as expected but only to a wind electricity production fraction of around 70% of the total consumption. Battery also still always increases the utilization as expected where the same arguments can be made as for the current consumption scenario. With this, the studied electricity production and energy storage systems with 4.6 MW PV, 3 MW wind and 14 MWh balance battery system (Scenario 8.0.5) resulted in the highest utilization of 78%. An overview of this system can be seen in Figure 6.2. For profitability, both PV and wind (Scenario 6) and PV and wind with balance battery (Scenario 8) is now profitable with both the low and high electricity price. For just the high electricity price PV (Scenario 5) and PV and wind with double balance battery (Scenario 8.0.5) is still profitable but now PV and wind with backup battery (Scenario 8.2) is also profitable. The same arguments that profitability increases with wind and decreases with batteries can be made here. The reason for PV and wind with balance or backup battery being more profitable in this scenario is because of the battery providing higher utilization than in the current consumption scenario.

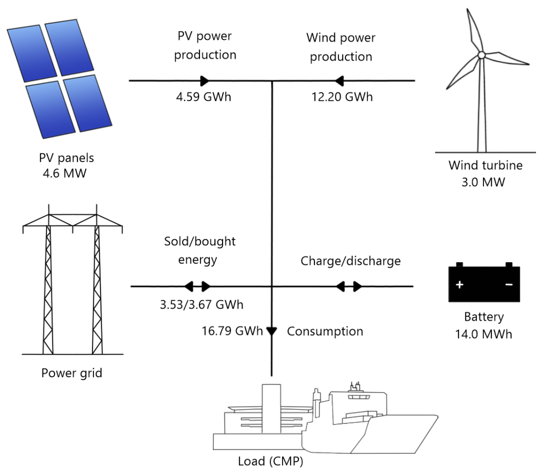

Figure 6.2: Overview of the system with the highest utilization for the shore power scenario (Scenario 8.0.5). Energy flows and capacity are presented with arrows representing energy flow directions.

6.2 Future work

This thesis is only a preliminary study to get a baseline of what solutions is possible for renewable power generation and energy storage for CMP's operations to be self-sufficient. To make this into a realistic project more things have to be researched and accounted for. Some of the things that has to be researched and accounted for is for starters the infrastructure mentioned in Section 5.2, which has to be studied to see what is actually possible to do. A closer look at system interactions is needed to figure out how PV, wind and battery works together and what limitations are present in their symbiosis. This by for example taking a look at the power electronics and the control methods needed and the limitations present with these. All the simplification made in this thesis which where discussed in Section 5.2 also has to be accounted for and not simplified for future work to get more realistic results. Especially the batteries where the modeled used in the calculations was very simplified. More research and work is as well needed to find if it is actually possible for wind turbines to be built in the harbor in the first place. As well as precise data needs to be gathered for the costs of everything from talks with actual suppliers, and much more.

As mentioned in Section 5.2, there are markets for reserve capacity. For future work it would also be interesting to research if the batteries could potentially become a profitable investment. This if consideration is taken to that it is possible to earn money from the batteries just from their capacity.

Maximum potential

In the maximum potential scenario we have a surplus of 44.6 GWh when the current self consumption and shore power are counted out. For future work it would also be interesting to dive deeper into the potential for this surplus and what it could be used for. Two things this could be used for is either to have electric ferries going between Malmö and Copenhagen or produce hydrogen for power-to-gas purposes mentioned in Section 2.5.1.

There are electric ferries going between Helsingborg and Helsingör which use 1 175 kWh per trip. [77] This trip is roughly about 5km long. If you compare this to a trip between Malmö and Copenhagen which would roughly be 30 km instead, this would mean that a similar ferry could go about 9 round trips each day of the whole year with the surplus.

The production of 1 kg of hydrogen through water electrolysis uses about 50 kWh of electricity [78], which adds up to roughly 900 tonnes of hydrogen being able to be produced with the surplus. A fuel cell electric truck (FCET) uses about 8.3 kg of hydrogen fuel per 100km and has a tank that can fill up to 55 kg of hydrogen which means that it can drive 650 km on a full tank. [79] This means that the surplus could be used to refuel about 16 000 FCETs to full tank which translates to about 44 trucks each day.

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Appendix A - Figures

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Appendix B - Tables

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