Assessing Offshore Wind System Integration:

Comparative Analysis of Floating Photovoltaics, Oscillating Surge Wave Converters, and Battery Energy Storage Systems

Thesis for the degree of Master of Science
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This degree project for the degree of Master of Science in Engineering has been conducted at the Department of Energy Sciences, Faculty of Engineering, Lund University.

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The project was carried out in cooperation with RWE Renewables and Hanna Henrikson.

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Abstract

The high penetration of wind power is increasing the intermittency and power variability into the existing power grid. This is forcing industries to look for optimal configurations in order to improve their systems performance and minimize these effects from the power production method. Studies show that there are different ways of reducing the power variability and therefore stabilize the energy supply. Hybrid offshore energy systems based on the combination of two or more marine renewable energy sources can reduce the variability and costs associated with the installation and operation of the systems. Battery energy storage systems combined with wind power could also smoothen the fluctuation of the power supply and improve the utilization and overall energy efficiency.

This master thesis was performed on behalf of RWE Renewables AB in Malmö, and conducted at the Department of Energy Sciences at Lund University, Faculty of Engineering. The purpose of this thesis was to examine the possibilities of system integration with one of RWE Renewables planned offshore wind farms, the Neptuni project. Extra focus was put on studying system integration of three different technologies, their power generation for the specific site, their economic feasibility and the potential reduction of power fluctuations with the hybrid systems respectively. The potential benefits and challenges of the three technologies were first studied in a literature review. Thereafter, a case study was executed to perform simulations and calculations of the technologies power generation and measure their and the respective hybrid systems potential revenues and mitigation of power fluctuations. Four different electricity spot price scenarios for the future are conducted enabling the calculation of the Net Present Value of each technology for each scenario.

The findings indicate that one scenario of floating Photovoltaics (FPV) yields a positive Net Present Value over its lifetime, while the other scenarios yields a negative value, as well as the Oscillating Surge Wave Converter (OSWC) and Li-Ion Battery Energy Storage System (BESS), are not currently profitable investments. However, economic viability should not be the sole determinant for investment decisions, as these technologies offer valuable contributions such as experience and innovation. Additionally, integrating FPV and OSWC with an offshore wind farm results in reduced variability. Also, increased correlation with the system load with higher installed capacity, enhancing grid stability, is confirmed for all technologies examined.

While the analyzed technologies may not be immediately viable for investment, their potential for future development, long-term cost stability, and enhanced energy security make investments in renewable energy strategic for the future. Starting with modest installed capacities and considering the broader benefits of renewable energy are advisable when making investment decisions.

Acknowledgements

This master's thesis was initiated on January 16, 2023, in Lund and primarily conducted at Lunds Tekniska Högskola (LTH). It constitutes the final component of the students' Mechanical Engineering degree at LTH, accounting for 30 credits. Throughout the thesis, the students maintained regular communication with their supervisors at RWE Renewables AB and the Department of Energy Sciences at LTH. The project was developed and executed by the students under the guidance and supervision of RWE Renewables. The discussions and conclusions presented herein are the students' independent work and may not necessarily reflect the overall views or opinions of RWE Renewables AB.

We would like to express our sincere gratitude to the following individuals who have been instrumental in the successful completion of our master thesis. Their invaluable support, guidance, and contributions have significantly enhanced the quality of our work:

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Contents

1 Introduction

1.1 Introduction to system integration

The focus of limiting climate change is central in the decision making of companies, organizations and governments all over the world. In order to reach the international stated goals and agreements, it is necessary to rapidly increase the share of renewable energy generation in the world. In 2021 wind power electricity generation increased with 273 TWh, which is a 55% increased growth rate in comparison to 2020. This was probably caused by a record breaking 113 GW capacity installed in 2020, a great achievement. However, to achieve the Net Zero Emissions by 2050 set by the International Energy Agency (IEA) the average annual capacity additions have to reach 250 GW, more than the doubled amount of 2020 growth.[1] There is a great capability for wind power to have a conductive role in this transition in Europe, since the wind resources transcends the electricity demand ten times over, with a generation potential of 33,000 TWh annually. The IEA predicts offshore wind power to be the largest source of electricity in Europe by the year of 2040, and the power source has already exceeded the electricity generated from coal making up 15% of the European Union (EU) 27's electricity mix in 2020.[2]

In Sweden, the government wants to make up for lost ground. According to WindEurope, Sweden already has a great share renewable energy in their electricity mix, where wind power accounts for 22%. However, the full offshore wind resource the Swedish coastline offers is not nearly utilized to its full potential with an installed capacity of 192 MW today. But, within the coming years a large increase of wind penetration is expected in Sweden with an impressive project pipeline.[3] The Swedish wind power market is heating up, attracting an annual investment volume of approximately €2 billion.[4] 15 GW offshore wind power is currently applying for permits but the total project pipeline includes a capacity of 90 GW in different stages of development. The direct electrification of today's society and economy is increasing the Swedish electricity demand severely, more than double from today until 2045.[3] This in turn expedites the transformation into a power grid even heavier influenced by offshore wind power.

The increasing penetration of renewable energy into the existing Swedish power grid is in many ways promising. Offshore wind power is however an intermittent power source, meaning that the wind energy extracted by the wind turbines varies on a fairly short time scale and cannot be controlled. This leads to a fluctuating power supply, which can be problematic. Even if it is possible to forecast wind to a certain extent, it can still change swiftly in a matter of minutes. A large implementation of wind power into the grid will therefore cause a greater power variability and unbalance, making the frequency of the grid hard to maintain. For example, an unpredictable increase of production or a drop in demand will create a surplus of supply to the grid which increases the frequency, and vice versa. The equipment connected to the grid could take damage if big frequency fluctuations occur. Thus, the wind power industry is forced to search for optimal configurations in order to improve their systems performance and minimize these effects. The market is recognizing an increased demand for the ability of power control to stabilize the grid and meet the demands from the transmission system operator (TSO).

Studies show that there are different ways of reducing the power variability and therefore stabilize the energy supply. Hybrid offshore energy systems based on the combination of two or more marine renewable energy sources can reduce the variability and costs associated with the installation and operation of the systems. Also, battery energy storage systems combined with wind power could even out the fluctuation of the power supply and improve the utilization and overall energy efficiency. The different hybrid systems act differently on the power grid and provide different kinds of benefits and challenges. By the completion of an energy production method the annual energy supply would increase and smoothen the variable curve caused by the wind power. In the case of a combined energy storage system, batteries can store energy during times of low demand and then release it during peak demand periods. This could help stabilize the grid in a cost effective way.

Efficient utilization of the existing hybrid systems is crucial for achieving optimal results in the integration of wind power into the grid. This involves selecting the appropriate operating strategies for different wind power technologies and taking into account the various factors that are involved in working with the grid. A holistic approach, where all aspects of the system are considered together, is essential for achieving the best outcome for both the TSO and the provider.

1.2 Purpose and research questions

The purpose of this study will be to analyze three different technologies, two energy producing and one energy storing, by their feasibility for integration with offshore wind projects in southern Sweden. By evaluating the possibilities, benefits and difficulties for the different technologies this analysis will finally show the extent to which the variability of power production will be reduced as well as if the investments will generate a positive Net Present Value (NPV) over their lifetime. By gathering and calculating the data needed for this to be investigated the thesis aims to contribute to RWE Renewables level of knowledge about system integration in general. This will hopefully help the company to choose a pathway in order to proceed with their aim to stabilize the power supply from their renewable energy resources in a cost effective and green way. This thesis aims to answer the following questions:

1. What are the largest costs and how are they distributed for a potential system integration of Floating solar Photovoltaics, Oscillating Surge Wave Converters or a Battery Energy Storage System?
2. How do the different considered technologies differ in power generation?
3. Which technology is the most suitable for integration with an offshore wind farm in southern Sweden if economic feasibility is considered?
4. Does a hybrid system, when the considered technologies are combined with wind

power, enable a reduction of the power fluctuations to the grid? Which technology mitigate the fluctuations from the wind farm the most?

1.3 Method - Overview

This thesis is structured into two main parts to address the research questions. The first part comprises a literature review that explores relevant research to establish the foundation for simulations and calculations. The focus is to gain insights into the current state of the examined technologies: Floating Photovoltaics (FPV), Oscillating Surge Wave Converters (OSWC), and Lithium-Ion Battery Energy Storage Systems (Li-Ion BESS). The review aims to highlight the pros and cons of these technologies, assess their maturity, identify potential financial support, and evaluate their integration possibilities with offshore wind farms. The literature review also serves to familiarize the reader with the subject and was conducted at the beginning of the research period.

The second part presents a case study focused around RWE Renewables planned Neptuni wind farm project located northeast of Öland's northern cape. Assuming the wind farm's construction and financing are already secured, this case study examines the integration of either FPV, OSWC, or Li-Ion BESS with the wind farm. The study investigates the technologies' individual power generation capabilities at the site through data collection. It also assesses the profitability of investing in these technologies over their lifespan and their potential to mitigate power fluctuations when integrated with the offshore wind farm. Based on the analysis, three potential courses of action are presented for RWE Renewables to consider.

The case study relies on MATLAB models for calculations and simulations, with data sourced from RWE Renewables, SMHI (Swedish Meteorological and Hydrological Institute), and open sources to facilitate the simulations and calculations.

1.4 Delimitations

Given the time constraints of a master thesis, it was not feasible to explore all aspects of the subject comprehensively. Therefore, certain delimitations had to be imposed to ensure the research remained feasible and achievable within the allocated time frame.

- RWE Renewables emphasized that this thesis should provide an overview of various technologies rather than diving into excessive detail. The objective was to assess the current maturity of these technologies and determine if further investigation into their investment potential is warranted. The thesis does not aim to examine the complications of connecting different power plants or their specific operations. Instead, the focus is on analyzing the behavior of these technologies when integrated at a specific site, primarily examining the results related to power generation and power fluctuations.
- The evaluation and presentation of pathways for RWE Renewables do not consider the environmental impact of the technologies. The thesis focuses solely on the three specified technologies: FPV, OSWC, and Li-Ion BESS, as requested

by RWE Renewables. Consequently, no other technologies, even if they have less environmental impact, will be discussed within the thesis since it is beyond the scope of this thesis.

- The thesis incorporates the authors original models of the examined technologies, developed using MATLAB, rather than being provided by the company. As a consequence, several simplifications and assumptions had to be made to enable the simulations required to generate results that could be presented to the company. These simplifications and assumptions were necessary to facilitate the simulations and derive meaningful outcomes from the models.
- During the development of models and calculations to obtain results, it was necessary to make assumptions regarding various parameters. The uncertainty associated with these parameters could have been minimized if specific values provided by RWE Renewables were available. However, as this information is classified and not publicly disclosed, the thesis had to rely on existing research to perform the required calculations. The utilization of previous studies allowed for the necessary calculations to be conducted within the scope of the thesis.

1.5 Outline of the report

- **Chapter 2:** This chapter aims for the reader to get insights and a hold of wind power, solar PV, wave energy converters and battery energy storage systems. It should give an overview of the different technologies, describing the concepts, highlight their pros and cons, investigate their markets respectively, and present different hybrid systems projects of today. This chapter will go through each technology individually but also examine hybrid systems, where the technology has been integrated with wind power. Each technology section will end with a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis of a hybrid system of the technology and wind power.
- **Chapter 3:** This chapter describes the methodology of the case study. It should provide a comprehensive overview of the case involving Neptuni wind farm where the focus lies upon integrating it with a floating PV system, a wave energy system, and a battery energy storage system. Various future scenarios will be examined, followed by a technical analysis of the combined wind farm and the proposed method of implementation. Additionally, an economic analysis will be conducted to assess the financial aspects, and a power fluctuation analysis will assess the potential of reduction of variability with system integration. This chapter mainly consist of descriptions of different measurements, calculations and models used in the case study. This chapter ends with a clarification of the assumptions which had to be made to simplify and keep the study within its scope.
- **Chapter 4:** This chapter provides an overview of the dataset collection process used to conduct the simulations that generate the results. The section is structured into subsections, each dedicated to a specific dataset, where detailed explanations are provided. The parameters used each technology is provided at the end of each subsection.
- **Chapter 5:** This chapter examines the wind, solar, wave, and battery storage

potential at the Neptuni site and investigates their variability. It analyzes the correlation and time lag between wind and complementary power sources to explore the synergy between renewable sources and their correlation with system load. Additionally, an economic analysis is conducted to determine the optimal sizing of complementary power systems for maximizing the NPV. Furthermore, a comparison is made between the variability of these hybrid power systems and a standalone offshore wind farm to analyze how connecting renewable and volatile power affects power fluctuations supplied to the grid.

- **Chapter 6:** This chapter aims to analyze and discuss the results gained in chapter 5. The results are discussed with a technical, economic and power fluctuating perspective to get an overall view of each technology.
- **Chapter 7:** This chapter presents three possible pathways for RWE Renewables to act from.
- **Chapter 8:** This chapter aims to conclude the findings from the thesis and present the answers to our research questions.

2 Background

2.1 Offshore Wind Power

The application of renewable energy has garnered significant global attention, driven by the progression of renewable energy technologies, the exhaustion of non-renewable energy sources, and the need for sustainable development and energy security. Today, the significance of renewable energy has increased due to the overexploitation of non-renewable energy sources and the resultant escalated emissions, leading to a rapidly increasing rate of depletion. Combined with an increasing population growth, urbanization and usage of electronic devices and appliances, Sweden has been implementing measures for increased energy production and development of renewable energy technologies such as wind power.

2.1.1 Wind farm structure

A wind farm is a combination of several components. There is not one way of constructing a wind farm, the design is decided by the circumstances the wind farm is operating within. The most important component of an offshore wind farm is arguably the turbines, which is converting the wind energy into electricity. The three-bladed Horizontal Axis Wind Turbine (HAWT) is a good trade-off between power extraction and costs, and is also the turbine design dominating the market. The utilization of various drive train technologies for wind turbines, incorporating either asynchronous or synchronous generators, with or without a gearbox, has its own unique set of advantages and disadvantages. Figure 2.1 below displays a typical setup of an offshore wind farm.[5]

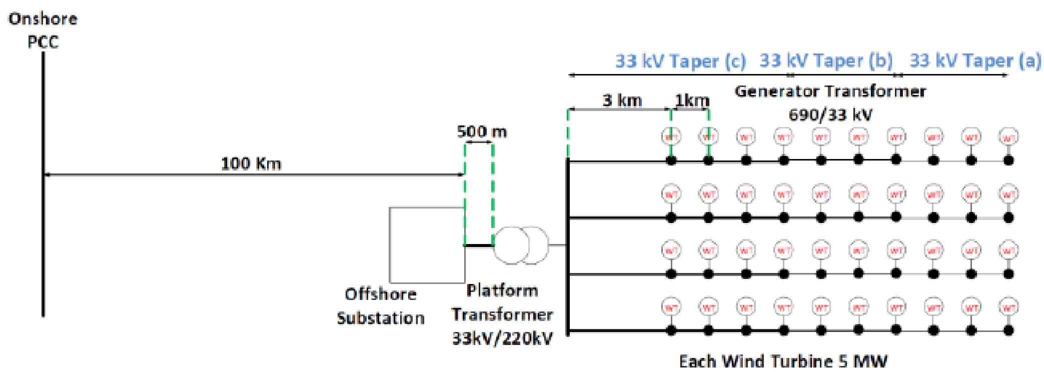

Figure 2.1: Typical offshore wind farm.[6]

The turbine generator voltage is usually around 690 V, which is not enough for economical direct interconnection with the other turbines. Therefore, an internal turbine transformer steps up the voltage and then transmits the power from the turbines through the inter-array cables to the offshore substation. Typically, wind turbines are connected in parallel in rows, with the one closest to the substation being linked to it. An offshore substation is utilized to minimize electrical losses through voltage amplification before transferring the power to land. Early offshore wind projects often lacked offshore substations due to meeting certain criteria, but today the farms are expected to require such facilities due to their large size or remote location. Offshore substations raise the voltage from 30-36 kV to a higher level (100-220 kV), reducing the number of export circuits and enabling more efficient power export. The substations can have one or more export circuits and will be more complex in the future. Currently, there is no standard design for these substations.[5] From the substation, a subsea high voltage (HV) cable transmits the power onshore to the onshore substation, where it is later transmitted onto the existing electrical grid. A High Voltage Alternating Current (HVAC) cable does not need any expensive converters when reaching the shore, but has a very high capacitance which reduces the power rating of the cable. The longer the distance to shore, the larger the reduction, which is why High Voltage Direct Current (HVDC) cables are recommended for usage. The HVDC cable reduces the losses which makes it a more suitable choice for transmitting the energy produced by very distant offshore wind farms with miniscule losses.[7] The design of the onshore substation is usually influenced by the network operator, which is the case in Sweden where the TSO is responsible for the transmission equipment. The onshore substation typically includes components such as switchgear, metering devices, transformers, and supporting equipment. Reactive compensation equipment may also be present, depending on the network operator's needs and the design of the offshore network.[5]

2.1.2 Swedish power grid

Energimarknadsinspektionen is the regulatory authority responsible for the power grid companies. The transmission network was previously referred to as the main electrical grid. It transports large amounts of electricity from major power producers to regional distribution networks and spans the entire country, from north to south, connecting Sweden's power grid with those of other countries. Large power production facilities and major electricity users are usually directly connected to the transmission network. The transmission network utilizes high voltages, such as 400 or 220 kV, in order to reduce power losses. It is managed and developed by Svenska Kraftnät (SVK).[8]

The Swedish electrical grid is closely interconnected with surrounding countries through international connections, which may be either Alternating Current (AC) connections or Direct Current (DC) connections. Electricity transmission between Sweden and other countries operates under market conditions. Sweden participates in the Nordic synchronous area and has AC connections with Finland, Norway, and Denmark. To trade and transfer energy between different synchronous areas, DC cables are used. Sweden has DC connections with Finland, Denmark, Germany, Poland, and Lithuania.[8]

2.1.3 The responsibility of Svenska Kraftnät

As the designated system operator, Svenska Kraftnät has the responsibility of ensuring that all components of the power system operate in a secure and stable manner. This is achieved through their own efforts and by coordinating the efforts of all other stakeholders in the power system. In practice, system responsibility involves regulating, monitoring, and clarifying the needs of the factors that influence the stability and balance of the power system. The organization also defines the requirements for connection to the power system. A crucial task is balancing, which involves controlling the power system in real-time to ensure that there is a balance between electricity consumption and production at every moment.[9]

As the owner and manager of Sweden's transmission network for electricity, Svenska Kraftnät is tasked with maintaining and developing the network. Svenska Kraftnät's responsibility for ensuring secure electricity delivery stems from its role as responsible authority of the transmission and sitribution network. Another responsibility is to analyze and report on current and future challenges. As the designated electric emergency authority in Sweden, Svenska Kraftnät is also dedicated to ensuring the reliability of the country's power supply in the face of extreme events that may pose significant stress to society.[9]

Svenska Kraftnät is supposed to maintain the operational reliability of the transmission system. As the system operator of the transmission system, they also has the responsibility of allocating capacity to the market while taking into consideration the reliability of the system. System reliability refers to the national power system's ability to maintain secure deliveries of power and energy. This entails maintaining the transmission system in a normal operating state, or restoring it to a normal operating state as soon as possible after one or more events.[10]

The delivery of electricity is also complex and involves more than just connecting a hose and opening a tap.The power system must constantly be stable based on various physical parameters. Svenska Kraftnät is responsible for the system stability. In order for the electrical system to function and deliver electricity, there must always be a balance between consumption and production of electricity. Disturbances in this balance also risk damaging or completely disabling technical equipment. One of Svenska Kraftnät's most important tasks is to maintain the short-term balance in the electrical system.[10]

2.1.4 Potential

Goals, objectives and progress

On July 14, 2021, the European Commission presented its new 2030 climate targets, including the proposal to amend the previously introduced Renewable Energy Directive in 2018. The Commission aims to achieve at least 40% of renewable energy sources in the EU's energy mix by 2030, an increase from the former target of 32%. The Commission published the REPowerEU plan on May 18, 2022, which outlines measures to reduce the EU's reliance on Russian fossil fuels before 2030 by promoting the clean energy transition. The plan consists of three pillars: energy conservation, clean energy production, and diversifying energy supplies. The Commission proposes to increase the renewable energy target in the directive to 45% by 2030. To further enhance the deployment of renewables, the Commission has also adopted a recommendation to promote power purchase agreements.[11] Offshore wind energy in particular is recognized by the Commission as having a substantial potential for the future due to its abundant and stable resources and favorable public perception. Europe holds a preeminent position in the offshore wind industry globally. In order to enhance the global competitiveness of the EU wind sector and to achieve the REPowerEU objective of rapid wind energy deployment, the EU expresses the necessity to fortify the supply chains and expedite the permitting process.[12] Meanwhile, the organization WindEurope predicts the EU to install approximately 17.6 GW per year from the year 2021 summing up reaching 140.8 GW before the year of 2030. This suggests further investments in the technology, since the yearly installed capacity should not fall below 32 GW in order to reach the Renewable Energy Directive goals.[13]

Sweden established similar goals which encompass a shared plan for a gradual shift to a completely renewable power system. This includes multiple targets, for example that by 2030, Sweden aims to improve its energy efficiency by 50% compared to 2005, measured in terms of energy relative to Gross Domestic Product (GDP). Ten years later by the year of 2040, the goal is to produce 100% renewable electricity, however this target does not entail a ban on nuclear power or closure of nuclear power plants through political decisions. In 2045, Sweden intends to reach net zero emissions of greenhouse gasses and to achieve negative emissions thereafter.[14] Furthermore the Swedish electricity certificate scheme was introduced in 2003 and led the way for renewable electricity generation, especially biofuels and wind power as seen in figure 2.2 below. In the electricity certificate scheme, the government awards electricity producers a certificate for each MWh produced from renewable resources. The cutoff date for the certificate scheme was December 31st 2021, meaning that any new facilities or plants established after this date was not qualified for electricity certificates.[15] Still, the scheme created a competitive market for renewable energy, driving down the costs and making it more accessible to consumers.

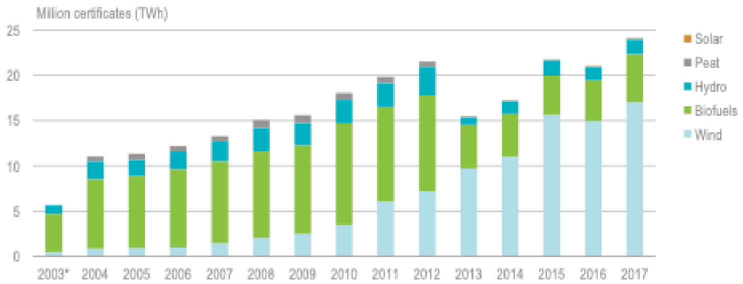

Figure 2.2: Electricity certificates by energy source in Sweden.[16]

According to the International Renewable Energy Agency (IRENA) the globally installed wind power capacity has increased from 7.5 GW in 1997 to approximately 733 GW in 2018, an increase by a factor of 98. The production of energy from wind power is still growing rapidly, with a factor of little more than 5.8 to 1,588 TWh between 2009 and 2020. The development of electricity generation from both onshore and offshore wind power globally are shown in figure 2.3 below.[17]

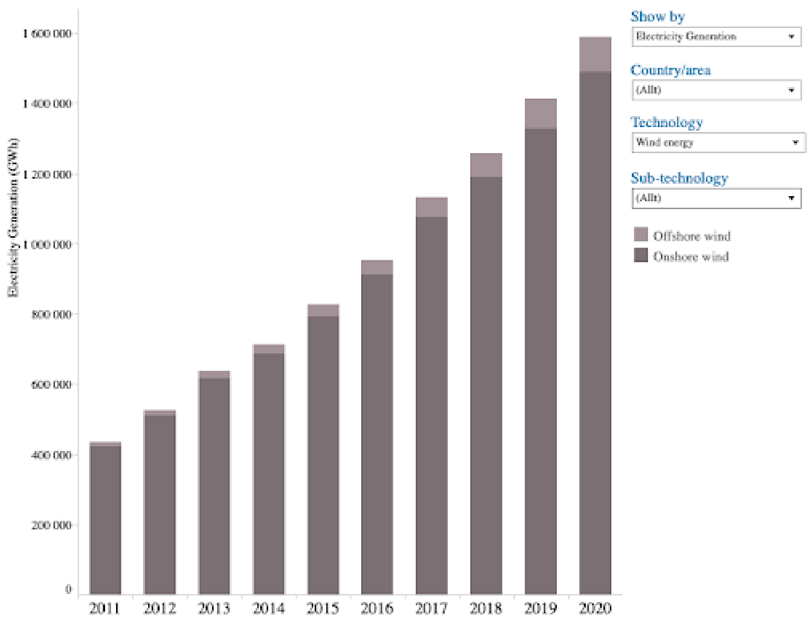

Figure 2.3: Electricity generation from wind power.[17]

In the past 20 years, the technology development of wind power has been remarkable. The power rating of installed wind turbines averages an increase of 0.2 MW/year, and it is still rising. The past 5 years the increase is 0.57 MW/year. Towards 2025, Swedish Wind Energy Association (SWEA) are forecasting the installed capacity reaching 18 GW making wind power the second largest power resource in Sweden.[18]

The increase in rated power of the wind turbines are driven by the recent success of offshore and component development. The wind turbines have grown in size, both in height and in blade length, generating more energy. Wind generally increase in speed with increased altitude, since the friction from obstacles near the ground is decreasing. This is the main reason for the rising hub height, to be able to extract more energy from the wind.[19] Figure 2.4 display an obvious trend of the increase of wind turbine rotor diameter. Based on the service Vindbrukskollen provided by Länsstyrelsen, an average rotor diameter of 141 meters was calculated from 492 wind turbines installed in Sweden 2021.[20] A larger swept area of the blades have the capability of capturing more wind energy and generating more electricity. This means that a larger amount of wind energy is able to be withdrawn from lower wind speeds, therefore increasing the amount of viable areas of wind turbine placements.[19]

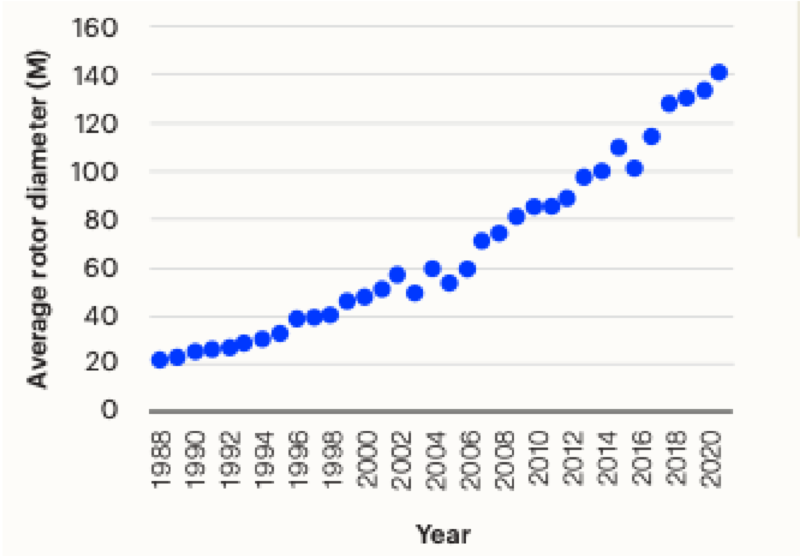

Figure 2.4: Rotor diameter increase the latest years.[20]

Moreover, a tendency towards decreased downtime has been observed as manufacturers have leveraged their operational experience from previous wind farm models to create new, more dependable designs. It is noteworthy to mention the progress made in optimizing Operations and Maintenance (O&M) procedures to minimize unscheduled maintenance, which has been enabled by the enhancement of data collection and analysis capabilities. This has facilitated the implementation of predictive maintenance and the optimization of production output. Additionally, advancements in the development stage, achieved through increased practical experience, have led to improved methods for characterizing wind resources and identifying optimal sites, as well as optimized wind farm designs that maximize operational efficiency.[21]

These factors have created a favorable environment for the progression of offshore wind technologies and their eventual commercialization. The growth in the size and capacity of turbines has exerted upward pressure on capital expenses as a result of the increased difficulties associated with constructing larger turbines and the necessity for larger foundations.

Economically tenable

Offshore wind energy is gaining momentum globally with developers and governments working towards reducing costs. Also, the evolution of capital costs for power generation technologies is heavily influenced by the presence of a robust pipeline of projects, and the development of offshore wind energy is no exception. Another notable important driver is the party responsible for the transmission costs. In some countries the transmission assets are owned by the TSO and in other cases the assets are owned by the wind farm developer. It is therefore important to analyze these cost trends by country-to-country to understand their development. This can be seen in the second figure 2.5 below, where it is clear how both Denmark and the Netherlands have a system where the TSO are responsible for the transmissions costs and owns the cables. Therefore these countries have a significantly lower capital cost than the rest of Europe.[21] In Sweden, the responsibility for paying for the connections for offshore wind power depends on the specific project and its agreements. In some cases, the energy producer may be responsible for paying for the offshore connections. In other cases, the Swedish government may provide financial support or incentives to encourage the development of offshore wind power and cover some of the costs associated with offshore connections. In Europe, cost reductions are driven by measures such as competitive auctions, policy support and clustering of offshore wind farms. The capital costs in Europe were around $4,000/kW in 2018 and are projected to decline to below $2,000/kW in 2030 and about $1,500/kW in 2040. The availability of sites with relatively shallow water depth is a crucial factor influencing project costs, as exemplified by the Netherlands, where the first-half of the next decade is likely to see projects commissioned at the lower end of the global cost range. The availability of sites with shallow water depth, proximity to shore and wind resource quality will continue to influence the capital costs of individual projects.[22]

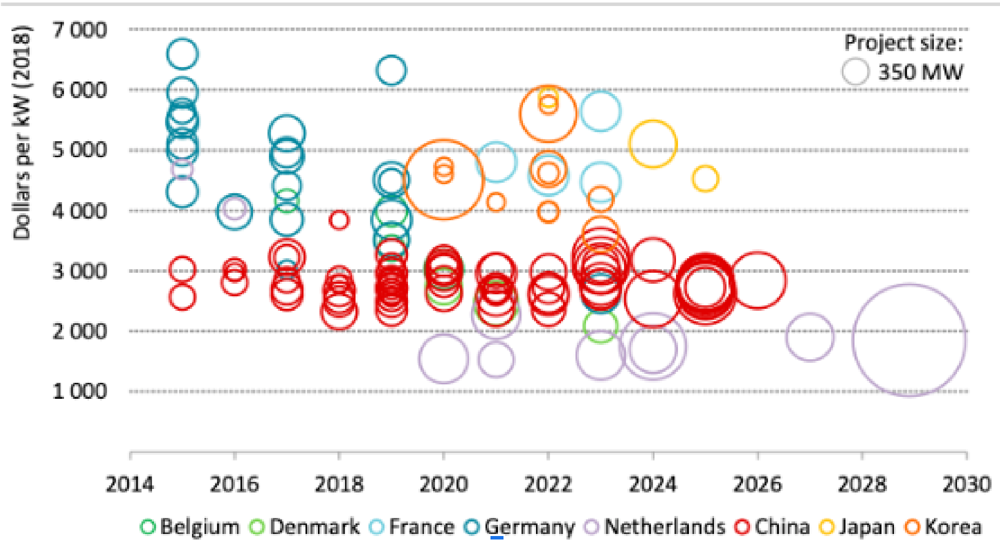

Figure 2.5: Global capital costs of wind farm projects, displaying a decreasing trend.[21]

Traditionally, offshore wind farms have been connected to shore using radial offshore transmission assets, but to reduce the impact of building multiple transmission assets and costs, offshore wind farms can also be designed as clusters and connected to an offshore "hub-and-spoke". In Europe, there are different models for developing offshore wind transmission, such as the competitive auction model in the United Kingdom, where wind farm developers can build and transfer the transmission assets to the TSO or a competitively appointed owner. In other countries, the system operator provides the offshore grid connection and substation. Denmark has announced its intention to include offshore transmission assets in its competitive bidding framework.[22]

The field of operation and maintenance (O&M) costs in offshore wind energy is undergoing a phase of significant development and improvement, resulting in cost reduction. According to projections, the global average O&M costs, which were around $90/kW in 2018, are expected to decrease by one-third by 2030 and reach $50/kW by 2040. Regions with more developed offshore wind markets, such as China, exhibit lower O&M costs compared to others. The advent of digitalization has introduced new techniques for monitoring that facilitate proactive identification of failures in not only turbines, but also in structures and connections, leading to reduced costs. Furthermore, synergies with the oil and gas industry have enabled offshore wind projects to benefit from the oil and gas industry's expertise in offshore structures in the planning and execution of maintenance activities. These advancements can extend the expected life span of projects, enhancing their economics and reducing the levelized cost of electricity (LCOE) for offshore wind.[22]

The LCOE is a comprehensive metric that captures all relevant cost components of a given technology into a single value that represents the average cost of electricity generation. The 2021 figure of $0.075/kWh represented a 13% decrease from its value in 2020, which was $0.086/kWh. The cost reductions of offshore wind energy are expected in all regions and individual markets and could further reduce costs by developing a robust project pipeline and efficient supply chains, thanks to the maturity of the technology. In the European Union, applying a Weighted Average Cost of Capital (WACC) of 4% results in the average LCOE of offshore wind projected to decline from $104/MWh in 2018 to just over $60/MWh in 2030.[22]

Sites and foundations
It is projected that by 2050, 380 GW out of the expected 450 GW of offshore wind energy capacity in Europe will be established in the North Seas, representing 85% of the total anticipated offshore wind energy generation. This region, comprising the Atlantic off the coasts of France, Ireland, and the United Kingdom as well as the North and Baltic sea, is deemed as a suitable location for the development of large-scale wind energy infrastructure due to its favorable wind resources and site conditions, as well as the limited economic viability for solar energy generation in comparison to southern European regions. In a study performed by WindEurope in November 2020 evaluating the 2050 vision of 450 GW installed offshore wind power, a potential of 83 GW was estimated for the Baltic Sea.[23] Another study provided by the Global Wind Energy Council (GWEC) report an estimated technical potential for fixed and floating offshore wind energy in Sweden, in terms of installed power capacity in MW, which has been calculated within 200 kilometers of the shoreline. According to the study, there is a technical potential of 228 GW fixed offshore wind power and 360 GW floating offshore wind power.[24]

However, water depth and greater distances to shore are adding complexity to existing successful and profitable sites, requiring significant effort to maintain the balance of secure, green, and affordable energy. Floating offshore wind (FOW) has become a necessary solution due to the limitations of other options. However, the wind power industry has limited experience with FOW, as only 73 MW have been installed globally as of 2020. It is projected that by 2040, FOW could reach a capacity of up to 70 GW. The use of floating foundations will not only enable the utilization of deeper waters for wind energy production but also bring new maintenance options, such as tow to shore.[25] The technology is still maturing and costs are therefore still high. Mass production is a crucial factor in reducing costs, and floating wind power offers greater potential for this than conventional offshore wind. Conventional wind foundations are often site-specific and dependent on soil conditions and other variables, leading to custom-made components. In contrast, floating foundations are less dependent on these variables and can be standardized, allowing for mass production. The greater flexibility in placement also enables floating wind power to be located where wind resources are optimal, leading to higher energy yields and reduced LCOE, making floating offshore wind more attractive.[26] The progress made in recent years is promising. Recently installed commercial and pre-commercial projects will play a crucial role in determining the cost of floating foundations and offshore substations, both of which are crucial to the success and deployment of offshore wind projects in deep waters.[16]

2.1.5 Limitations

The uncertainty of power generation from wind turbines is a problem, as the primary driving force behind wind turbines is wind speed, which exhibits temporal and spatial variability. The electricity generated by wind turbines is intermittent, making it unavailable when demand is high and unable to be controlled or scheduled in the same manner as thermal, nuclear, and hydroelectric power sources. The integration of substantial amounts of wind power into the power system will likely have implications for its operational security and stability. This reduces the operator's motivation to integrate wind power further into the power system. Wind power intermittency has become the biggest challenge for further integration and therefore to reach the national and international goals set for renewable energy generation. There are several issues with intermittency of wind power.

Impact on system reserves
Further integration of wind power into the power system imposes a larger uncertainty that Svenska Kraftnät has to cope with. For that reason, larger system reserves are required to cover load increases and wind power decreases.[27] A study where different cases have been compared show that there is a clear linear relationship between a growing wind power penetration and additional load-following and spinning reserve requirements.[28]

Impact on system reliability
System reliability is the evaluated ability of the system to meet the load demand. The correlation between variable sources and peak load demand is an important factor in determining the effectiveness of utilizing these sources to meet energy needs. While it is possible for fluctuating sources to match peak demand if their variability aligns with the load demand, this is not typically the case with intermittent wind power. In Sweden, the wind power capacity is larger in the winter than in the summer which matches the load demand to some extent. However, a study performed in Spain showed that peak wind power capacity peak occurred around midnight, while peak load demand is between 13:00 and 22:00 [29]. This meaning, intermittent wind power cannot guarantee that peak capacity will respond to peak load demand, and thus high wind power penetration has a large impact on the system reliability.

Another challenge for wind turbines is their lack of inertia. The mechanical inertia in the power system comes from the possibility of storing, or using, kinetic energy in the synchronously rotating mass of turbines and generators. The inertia in the electrical system is usually provided from either nuclear, fossil fuel or hydro power plants. The coveted function of mechanical inertia in the power system's rotating parts is the ability to quickly receive or release energy in order to balance the electrical system. If more power is supplied than extracted the frequency increases and vice versa if less power is extracted than supplied. Inertia makes the balancing easier since it provides time to act if a crisis should occur. If a hydropower plant has to shut down due to technical issues, the rotors of the other synchronous generators would decelerate using energy previously stored as rotational energy in order to maintain the electrical frequency. Without inertia the balancing of the system would have to be made through removing or adding load to the system leading to more frequent and severe power outages.[30] Wind power is inverter controlled and does not naturally contribute inertia to the system. When the amount of inverter controlled units increases the inertia and the balance of the system decreases. With a smaller share of the electricity mix providing inertia the conditions for maintaining a stable system are negatively affected and require faster responses from control functions.[30]

Generation solutions

Implementation of other power generation methods is a proven mitigation method for compensation of power fluctuations from wind power. A rule of thumb is that these power generation methods should respond rapidly and be more flexible than wind power. Therefore, these methods are often gas turbines or diesel generators driven by fossil fuels. Also, wind and solar energies combined via optimal allocation can reduce power fluctuations to some extent.[31] A study analyzing a hybrid wind and solar power system indicated a reduction in fluctuations is approximately 50-60% on a 0.5 hour time scale and 17-33% on a 4 hour time scale. In general, the use of renewable energy technologies that possess variation patterns that complement wind power can help mitigate its power variability.[32]

Storage solutions

Several different storage techniques can be applied with wind power, including Pumped Hydro Storage, Compressed Air Energy Storage, Flywheel Energy storage and BESS. The response time of BESS is generally rapid, within a matter of seconds, making it an effective method to address the intermittency of wind power. BESS possess several advantages, including high efficiency, quick response time, and a long lifespan. Additionally, due to their high power density, BESS tend to be smaller in size compared to flywheels and Pumped Hydro Storage systems. These advantages make BESS technically suitable for various applications, such as uninterruptible power supply, load leveling, load following, fast response/conventional spinning reserve, renewables backup, and more.[33] A study of control algorithms of BESS to mitigate wind power intermittency using a model predictive control methodology showed that the operation costs and wind curtailment can be effectively reduced with the use of BESS compared to conventional reserves, and that a 400 MWh Li-ion battery is sufficient to cover the uncertainty of an 800 MW wind farm with wind power curtailment under 1%.[34]

Grid limitations

The siting of wind power plants can pose significant challenges, particularly when they are located far from traditional load centers. This distance can result in increased stress on the transmission infrastructure and weaken the connection of the power source to the grid. The resulting transmission congestion is widely recognized as a primary factor contributing to the curtailment of wind energy generation. This leads to the deployment of more expensive energy generation sources, rather than the comparatively inexpensive wind power. Additionally, the construction of long-distance transmission corridors can be more time-consuming than the construction of wind power plants, further hindering the transmission of available energy to load centers.[35]

Permitting and administrative procedures
The permitting process for wind power plants in Sweden is known to be lengthy, taking approximately 10 years, and characterized by unpredictability, particularly due to the potential veto power of municipalities. This has been one main reason for relatively slow development of offshore wind farms in Sweden throughout the years. It is in many ways important for citizens to have opinions in matters that affect them, but it is problematic when investments and projects stop that aims for advancing a sustainable energy transition. It is therefore now suggested that municipalities should retain the right to reject wind power projects, but with some modifications. This suggestion seeks to distinguish clearly between the role of the municipality in determining the suitability of wind power in their jurisdiction and the licensing authority's review of the permit application.[20]

2.2 Photovoltaic systems

Marine Renewable Energy systems (MREs) have the potential to contribute a significant amount to the energy mix of the future, because of the vast energy resources offshore. With land availability becoming a more prevalent problem around the world, floating solar technology emerged as a solution more than a decade ago. Currently the majority of floating solar power is located in inland freshwater bodies such as lakes and ponds, but the technology is increasing the field of application to marine environments.[36] The technology is immature and still evolving, but there is great potential and belief for FPV systems to emerge as a great contributor in the future electricity mix.

2.2.1 PV system technology

The most common way to extract power from solar radiation is by using PV systems. PV systems consist of electronic devices made of materials that take advantage of the photovoltaic effect which converts solar radiation into electricity. When solar radiation hits the cell, photons are absorbed creating electron-hole pairs. This in turn creates a voltage difference across the p-n junction which drives electrons, creating an electric current in an external circuit which then is extracted.[37] Typically PV cells are made of semiconductor materials with a p-n junction, where the p-side has an excess of holes and the n-side has an excess of electrons allowing electric current to only travel in one direction. This is illustrated in figure 2.6.

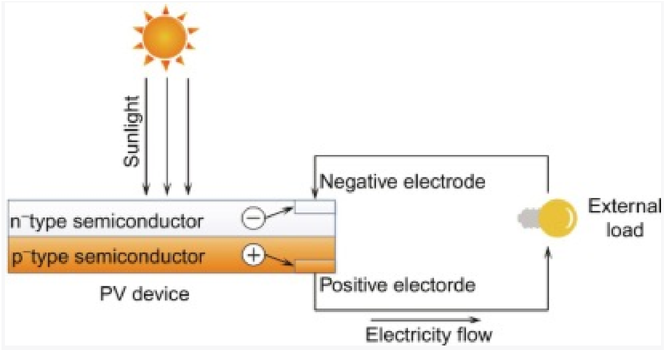

Figure 2.6: Generic PV cell technology.[38]

2.2.2 PV system structure

Floating PV systems today are still limited to inland freshwater bodies mostly associated with calm water motions. The generic structure of a FPV system consist of several elements. The floats provides buoyancy to the system and overall support to the PV cells and their supporting system. The most common PV modules in floating systems are crystalline solar PV modules with a glass-glass structure. Multiple modules are mounted on the float with support structure to keep them in place. Inverters are installed, on the float or at land, with the main purpose of converting DC from the PV modules to grid compatible AC. The mooring system keeps the float at the projected site. Varying design and anchorage of the moors depends on the seabed conditions of the site. Anchor systems normally consist of concrete ballasts or helical piles.[37]

The float structures installed on calm waters can withstand wave heights of up to 1 m. To ensure the survival of the technology in a harsher marine environment new structures are emerging as a solution. The thin-film panels is a more flexible and lighter solution compared to the more generic and traditional glass-glass panels. These thin-film panels are mounted onto a pliable float connected with a DC/AC inverter. The goal of this structure is to manufacture an array of these modules in a hexagonal structure to minimize the number of anchor points while also allowing the structure to be grouped up. This structure yields to waves but is still able to withstand the harsher marine environment.[39] Figure 2.7 below illustrate the generic FPV system structure with its components.

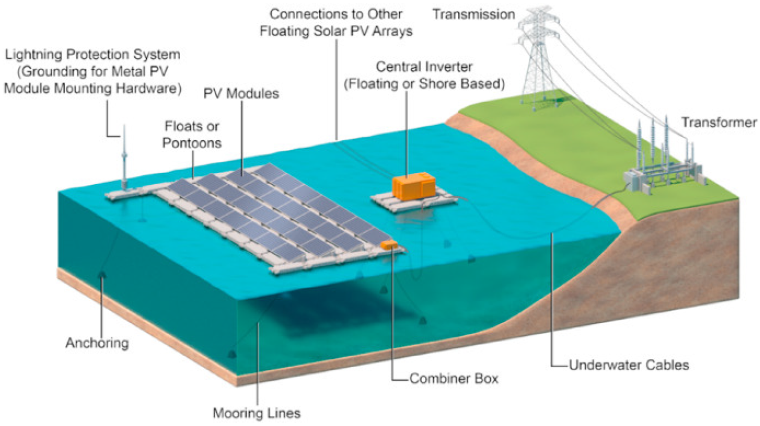

Figure 2.7: Generic FPV system structure.[40]

2.2.3 Markets

Floating PV

After the first installation of FPV 2007 in Japan with the capacity of 20 kW,[41][42] applications have expanded greatly worldwide with many more locations located in Asia, Europe and the Americas. However, the first projects were only small-scale systems designated to research and development (R&D). It was not until 2014 the average plant size rose to 0.5 MW and the turning point was in 2015 when a plant was installed in Japan with a capacity of 7.55 MW, at the time the largest FPV in the world.[36] This accelerated installed capacities of different projects, leading to the largest FPV in the world today located in China with a capacity of 150 MW.[41] Overall the cumulative installed capacity almost doubled in one year between 2017 and 2018 as shown in figure 2.8 below, rapidly turning the sector into a GW industry.[41]

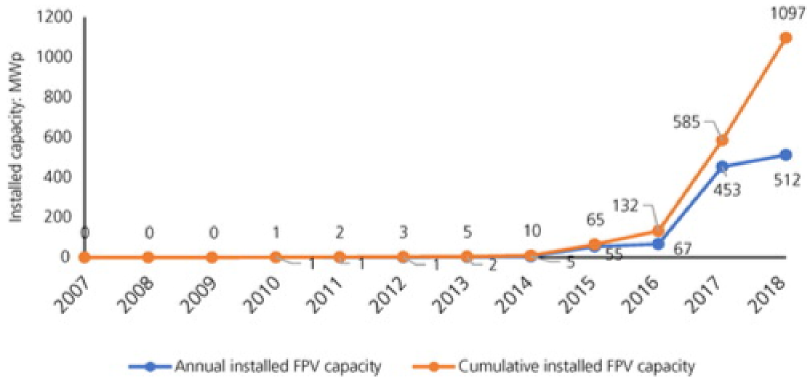

Figure 2.8: Cumulative and annual capacity installed over the years.[36]

In 2021 Asia held the majority of the market share at around 73%.[43] The European market is on the rise with Germany being at the forefront followed by Spain and the Netherlands.[36] The interest of investors are on the rise with many planned projects for countries in Europe are in their finalizing stages.

Ground mounted PV

The European market just as the global market has had a rapid increase in installed capacity over the years, with 41.4 GW installed in 2022 alone around the 27 member states of the EU.[44] This was a 47% increase from the record breaking year before which marked the best year in history for solar power. Germany is steadily at the forefront and has been since the early 2000s for ground-mounted solar power with a cumulative installed capacity of 68.5 GW throughout the whole country. Spain who is a close second to Germany has increased their solar power capacity in the energy mix by a staggering 55% since 2021 bringing the market to 7.5 GW in the country. Overall the solar industry has been on an upward trend in recent years, however, its progress has been hindered by several external factors. The year 2022 brought a significant change in the perception of solar energy in Europe. For the first time, top policymakers recognized the true potential of solar energy in the European Union. The lifting of COVID-19 restrictions and the resolution of supply chain bottlenecks played a crucial role in demonstrating the cost-effectiveness and scalability of solar energy The Swedish solar industry has seen a steady rise over the years, starting from a low base in the early part of the last decade. By 2017, the annual installations had exceeded 100 MW and by the end of 2021, the installed capacity in the country had reached 1.6 GW. Despite this growth, the share of electricity produced from PV in the energy mix remains relatively low, estimated at 1.5%. However, it is expected to produce 2 TWh in 2022.[44]

The high electricity prices in Europe, especially in southern of Sweden where conditions for PV generation adequate, have played a significant role in the growth of the Swedish solar market. The residential market drives the Swedish solar industry, accounting for roughly 50% of the installed capacity, followed by the commercial and industry sector at 35-40%, and the utility-scale market at 10-15%.[44]

2.2.4 Support schemes

EU

To give more exposure to the renewable market the EU commission has introduced different support schemes to create an incentive for member states to invest in the renewable energy sector.

- Feed- in premiums are an advanced form of the Feed- in Tariff (FIT) system, with different levels of market exposure for producers. According to an analysis made by the European Commission, premium systems have several benefits over other support schemes. They require renewable energy producers to find a buyer for their production and ensure that market signals reach the operators through different levels of market exposure. An efficiently designed premium scheme will also control costs and drive innovation through competitive allocation processes and automatic, predictable adjustments to cost calculations, providing investors with market signals, confidence and foresight.[45]
- In some countries, energy suppliers are required to purchase a certain amount of renewable energy or green certificates that represent the production of such energy. This creates a market between renewables producers and energy suppliers, who can trade energy or certificates at a price determined by the market. The energy producer is exposed to market prices as they must sell the energy and the green certificate separately. In most countries with quota obligations, a penalty is imposed for non-compliance, setting a limit on the green certificate price.[45]
- Investment support usually covers capital costs, unlike operating support which covers production related costs. Investment support can take the form of grants, preferential loans, or tax exemptions/reductions. Unlike operating support, which is often criticized for maximizing production regardless of price, investment support decouples production from sales price and can be suitable when production incentives are not necessary or desired. Investment support is often provided by EU-funded instruments and should be coordinated with other national or regional support schemes. It has the advantage of not affecting operating costs and being a one time measure that does not need to be adjusted later due to changes in technology or markets to avoid overcompensation.[45]

Sweden

Sweden follows different support schemes, these include: the quota system, subsidies and tax regulation mechanisms.[45] For solar power these are investment support, operating support as well as tax exemptions according to the Swedish Energy Agency.[46] The investment support is called "Skattereduktion för Grön teknik". However the support schemes are limited to the residential sector and does not cover the commercial sector.

2.3 Wind-PV hybrid system

The hybrid energy structures, both onshore and offshore, have a similar underlying concept. By combining two different sources of energy generation, the stability and consistency of the energy supply can be improved. Offshore deployment of these systems has the added advantage of increased resource availability, enabling the system to more easily meet the growing energy demand.

2.3.1 Structure

A key driver for marine solar power exploitation is the need for more efficient land management. A wind-solar hybrid system utilizes the water between wind turbines for solar panels, displayed in figure 2.9 below. In this way the hybrid system makes optimal use of available resources.

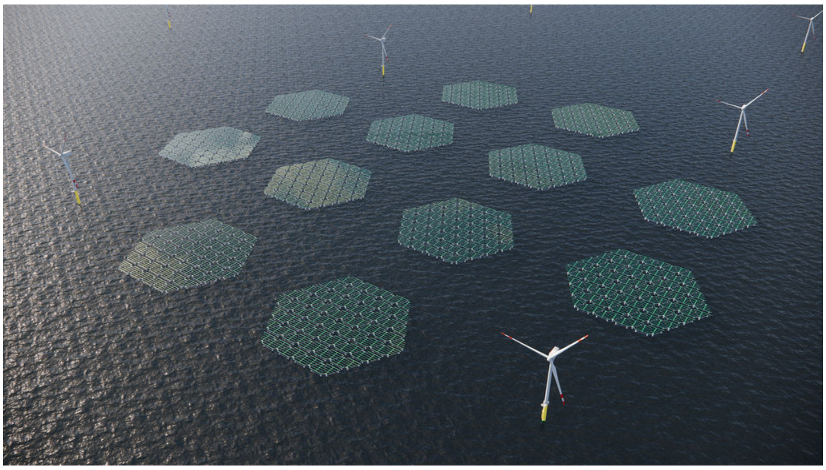

Figure 2.9: RWE and SolarDuck demonstrator of a hybrid wind-PV system.[47]

When considering a wind-solar hybrid system it is of much importance to understand the technology options available for connecting to the grid. One option is a shared substation and grid coupling point, which involves separate components for the wind and solar structures, but with a common connection point to the grid. A shared substation and grid coupling point is generally considered to be the most cost-effective. However, this may change as all technology continues to advance and new solutions become available.

2.3.2 Specific costs

Immaturity of the technology are resulting in high prices. But, as experience grows, best practices are developed, and new configurations and technologies emerge, there is potential for a gradual reduction in the costs of FPV systems over time.[48] The main costs affecting the system are the costs of the initial investment, the operation and maintenance costs and the cost of replacing components which are at the end of their technological life. This subsection aims to help answer research question number one on the costs associated with a FPV installation.

Module costs

One of the largest fractions of the cost is the module costs. PV-modules are a research-intensive industry meaning R&D costs are accounted for in the module costs. The largest fractions of the module costs include the costs of balance-of-module materials, silicon costs and wafer processing costs, which is tied to chemical and processing costs.[49]

Site staging

The deployment of FPV systems necessitates a comprehensive evaluation of hydrodynamic factors, including the speed of waves through a thorough hydrodynamic survey. In addition, it is imperative to conduct a bathymetry survey to assess water depth and water level fluctuations, as well as a geotechnical study to appraise soil conditions within the basin. Compared to land-based systems, these assessments entail additional expenses. The total cost of site staging is contingent on the type of water body under consideration and the extent of the survey area.[48]

Structural Balance of System (SBOS)

Various types of floats utilizing different materials and configurations are available. Typically, these floats are made from high-density polyethylene (HDPE) and are less costly than pontoons, containing fewer metal parts. This HDPE floating structure simplifies the assembly and deployment of the modules, as opposed to installing them on a pile-driven structure. In contrast to ground-mounted systems, most FPV installations do not require site preparation activities such as soil stripping, grading, and compacting using heavy equipment, or removal of existing vegetation. Limited ground disturbance may occur during the installation of onshore components, such as inverters and pile-driven anchors.[48] Depending on the water profile and soil conditions in the basin, project developers may choose between bottom anchoring and bank anchoring. While bottom anchoring has been more common in the past, recent research suggest that pile-driven anchors on the banks are becoming increasingly popular for inland and artificial water bodies due to their cost-effectiveness. The type and quantity of mooring lines are selected to account for ambient stresses and variations in water level. In our analysis, we assume projects use elastic mooring as it extends the longevity of the FPV system. [48]

Electrical components

In FPV systems, the PV modules on the floating array are connected through junction boxes and electric cables suitable for both marine and freshwater environments. These cables are connected to the shore using marine-grade submersible cables. A central inverter installed onshore is used in most installations due to its relatively lower cost. While string or central inverters can be installed on floats, the inclusion of additional floats may result in a substantial increase in expenses.[48]

Soft costs

Soft costs refer to various expenses involved in FPV system installation, such as permitting, inspection, and interconnection costs, sales tax, shipping and handling expenses, contingency expenses, developer overhead, engineering, procurement, and construction (EPC) overheads, and profit markup.[48]

O&M costs

O&M costs refers to preventive maintenance of the PV-cells, anchorage, mooring and foundation. Costs included here are transportation costs, salary for maintainers, boat maintenance, fuel costs. These costs are in most cases comparable to the costs of ground-mounted PV.[48]

Merging costs

The highest costs of FPV systems are attributed to installation and operation and maintenance. The offshore wind power plant also faces similar challenges, with varying O&M costs for different projects. However, the O&M costs can be reduced when the wind and solar power plants are combined into a hybrid power plant. In this scenario, the wind and solar power plants share the same location and connection point, reducing the overall O&M costs. Additionally, combining the wind and solar power plants in a single location can also reduce the transmission costs. By sharing the same connection point and cables to the substation, the transmission costs are lowered because the amount of cables are reduced. However, the cables may need to be upgraded to withstand higher voltages due to the increased energy production when both the wind and solar conditions are optimal.[50]

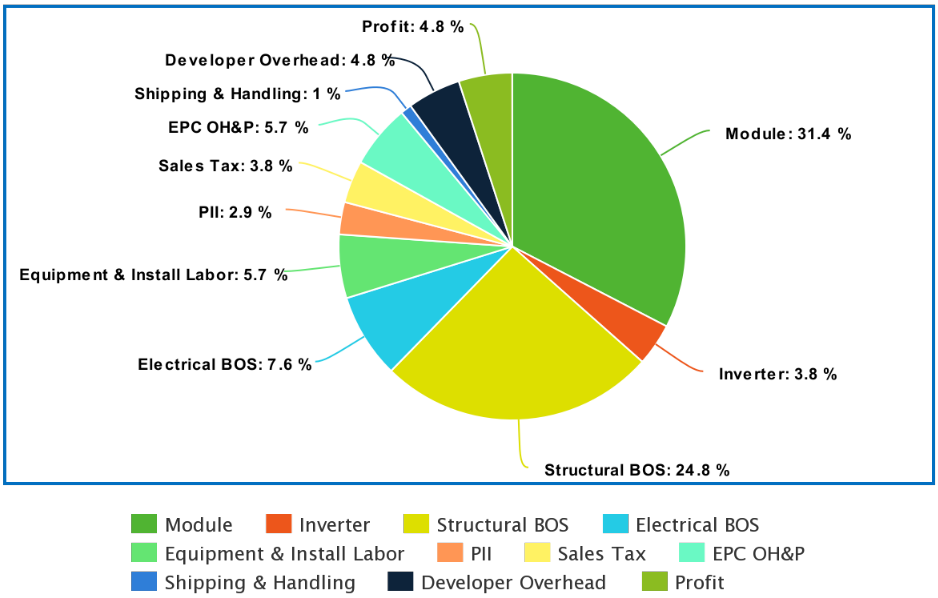

Figure 2.10: Specific cost sections FPV.

2.3.3 Potential

The wind-solar hybrid power plant system presents several advantages compared to a conventional offshore wind power plant or a solar power plant. Conventional offshore wind farms require large empty marine surface areas between the turbines to reduce the wake effect, these empty areas are used by the FPV systems in a hybrid power plant. This in turn increases the capacity density as shown by figure 2.11 below, meaning that more energy can be generated in a smaller area.[51]

Another advantage of combining FPV systems with offshore wind turbines is the reduction of the intra-annual variability of energy output, which is a downside of most renewable energy sources. Research show that the power smoothing index, which measures variability of the power output, is experiencing a substantial reduction in a hybrid system compared to wind turbines alone. Also, the coefficient of variability can be lowered up to 20% compared to a stand alone FPV system.[51]

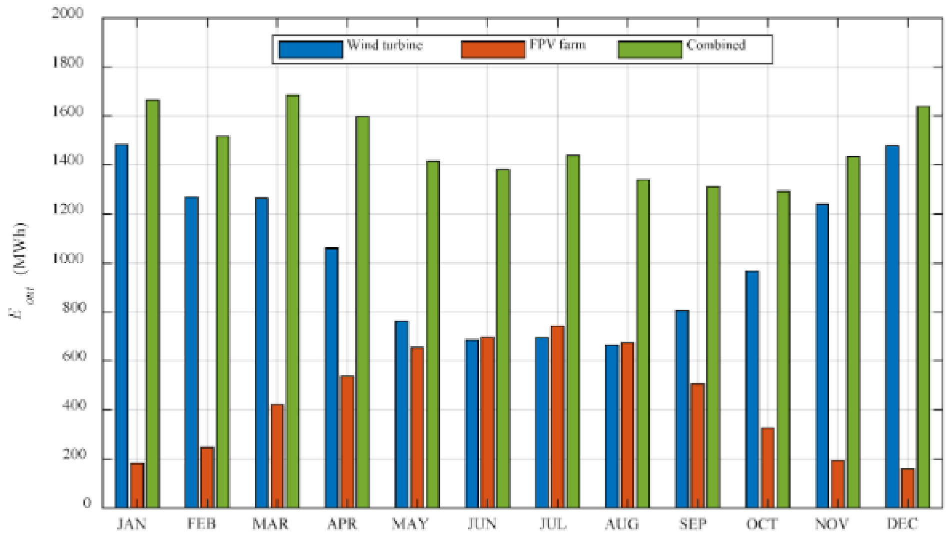

Figure 2.11: Hybrid wind-PV system combined and stand alone power output.[51]

2.3.4 Challenges

Cost of parts and appropriate design implementation

One of the significant barriers to research in the industry is the cost of parts required for manufacturing and fabricating of hybrid systems. The cost of parts pushes scientists towards improvisations that may be cost-effective but compromise the quality of the research output. The high cost of parts restricts the quality of research, forcing researchers to limit their work to simulations and theoretical analysis. However, simulations do not provide an accurate reflection of real-life scenarios. Most prototypes fail in the implementation phase, making effective design implementation critical as it highlights the fabrication paths and the challenges of specific design in actual practice. Due to these limitations of simulations, some solutions proposed may not match the actual devices produced, possibly due to modification during fabrications. All of this stems from the technology being in its early stages and there is no "right" or optimal way to implement the technology.[52]

Scalability

Some proposed solutions face challenges in terms of design implementation for mass production. All research is aimed at addressing real-life problems and enhancing people's lives, and thus, the designs must meet certain criteria such as functionality, ease of use, durability, ease of implementation. These are common characteristics of mass-produced goods. Hence, designs should aim to meet the minimum standards for future implementation and potential usage.[52]

Overproduction

The widespread adoption of wind-solar hybrid systems, and even solar energy in general, has been hindered by the tendency of photovoltaic systems to overproduce energy that cannot be consumed within a given time frame. The auxiliary components such as converters, controllers, and storage units also play a role in overall energy generation. Integrating wind power, photovoltaic and storage systems can help mitigate overproduction. Overproduction has been modeled as the "duck curve" where solar produces too much energy during midday and not enough during the evening when the demand is higher, as displayed in figure 2.12 below. Although this issue has recently gained attention, institutions and governments have been funding studies on the duck curve for years.[52]

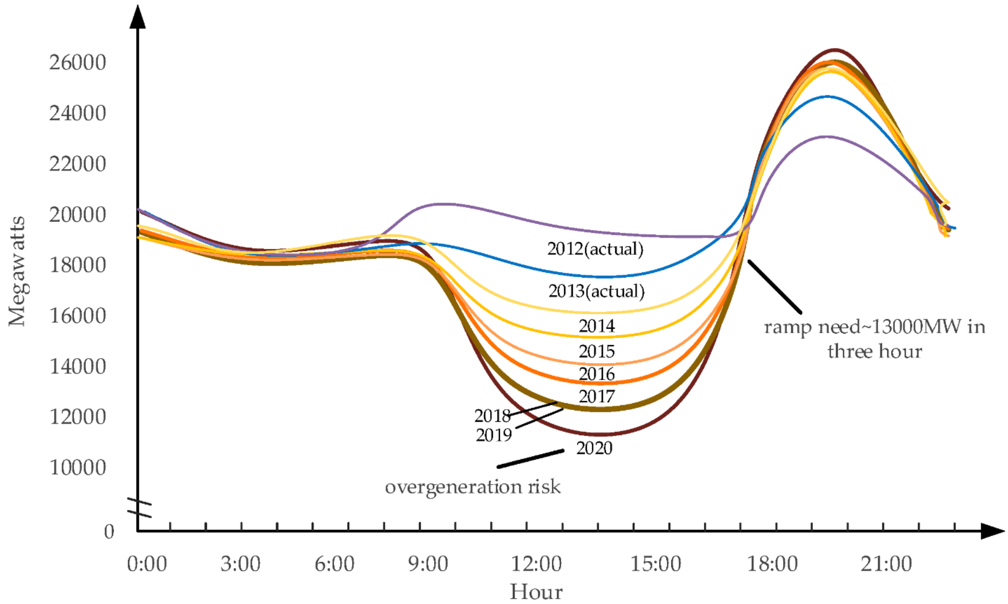

Figure 2.12: Solar duck curve.[53]

2.3.5 Existing and planned projects

- **SPIC and Ocean Sun 0.5** MW_p: State Power Investment Corporation (SPIC) launched the first-ever offshore wind-solar power plant hybrid located off the coast of the Shandong Province in China. Together with the use of patented floating solar technology from the Norwegian firm Ocean Sun, SPIC commissioned the world's first commercial offshore floating solar power plant containing two floating solar panels each with a capacity of 0.5 MW_p and integrating it with an offshore wind turbine's transformer and then linking it to the power grid via the wind farm's subsea cables for the first time [54].
- **RWE and SolarDuck 5 MW demonstrator:** SolarDuck, a Dutch-Norwegian company, has plans on constructing the largest hybrid offshore floating solar power plant in the world at the Hollandse Kust West VII offshore wind park in the Netherlands. This is to be done in collaboration with RWE. As part of the collaboration agreement between SolarDuck and RWE in July 2022, SolarDuck

announced plans to build a 5 MW floating solar demonstration project that incorporates energy storage solutions. The agreement designated SolarDuck as the exclusive provider of offshore floating solar technology with integrated energy storage for RWE's bid for the HKW VII wind farm. The project is scheduled to become operational in 2026.[47]

- **SINN Power ocean hybrid platform:** In October 2020, SINN Power deployed its OHP demonstration project near the port of Heraklion, where the company operates its research and development facility. The modular platform currently includes 192 PV modules (72 cells) provided by project partner Schmid Pekintas from Turkey, rated at $390W_p$ each. According to SINN Power, the OHP will be enhanced with four Huracan wind turbines rated at $10kW_p$ each, which will be supplied by German-based LuvSide in the first quarter of 2021, followed by four SINN Power wave energy converters to be installed in 2022.[55]

2.3.6 SWOT

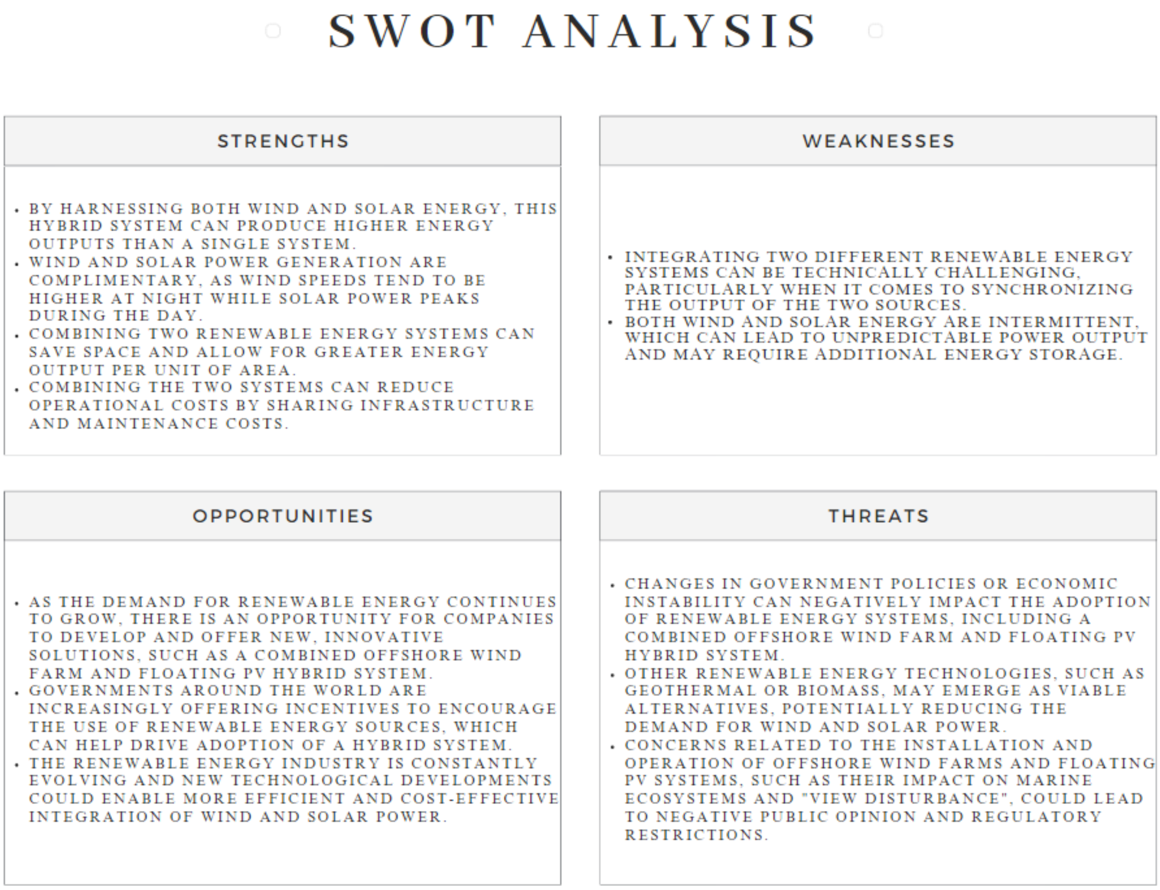

Figure 2.13: SWOT analysis for a Wind-PV hybrid system.

2.4 Wave Energy Converter systems

Wave energy converter (WEC) systems have emerged as a renewable energy technique to take advantage of the wave movement offshore. The amount of energy harnessed depends on multiple factors such as the wave height, wave frequency and the water density. They are designed to operate in the harsh marine environment and can be deployed near the shore or offshore, depending on the specific design. There are several types of WECs, but most of them work based on the principle of converting the linear or vertical motion of waves into rotational motion, which is then used to generate electricity. WECs have the potential to provide a significant amount of clean, renewable energy, but they are still in the early stages of development and face challenges such as high capital costs and variability in power supply. However, ongoing research and development are working to improve the performance and efficiency of WECs and make them a more viable source of renewable energy.

2.4.1 WEC system technology

There are three main methods to transform wave energy into electricity. The first is through the use of buoy or float systems, which harness the vertical movement of waves to drive hydraulic pumps. This works by the systems flexing and bending as the waves pass, activating the wave energy converter which converts kinetic energy into electricity.[56] One example of this is the OSWC which uses a flap that bends as the waves pass, which activates the hydraulic power take-off system to generate electricity.[57]

2.4.2 WEC system structure

In this thesis, we will focus on the technology of an oscillating wave surge converter. This type of wave energy converter acts as a pendulum under the wave action. However, new technology focus on moving the system to offshore environments. To handle the deep offshore environment the system need to move from the seabed mounted structure to a floating structure. This structure is displayed in figure 2.14 and typically consists of the flap which utilizes the surge wave motion, the frame on which the flap is mounted on, the tendons which keep the structure in place and the power take-off (PTO) system which converts the kinetic energy to electric energy.[57]

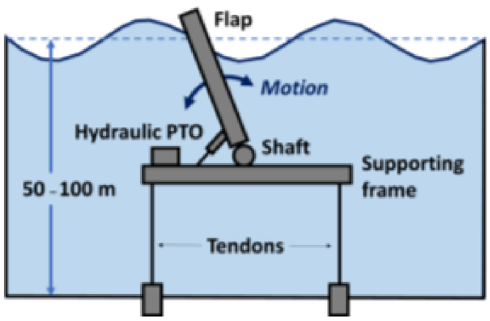

Figure 2.14: OSWC structure.[58]

The PTO typically used for an OSWC is the hydraulic system PTO, this is due to the fact that conventional rotary electrical machines are not directly compatible.[59] The energy conversion with the hydraulic PTO is displayed in figure 2.15 as the first option, and can be summarized like this: The flap connected to the hydraulic cylinder moves with respect to the actuator, forcing fluid through controlled hydraulic manifolds to the hydraulic motor, which in turn drives the electric generator.[59]

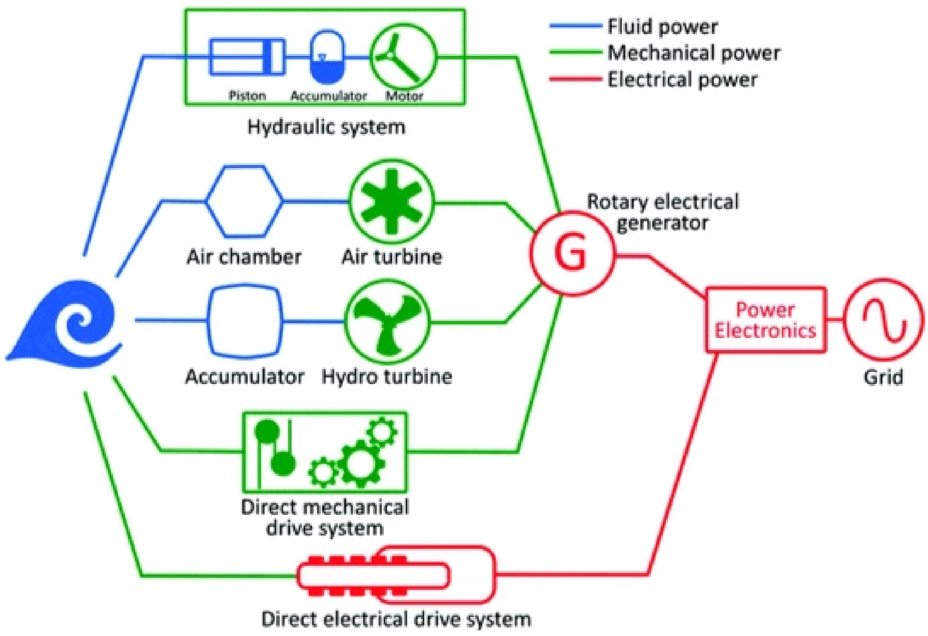

Figure 2.15: PTO system structure.[59]

2.4.3 Markets

Global

The market size is expected to increase in the next few years. This is mainly due to the rising demand of electricity from renewable energy sources worldwide and WEC systems low environmental impact. This in conjunction with the focus on research and development of the sector as well as the increased access to the power contained in ocean waves are expected to push the industry forward.[60]

The oscillating body category holds the largest market share which is due to their small size, high operating efficiency, and reliability. They are more complicated than Oscillating Water Columns (OWC), with respect to the power take-off systems. The small size and floating nature of the oscillating body converters make them very versatile. The potential is obvious but the market needs to grow by 33% every year to achieve a net-zero world by 2050 according to the IEA.[61]

Europe

Europe holds the largest revenue share in the market for wave energy converters in 2022 due to most of the research and development in the sector is located at the continent. Around 11.4 MW of capacity was installed between 2010 and 2021, but only 1.1 MW was still in use in 2022 while the rest 10.3 MW had been decommissioned after testing programs were completed.[60]

It is clear that the biggest market share is held by Europe.[62] In 2021 681 kW of wave energy was installed in Europe, three times more than that of 2020. Scotland, the Netherlands and the Iberian Peninsula are all shaping up to become hotspots for wave energy development, with multiple new installations in later years and more planned over the coming years.

2.4.4 Support schemes

The development of the technology is not just attributed to the innovation and industrial innovation of the sector, it is also thanks to the major pieces of legislation which support the development of the technology.

Global
The US is challenging Europe on the market. USA's House of Representatives passed a bill which authorizes the administration to invest $600 million in the development of ocean energy between 2021 and 2025. Public investments into the sector also included $96 million of increased R&D.[63][62] The US also provided the biggest ever investment for clean technologies in the Inflation Reduction Act (IRA). In addition, the infrastructure law provided $112 million for ocean energy in 2022. Another $110 million was requested by the Biden administration for 2023.[64] Also, Canada has introduced a comprehensive policy package including feed-in-tariffs which resulted in a 32 MW pipeline of projects in 2022.[64] China is also ramping up their support of technology development. India recognised ocean energy technologies as renewable energy sources. This makes tidal and wave energy eligible for meeting the non-solar Renewable Purchase Obligation which mandates that all electricity distribution licensees should purchase or produce a minimum specified quantity of their requirements from renewable energy sources[65]. China promoted the large scale development of ocean energy in the outline of its 14th five-year plan.[64]

Europe
The French Government launched a new mechanism in 2021 allowing innovative renewable energy project developers to negotiate revenue support on a bilateral basis with the French energy regulator. In Spain the government launched a new marine renewables roadmap. The roadmap contains deployment goals of 60 MW by 2030 for pre-commercial marine energies such as wave or tidal energy. They also pledge at least €200 Million by 2023 on the advancement and development of offshore renewable energy technologies.[62] The Spanish government also released €200 million in grant programmes to support R&I and testing of offshore projects in 2022.[64] €78 million of the Horizon Europe 2023-24 Work Programme has been allocated to wave & tidal pilot farm demonstrations. The Innovation Fund has a 2022 "Mid-sized Window" which is more favourable to renewables including ocean energy. "Non-binding commitments" between national governments for each sea basin establish a framework which may benefit ocean energy in the future.[64]

2.5 Wind-Wave power hybrid system

The relationship between wind and wave action is close and as such the next step in the marine renewable sector is the development of hybrid power plants. These hybrid projects combine wind power and wave energy converters in order to capture more energy from the offshore area and reduce initial investments in comparison with two separate energy systems. The appeal lies in the mixed energy output of the hybrid power plant, which is characterized by a higher density of power and a smooth integration into the grid network. A hybrid energy system can offer economic and operational benefits such as sharing the same infrastructure, resulting in reduced installation costs.

As a result, it may be possible to speed up the transition of wave energy converters from the R&D stage to a fully operational wave farm.

2.5.1 Structure

The simplest option for combined wave-wind systems currently available is the co-located system. This involves combining an offshore wind farm with a WEC array that has independent foundation systems but shares other resources, such as the marine area, grid connection, O&M equipment and personnel, and port structures. This integration does not require major technological advancements and can be achieved through appropriate grid planning.[66]

Combined arrays

Combined arrays involve offshore wind and wave energy devices sharing the same marine area and associated infrastructure, effectively forming a single integrated array. Combined arrays can be divided into three types: Peripherally Distributed Array (PDA), Uniformly Distributed Array (UDA), and Non-uniformly Distributed Array (NDA). The PDA involves the deployment of WECs at sections along the perimeter of the array that align with the prevailing wave direction, acting as wave shields. The UDA involves uniform distribution of both offshore wind turbines and WECs throughout the array. The NDA involves a non-uniform distribution of WECs throughout the offshore wind farm. The WECs are placed strategically to optimize their performance by taking into account the interaction with other WECs and wind turbines.[66] The array structures are all displayed in figure 2.16 below.

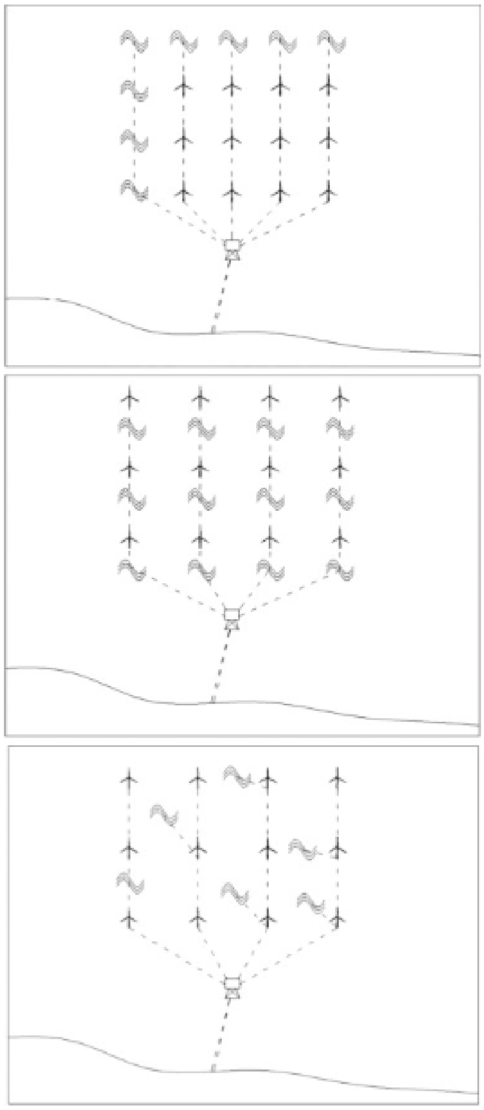

Figure 2.16: Schematic of the combined arrays: PDA, UDA, NDA.[66]

2.5.2 Specific costs

Wave energy is a maturing technology that exists in many different variations with deployment in open waters. Before a consistent reduction in costs can be achieved, the wave energy sector must reach a certain level of deployment. Due to the lack of installed WEC systems and available data it is hard to break down specific costs of a system. Therefore estimations of the future standardized specific costs for the system are made. The type of variant of wave energy chosen for this cost breakdown is a floating OSWC.[58] This subsection aims to help answer research question number one on the costs associated with an OSWC installation.

Energy Converters (EC)

Several systems cooperate in the EC. The hydrodynamic system is in our case the vertical flap. Ancillary systems such as navigation lights, bollards, and deck cranes are also included in the hydrodynamic system.[58] Another system of the EC is the PTO which converts the mechanical energy from the hydrodynamic system into electrical energy. The prime mover of an OSWC is a hydraulic PTO.[58] Instrumentation, control and safety systems is another cost of ECs. EC systems include sensors that measure various parameters such as wave height, wave period and the position of the EC compared to the starting position. Cooling and lubrication systems ensure the proper functioning of the wave energy converter, while firefighting systems provide protection in case of fire. Back-up power systems provide power in case of a power failure.[58]

Balance of Plant (BoP)
The balance of plant refers to all the supporting infrastructure and auxiliary systems required to deliver the energy generated by the WEC to the grid. BoP includes numerous components one of which being station-keeping which is responsible for keeping the WEC in place and stable during operation. It includes the foundation, such as anchors and piles, and mooring lines for compliant systems or substructure for rigid systems.[58]

Another component is the grid connection which includes the cables required to connect the WEC to the electrical grid. It includes the umbilical cable that connects each WEC to the offshore substation and the intra-array cables that connect multiple WECs together. The export power cable connects the offshore substation to the onshore substation [58].

The offshore substation and switchgear are responsible for receiving the electrical power from the WEC systems and conditioning it for transmission to the onshore substation. The offshore substation includes switchgear, transformers and other equipment required to convert the electrical power generated by the WECs into a form that can be transmitted to the onshore substation.[58]

Operational Expenditures (OPEX)
Typical OPEX includes expenses for site leases and insurance coverage during operation. Insurance transfer the costs or risk of faulty component replacement during a specific time period, which usually is 5 years. The OPEX also includes periodic inspections and corrective actions to restore the operational capabilities of the farm.[58]

Merging costs
Shared electric grid infrastructure can significantly reduce costs, which could represent up to one third of an offshore project's overall expenses. Also, The use of expensive marine equipment and facilities for offshore renewable energy projects, such as port space or installation vessels, can be reduced by combining projects and sharing resources. Combining wave and offshore wind technologies on the same structure or hybrid platform can lead to significant cost reductions compared to separate projects. The use of dedicated installations by specialized technicians is necessary for effective O&M in offshore renewable energy projects. Combining both energies can lead to cost saving through shared use of these installations and technicians.[67]

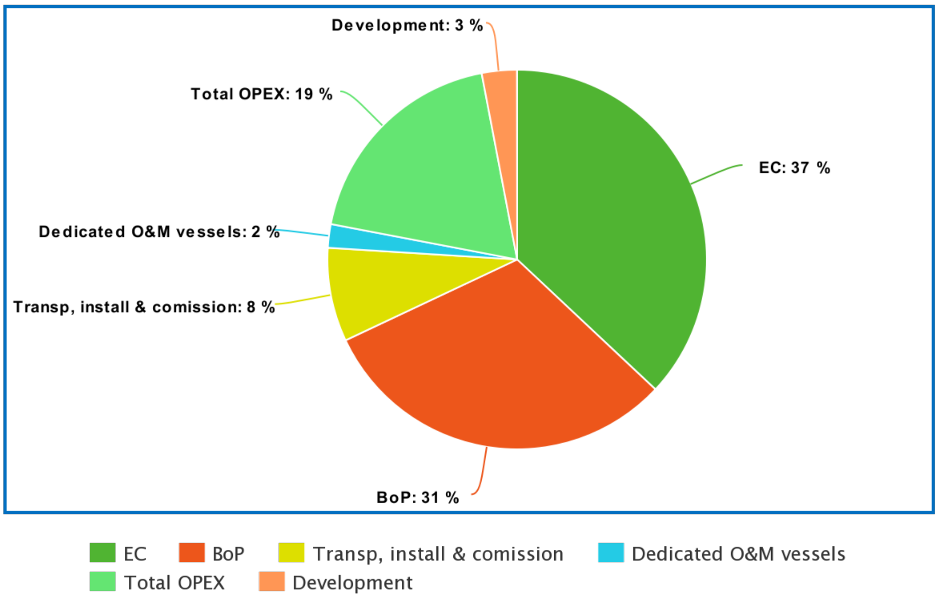

Figure 2.17: Specific costs of an OSWC.

2.5.3 Potential

Combining the exploitation of waves and offshore winds is beneficial due to cost reductions and synergies between the technologies. They face many administrative and technological barriers and share the same hostile marine environment. The marine natural resources need sustainable exploitation and both industries need to reduce costs, which provides the incentive to combine wave and wind energy. The synergies between these technologies can be divided into legislative and project/technology synergies.[67]

The demand for energy converters is anticipated to increase due to the innovative advancements in renewable resource utilization, along with the growing electricity requirements of the marine and construction industries, and the escalating investments and governmental initiatives in the renewable energy sector. Additionally, the simple design and the high dependability of these systems, which lack moving parts, are further contributing to the market expansion.

Legislative synergies

Marine energy projects, like other renewable energy sources, require long investment periods and face high energy costs during their long development stage. Strategic decisions and political commitments, such as investment priorities and national or EU energy targets, play a critical role in their development. As seen in previous section, the WEC industry is growing and gaining more ground in the renewable energy market thanks to various support schemes and beneficial goal for further development.[67]

Project/technology synergies

The combination of marine energies can increase the overall energy yield per unit of marine space, which can lead to more efficient use of natural resources. The wave resource is also more predictable and less variable than wind, which indicates that the combination of both can reduce system balancing costs. Combining wave and wind energy can also reduce sudden disconnections from the electric grid, increase availability, and provide more accurate output forecasts as the wave climate peaks trail the wind peaks. In addition to energy synergies, WECs reduce the requirements for the foundations of the wind turbines. Energy extraction from an array of WECs creates a wake that modifies the local wave climate and reduces the mean wave height. Combining WECs and offshore wind parks in a way that uses this shadow effect can lead to more weather windows for O&M and reduced loads on the structures.[67]

2.5.4 Challenges

The WEC faces a range of challenges including techno-economic and operation and maintenance. However, the biggest challenge is the lack of industry standards and the immaturity of the technology. Currently, there are numerous variations of WEC systems which hinder the development of the technology as the best version of it has yet to be developed. This in contrast to wind and solar technologies, which have established industry standards that continue to be improved upon.[68]

Public authorities lack of experience and knowledge of licensing procedures is a challenge for marine energy developers, resulting in long consenting periods, particularly regarding environmental impact assessments. Standard and simplified procedures could unify consenting procedures under the same regime, providing a combined advantage for marine energies. Also, proper planning of electric grids and auxiliary infrastructure is fundamental for offshore developments. A comprehensive infrastructure plan is necessary for the development of marine energies, whether combined or separate.[67]

In addition to the administrative issues, the corrosive nature of seawater and its high salt levels pose a challenge for the operation and maintenance of the WEC, as do extreme weather conditions. Accessing offshore structures is also difficult and expensive. However, these challenges can be reduced by implementing a hybrid structure of wind and wave. Nevertheless, this increases the risk of accidents due to mooring failures and limited operating space for maintenance vessels.[68]

2.5.5 Existing and planned projects

At the moment all of the designs of a hybrid wind-wave system are in the precommercial phase and most of them have not yet left the idea room. However, there are a few demonstrator projects that have been developed by different companies. Some of these have been discontinued and some are still in function.

Poseidon-37

The Poseidon-37 is a 37 m wide floating wave energy system which functions as a foundation for two wind turbines. The plant transforms wave energy into electricity through hinged floats, piston pumps and a water turbine. The concept is scaled down but there are plans of scaling up the system to 80 m with larger wind turbines with a rated power of 5-8 MW. The concept was developed by the Danish company Floating Power Plant and had its start date in 2008. The Poseidon was the first operational wind-wave hybrid which produced energy to the grid with an installed capacity of 50 kW.[69]

W2Power

The W2Power concept is a floating hybrid wind-wave power system. The design contains two floating wind turbines and a wave power PTO, in this case a Pelton turbine. The three energy systems are combined on a triangular floating foundation. The Pelton turbine is driven by three lines of wave-actuated hydraulic pumps mounted on the platform's sides. The concept is developed by the Norwegian company Pelagic Power AS and is still in the development phase. It is planned for the project to include at least two 3.6 MW wind turbines with a high probability of upscaling.[70]

2.5.6 SWOT

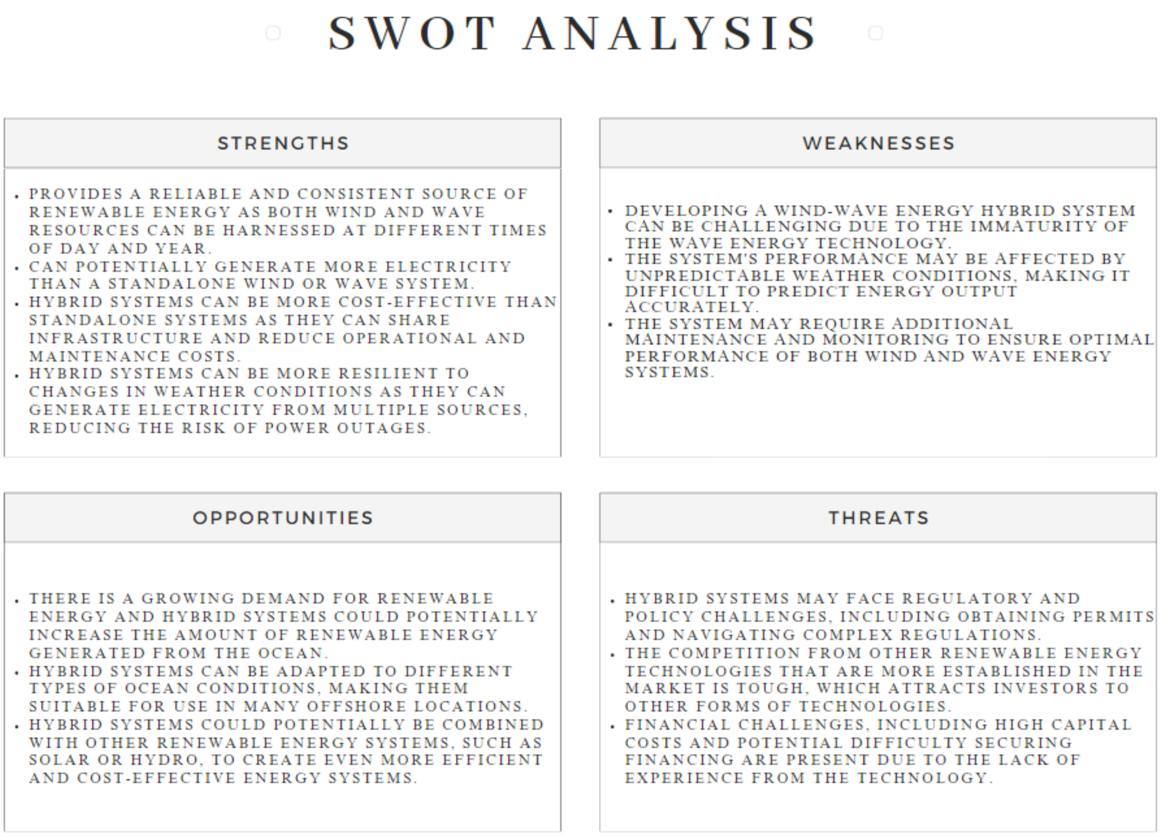

Figure 2.18: SWOT analysis for a Wind-Wave power hybrid system.

2.6 Battery Energy Storage System

To address the issues with intermittency and unstable renewable power generation, development and usage of BESS has increased in recent years. The integration of BESS into a renewable energy system can enhance the efficiency and address the shortcomings. In fact, during periods of decreased wind speed or during peak demand events, the utilization of these storage capacities becomes crucial. BESS are emerging as a promising solution for enhancing system flexibility, owing to their distinctive ability to rapidly absorb, retain, and re-inject electricity. An increasing number of individuals and organizations seek connection to the electrical grid, however, the current permitting processes are slow which is obstructing the possibility to accommodate this demand. As a result, more expedient solutions are required, with batteries being one such solution.

2.6.1 BESS technology

There are many different types of batteries to choose among. Li-Ion batteries are today the most common for battery energy storage systems, with their high energy density, light weight and rechargeable ability. To explain battery technology, a Li-Ion battery will be used as an example.

A battery consists of several essential components, including an anode, cathode, separator, electrolyte, and two current collectors (positive and negative). The anode and cathode serve as the reservoirs for the lithium, while the electrolyte transports positively charged lithium ions from the anode to the cathode and vice versa via the separator. This ion movement leads to the generation of free electrons in the anode, resulting in the accumulation of charge at the positive current collector. The electrical current flows from the positive current collector, powers a device, and then returns to the negative current collector. The separator plays a crucial role in impeding the flow of electrons within the battery. During the discharging phase of a battery, as it supplies electrical current (in this case to the grid), the anode relinquishes lithium ions to the cathode, initiating the transfer of electrons from one terminal to the other. Conversely, upon connecting a device to the battery, the cathode yields lithium ions that migrate towards and are received by the anode.[71]

2.6.2 BESS structure

The battery is only one part of the total system structure. There are various components required in an energy storage system for it to function as efficiently as possible and to mitigate power fluctuations. In addition to the battery the system includes components such as monitoring and control systems and a power conversion system. Cell-based batteries, such as the Li-Ion battery, are composed of discrete cells that are aggregated into modules, which are, in turn, organized into packs. The battery management system encompasses monitoring and control systems that are integral to ensuring the safety and optimal performance of a battery. Specifically, the battery management system serves to regulate the charge and discharge of a battery, and guards against individual cells from being overcharged. The implementation of such measures is crucial for safeguarding the safety and reliability of the battery. Depending on the specific battery type, the focus of cell and component monitoring may vary to address particular concerns. For instance, thermal monitoring and controls are essential in lithium-ion battery packs due to their susceptibility to overheating. Furthermore, it is also necessary to integrate power electronics into the system to enable communication with the local utility and conform to grid interconnection mandates. Notably, conventional electrical systems operate on AC, whereas batteries supply electricity in the form of DC. Consequently, a power conversion system comprising bi-directional inverters is essential to convert the DC power from the battery to AC power for either grid utilization or on-site demand. Following the conversion to DC power, an AC flow directed back to the battery for recharging necessitates the use of a rectifier.[72]

2.6.3 Markets

Global market

According to the World Economic Forum, the global demand for batteries is expected to increase from approximately 282 GWh in 2022 to around 2,623 GWh in 2030, corresponding to an annual growth rate of approximately 25% which is shown in figure 2.19 below. This growth is primarily driven by the rapid electrification of the transportation sector. Nearly 90%, or 2,333 GWh, of the projected demand for batteries globally in 2030 is related to the transportation sector, with the remainder being largely associated with energy storage by electricity producers. The significant decline in the cost of lithium-ion batteries has been crucial for the rapid introduction of batteries in the market. Between 2010 and 2019, the price of lithium-ion batteries decreased by 87%. Thanks to new manufacturing techniques and simplified designs for the assembly of battery cells into battery packs, prices are expected to decline by a further 30% by 2030. However, due to the sharply rising prices of raw materials such as lithium, cobalt, and nickel, these projections are now considered more uncertain. Since the end of 2021, the price of batteries has generally increased, while shortages of raw materials and components have made the delivery situation more uncertain.[73]

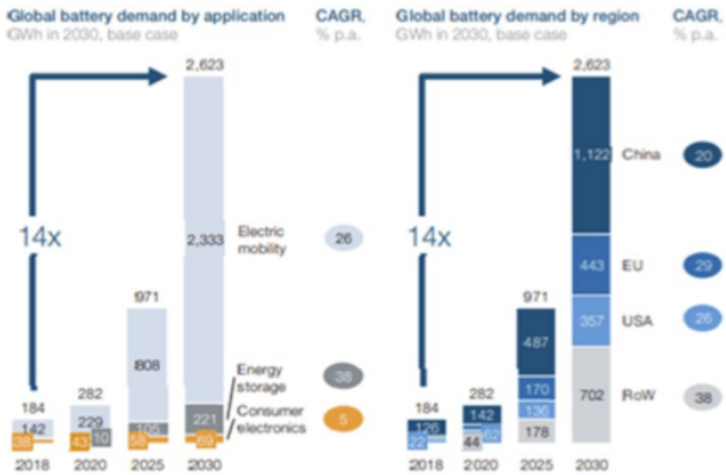

Figure 2.19: Global battery demand by application and region.[73]

Although pumped-storage hydro power currently dominates the grid-scale storage industry, grid-scale batteries are rapidly catching up and are projected to drive most of the storage growth worldwide. As of the end of 2021, the total installed capacity of grid-scale battery storage was approximately 16 GW, with the majority of this capacity added over the previous five years. Installations of grid-scale battery storage continued to increase strongly in 2021, rising by 60% compared with 2020, with over 6 GW of storage capacity added in that year. The market was led by the US, China, and Europe, each registering GW-scale additions.[74]

China has a significant presence in the global supply chain for Li-ion batteries, with control over 80% of the world's Li-ion battery raw material refining capacity, 77% of cell production capacity and 60% of battery component manufacturing capacity.[75] Recent research deem European manufacturers would have to invest an extreme of $102 billion across the supply chain to meet their domestic demand for batteries in 2030.[76]

European market
Batteries are poised to play a crucial role in realizing the objectives of the European Green Deal and the implementation of the REPowerEU plan. They offer the potential to reduce the reliance on fuel imports in the transport sector, optimize the use of renewable electricity and minimize curtailments. It is expected that by 2030, there will be over 50 million electric vehicles (EVs) on the roads in the EU, which would require at least 1.5 TWh of batteries, in addition to over 80 GW/160 GWh of stationary batteries. While lithium-ion batteries are expected to continue to dominate the market beyond 2030, there is ongoing research and development of other battery technologies.[75]

The vast majority of lithium-ion battery mass production in the EU during 2021 was conducted by Asian manufacturers who had established their operations in the EU, primarily in Hungary and Poland. However, the EU's position in the market is expected to grow gradually as new gigafactories are constructed, particularly in Germany and Sweden. At the end of 2021, Swedish company Northvolt announced that it had produced its first battery cell using 100% recycled nickel, manganese, and cobalt, with commercial deliveries commencing in 2022. Northvolt claims to have a highly efficient recycling process that can recover up to 95% of battery metals.[75]

Swedish market
In recent years, Sweden has followed the global trend of integrating grid-scale battery energy storage systems. The Swedish company Vattenfall AB is at the moment developing new battery energy storage systems for implementation at grid-scale, expanding their capacity with approximately 45 MW. Different projects are combining different power generation systems such as wind and solar power.[77] As mentioned earlier, the Swedish company Northvolt is mainly targeting reducing the carbon footprints of batteries, with their cells reducing the carbon dioxide emissions by 80% in comparison with cells produced with coal power. With a broad span of solutions including for the grid, Northvolt targets an annual cell output of 150 GWh by 2030. The company is mainly targeting the increasing demand of battery production within the transportation sector, but recently a grid-scale battery energy storage system was commercialized. The Voltpack Mobile System is a battery storage system delivering sustainable power. It is scalable up to 1.4 MWh, and can be used for integration with solar or wind power generation.[78]

2.6.4 Support schemes

EU
There are plenty of support schemes for increased development and utilization of battery energy storage solutions in the EU. From the European Union themselves, the development of the energy union's all-inclusive governance structure, together with the strategic action plan on batteries has been a significant advancement in facilitating the creation of an industrially competitive, sustainable, and globally integrated battery sector within the European Union.[79]

In 2019, Batteries Europe launched as the European technology and innovation platform of the European Battery Alliance, a collaborative initiative between the European Commission and battery industry stakeholders. The majority of new collaborative research projects on batteries in the European Union are being conducted under the

BATT4EU Partnership, with a total of €925 million earmarked for the current 7-year financial perspective. In parallel, several EU member states have joined forces to form Important Projects of Common European Interest (IPCEI) on batteries research and innovation.[79]

Another support scheme is the European Commission Horizon Europe which is a research and innovation funding programme. Recently mentioned BATT4EU is a Co-programmed Partnership that has been established under Horizon Europe. The primary objective of this partnership is to establish a competitive and sustainable European industrial value chain for e-mobility and stationary applications. As the EU's battery value chain stakeholders can benefit from a coordinated and long-term effort involving industry, research, and the public sector, BATT4EU aims to pool Europe's resources and knowledge to provide predictability.[80].

There is also investment support from the European Investment Bank (EIB). In the year 2020, the Bank invested in battery-related initiatives to an amount exceeding €1 billion. This figure corresponds with the level of financial aid furnished by the EIB during the phase of 2010-2019, whereby battery-oriented ventures were provided with €950 million of funding, contributing to a total of €4.7 billion of project expenditures. The annual amount of investments from the EIB has been growing ever since, and it has been made possible through a prosperous collaboration with the European Commission, which has fostered novel financial instruments.[81]

Sweden
The Swedish Government has been proactive in supporting battery storage development and utilization, recognizing the potential of battery energy storage system technology to facilitate the transition to a more sustainable energy system. One scheme is Batterifondsprogrammet. If you research within recycling of batteries or within batteries for stationary or vehicle applications, you are welcome to apply for support from the Swedish Energy Agency. This is aimed at supporting practical, behavioral, and regulatory factors that can accelerate or impede the production, use, reuse, submission, and recycling of batteries. The program also seeks to promote resource efficiency and circular economy principles, support research on safety issues, and increase the long-term competitiveness of Swedish industry in the battery area. The program is open to applications from industry, academia, institutes, and the public sector.[82]

2.7 Wind Power Battery Energy Storage Hybrid System

Wind turbines and battery energy storage systems are increasingly being coupled to mitigate variability and uncertainty in wind energy generation. A hybrid energy system can offer economic and operational benefits that surpass the cumulative advantages of its individual components. Wind-storage hybrid energy systems have recently garnered commercial attention, owing to their ability to supply dispatchable energy and grid services, despite the variable nature of the wind resource. As mentioned before there are many different storage solutions optimal in different projects and cases. Some recent studied solutions are projected to be very promising, but are still in very early phases of development. For this thesis a Li-ion BESS is analyzed since most of the research and commercialized battery storage solutions include this type of battery chemistry.

2.7.1 Structure

In wind power farms, consisting of multiple wind turbines, energy storage is usually located as a central storage. This requires additional equipment such as a dedicated power converter, switchgear, and transformer.[83] The coupling of a hybrid system can occur on a shared DC bus, AC bus, or both, depending on the wind turbine type. A review paper [84] provides an overview of power electronics topologies and control strategies for hybrid systems.[83]

One way of configuring a hybrid wind-storage system is to use an AC-coupled hybrid system. An AC-coupled wind-storage system is designed to integrate wind power generation and battery storage on a common AC bus, as illustrated in figure 2.20 below. This system employs an industry-standard phase-locked loop feedback control system to synchronize the phase of the generated power with that of the grid. Grid-side inverters are utilized to match the voltage and phase of the grid's sinusoidal AC waveform, ensuring that electrical power from the wind turbines is efficiently and safely integrated into the grid. One advantage of AC-coupled systems is their use of standardized equipment that is readily available in the market, making them easy to install. In addition, the battery storage can be decoupled from the wind turbine output, allowing the system to be sized and operated based on the energy and grid services that the project will provide. As a result, both the wind turbine and battery can operate at full capacity, which increases the total capacity of the system. This, in turn, can lead to fewer charging/discharging cycles for the battery than in a DC-coupled system.[85]

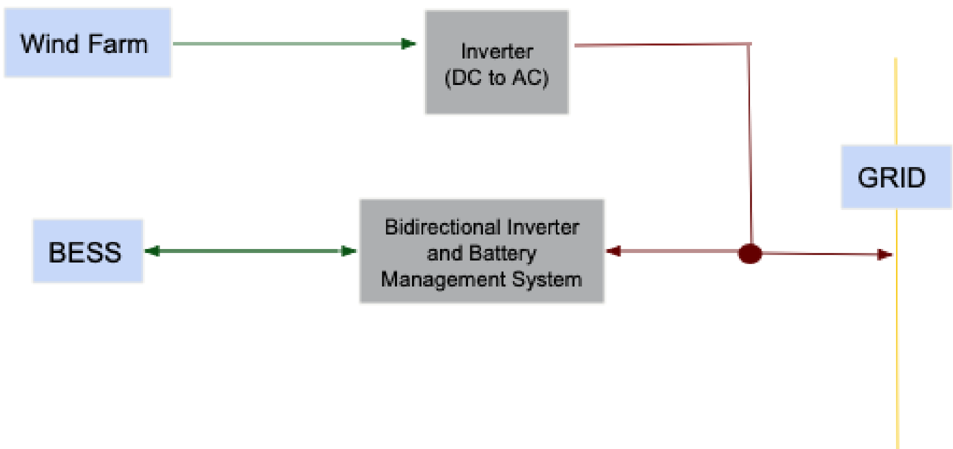

Figure 2.20: Common topology of an AC-coupled wind-storage hybrid system.

Another type of configuration is a DC-coupled hybrid system. In a DC-coupled wind-storage system, the wind turbine and battery are integrated at the DC link behind a common inverter, which rectifies the electricity generated by the turbine and couples it with the battery. The grid-side inverter can be either one-directional or bidirectional, and the battery can store energy from both the turbine and the grid. This is displayed in figure 2.21 below. The use of a bidirectional inverter allows for additional value streams for the battery, such as energy-shifting and energy arbitrage.[83][86]

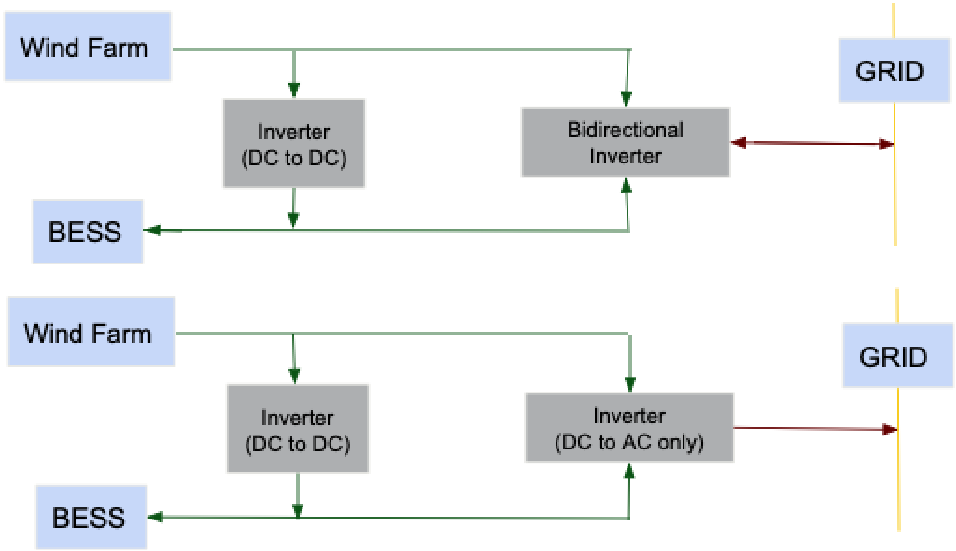

Figure 2.21: Schematics of DC-coupled wind-storage systems.

2.7.2 Specific costs

The main costs affecting the system is the capital costs, which include the initial investment in equipment and installation, and the operating costs, which include ongoing maintenance, replacement of components, and the cost of electricity needed to charge the batteries. This subsection aims to help answer research question number one on the costs associated with a BESS installation.

Battery module

The battery cells account for large fraction of the costs. Since Li-ion batteries are a research-intensive industry, R&D costs also account for a part of the module costs. Included is also the electronics of the module, which mainly are mechanical and electronic components. The type of battery chemistry is of course one major factor affecting this cost, but also the energy and power capacity (storage and discharge rate) of the module. A battery module with higher energy and power capacity tend to increase the costs.[87][88]

Balance of System (BOS)

Typical BOS costs for Li-ion BESS include the module containers, climate control, power management system, fire suppression system, and related components. The BOS components can be divided into electrical and structural BOS. Structural BOS includes foundation, battery containers and inverter house. Electrical BOS includes conduit, wiring, DC cable, energy management system, switchgear, transformer, and monitor and controls for each container. The total BOS is determined by the number of containers, transformers and inverters.[89]

Inverter

The cost of the inverter vary depending on factors such as system size and capacity and type of inverter used. Central inverters are typically used in larger utility-scale BESS applications and can handle high power levels, and are crucial to invert the DC stored to AC for grid transmittance. They are typically designed as a single large unit and are installed in a dedicated inverter building or container. Increased size of the system often implies larger inverter and O&M costs for the inverter alone.

Soft costs

Soft costs refer to various expenses involved in the BESS installation, including installation labor, sales tax, EPC overhead and profit, developer costs, permitting and land acquisition.[89]

O&M costs

These typically include the costs associated with operating, maintaining, and repairing the system over its lifetime. These costs can vary depending on a number of factors, including the size and capacity of the system, the specific requirements of the site, and the type and quality of the components used in the system. The monitoring and control costs include the cost of operating and maintaining the control and monitoring systems used to manage the performance of the energy storage system. Also, the maintenance and repair costs include the cost of regularly inspecting and maintaining the energy storage system, as well as the cost of repairing any issues that arise. This can include the cost of replacing worn or damaged components, as well as the cost of labor and equipment needed for maintenance activities. The O&M costs also includes insurances and warranties.[88]

Merging and future costs

In some cases, there may be electrical components already installed at a wind farm that can be utilized by a BESS when integrating it with the grid. This will depend on the specific configuration of the wind farm and the existing electrical infrastructure. These components would typically be circuit breakers, communication equipment, and other interconnection equipment. The costs associated with battery storage have undergone a rapid evolution over the past few years, rendering an update to existing storage cost projections essential for long-term planning models and other associated activities. Research findings present a broad range of storage costs encompassing current and future costs. Despite a notable range in the projected costs, there is a clear indication of a decline in capital costs, with projected reductions of 14-38% by 2025.[90]

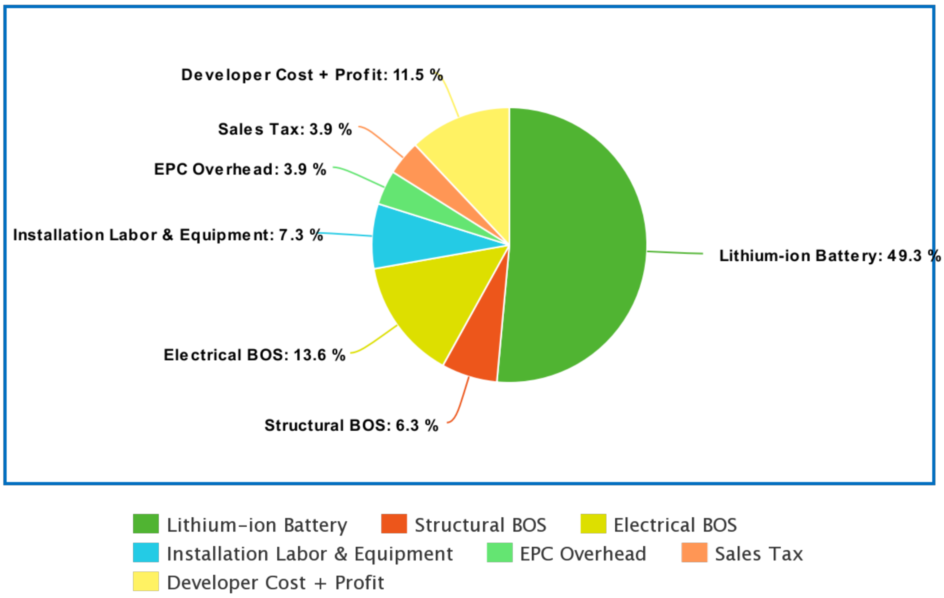

Figure 2.22: Specific cost section BESS.

2.7.3 Potential

The services offered by battery energy storage systems are many. The integration of high levels of wind energy into the grid presents a significant challenge for grid operators due to the variability and uncertainty of the energy production, resulting in fluctuating power generation. BESS presents a solution to this challenge by providing a wide range of services that can effectively facilitate the integration and consumption of renewable energy. BESS systems can offer voltage and frequency support to transmission and distribution systems, which helps to mitigate voltage and frequency deviations that result from the erratic nature of renewable energy sources.[91][92] From a power systems perspective, BESS provide three key resources: power regulation, energy storage and discharge, and capacity resources. Grid applications can leverage the potential of BESS to quickly and bidirectionally ramp power, particularly for tasks such as frequency regulation, voltage control, and smoothing of the wind energy generation to reduce power fluctuations. BESS can also be utilized for energy arbitrage, wherein large amounts of electrical energy can be stored and released for economic benefits.[93]

Energy arbitrage

The use of BESS for energy arbitrage involves the charging of the BESS with cheap energy from the wind farm (or from the wholesale energy market), which is then discharged during times of higher demand and more expensive energy prices. The optimization algorithms for energy arbitrage can assume BESS as either a price taker or a price maker, with the latter potentially earning more profit through strategic bidding in the wholesale energy market. Different optimization frameworks have been proposed for BESS as a price maker in the wholesale energy market, including coordinating charge and discharge bids to influence local marginal prices and considering ramping limits and wind generation uncertainty in strategic operation. It is suggested that the potential arbitrage revenue of BESS may be overestimated if their impact on electricity prices is ignored.[94]

2.7.4 Challenges

Despite the progress made in integrating wind power generating systems with BESS, there is still significant room for further research in this area. Numerous challenges need to be addressed to enable successful utilization of BESS in wind power applications. One major challenge is the cost of installing a BESS. As such, cost-effective and efficient BESS technology is needed to entice wind farm owners. Additionally, the selection of an appropriate battery storage system to match the overall system dynamics is crucial. Furthermore, the inclusion of a BESS in wind farms necessitates an additional bi-directional converter, making the development of a cost-effective topology critical for optimal BESS utilization.

Active and reactive power management is a significant challenge in integrating wind power generating systems with BESS. Active power is the real power that is used to perform useful work, while reactive power is the imaginary power that is required to maintain the voltage level in the power system. In a wind power generating system, the power electronics interface is responsible for managing the active and reactive power flow between the wind turbine and the grid. BESS can be used to improve active and reactive power management by providing fast and accurate responses to changes in wind power output. This requires additional power electronics. Development of advanced control algorithms are crucial for development to improve the efficiency, flexibility, and cost-effectiveness of these systems.

Accurate forecasting is also important for effectively utilizing BESS in wind power systems. To address this challenge, researchers are developing improved short-term wind forecast techniques to enhance the dispatchability of wind farms. Furthermore, the application of short-term wind forecasting in short-term energy markets is being explored, which can help to improve the economic viability of wind power systems with BESS. With more accurate forecasting, wind power systems with BESS can participate more effectively in energy markets, providing additional revenue streams for wind farm owners.

2.7.5 Existing and planned projects

There are plenty of existing projects where BESS have been implemented together with wind farms, all over the world. This demonstrate the increasing trend of BESS implementation for increasing reliability and performance. Since the recent technology developments and cost decreases, it is likely that we will see even more implementations in the near future.

Vestas manage plenty of projects including BESS together with a wind farm. In 2012, the Lem Kær hybrid power plant was erected, which integrated a fully operational grid-connected battery energy storage system, consisting of two batteries, into an already existing 12 MW wind power plant. The project marks a significant milestone in the realm of large-scale wind power plants as it represents the first instance where wind power is combined with electrical storage technology and connected to the grid. Also, Kennedy Energy Park Phase I is a hybrid power plant with a total installed capacity of 60.2 MW, comprising of 43.2 MW of Vestas V136-3.45 MW wind turbines, 15 MW of solar PV power capacity, and 2 MW/4 MWh of Li-ion electrical storage.[95]

There are also plenty of projects in early project phases planning on integrating BESS with offshore wind farms. For example, Pattern Energy has successfully secured financing for an offshore wind project located in northern Japan. The project will involve the integration of a 100MW BESS in addition to 112MW of wind power generation from 14 Siemens Gamesa 8MW wind turbines. Pattern Energy has received funding from several Japanese financial institutions along with French multinational investment bank, Societe Generale.[96] Regulatory authorities in the UK have authorized renewable energy developer Ørsted to proceed with the construction of a utility-scale battery energy storage project that will serve the Hornsea 3 offshore wind farm. The South Norfolk Council, responsible for the planning of the region, has approved the storage facility, featuring Li-ion batteries, which will be built on a 35-acre site adjacent to Hornsea 3's onshore substation. The storage project will deliver energy into the UK's national power grid when required. Hornsea 3, situated in the North Sea, is a 2.4 GW installation currently under construction.[97]

2.7.6 SWOT

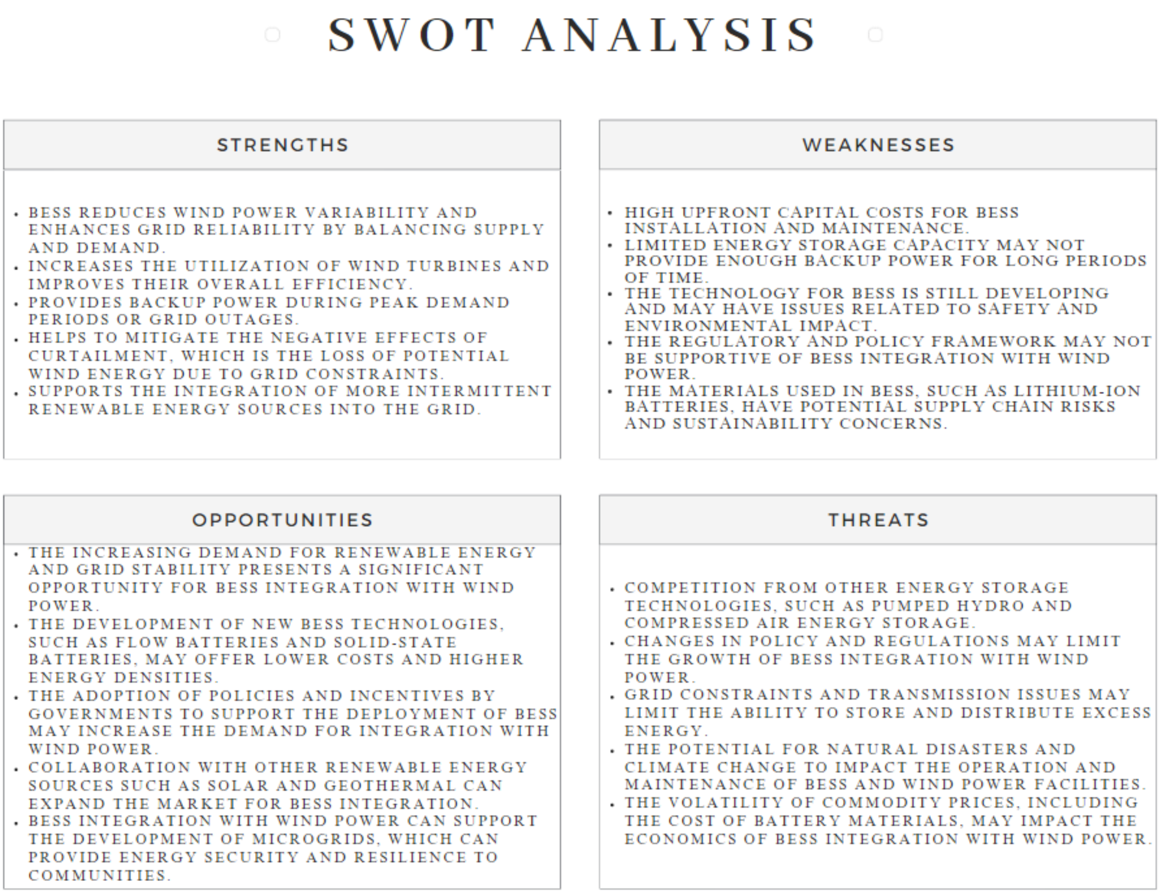

Figure 2.23: SWOT analysis for a Wind Power Battery Energy Storage Hybrid System.

3 Methodology

In this chapter details of the case study wind farm Neptuni are described, followed by combining it with a possible floating PV system, a wave energy system and a battery energy storage system. Different scenarios of the future will be reviewed, followed by technical analysis of the combined wind farm and method of completion and an economical analysis. The data collection is further explained in chapter 4.

3.1 Wind park site description

The Neptuni project is in an early stage of development, meaning that RWE Renewables is in the first stages of examining the technical and environmental conditions for implementation of an offshore wind farm in the area. The plans are at the moment indicating for the wind farm to be one of the largest in the Baltic Sea and would be crucial to strengthen the energy supply in southern Sweden. There is a large demand for renewable energy in the region which is required to be able to electrify industries and the transport sector. The area is located northeast of Öland's northern cape, approximately 5–20 km from the coast, and is in Sweden's economic zone, where Sweden has sovereign rights to explore and exploit the natural resources with man-made facilities as well as for the protection and preservation of the environment. The area RWE is investigating is approximately 640 km^2 large, and a possible future wind farm would have an area of around 300 km^2. The entire area in question is designated as being of national interest for wind farms. There is a great potential for wind power with both good wind conditions and a limited water depth.

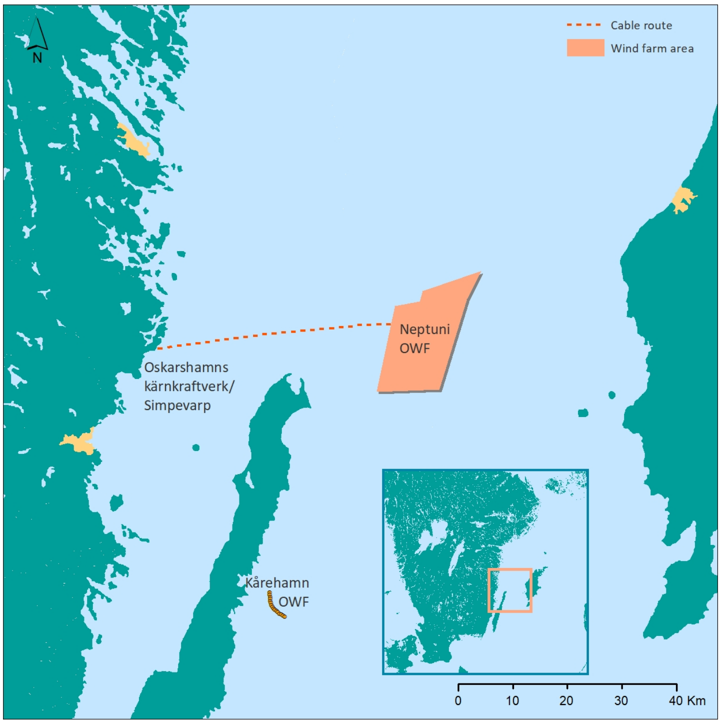

Figure 3.1: Location of the Neptuni project.

Since the project is still in its early stages there are still multiple permits to apply for in different stages of the process, which will provide a basis to the decisions to be made about absolute location and design of the park, but also for a future route for the power transmitting cable required for the wind farm to transmit the generated power to shore. The size of the wind farm and the cable capacity are still unknown, but assumes values suggested by RWE in the analysis.

3.2 Technical Analysis

3.2.1 System modeling

To assess the practicability of the previously described hybrid power system, a precise mathematical model is essential. This model will facilitate a comprehensive technical and economic analysis. The primary objective of the technical analysis is to appraise the overall energy output of the combined hybrid power system studied. This evaluation encompasses three principal stages:

- Based on historical wind data provided by RWE, calculations of the potential energy production of the Neptuni wind farm will be calculated;
- Based on historical open source data for nearby sites provided by SMHI the separately potential energy produced (and discharged) of a floating PV system, a wave energy system and a battery energy storage system will be calculated for different installed capacities;
- These datasets are then combined to estimate the total energy production (or discharged) from the system.

3.2.2 Offshore wind model

The wind speed of the specific location of the Neptuni wind farm was provided by RWE, at a height of 10 m. The measurements are on site, between the dates of Jan 1st 2021 and Jan 1st 2022. The wind power generation is heavily affected by the wind speed variation, which in turn is due to altitude and friction the air experiences as it moves across the earth's surface. To characterize the impact of the height and roughness of the blowing surface wind speed, this analysis will use eq.3.1 below:

$$v_{hub} = v_{10}(\frac{z_{hub}}{z_{10}})^a \tag{3.1}$$

where v_{hub} is the wind speed at the hub height chosen for the analysis, v_{10} is the wind speed at 10m provided by the data set, z_{hub} is the chosen hub height, z_{10} is 10 m and a is the friction coefficient that is a function of the terrain. The friction coefficient is assumed to be 0.1 which is commonly used for open water terrain as of this case.

Calculating the potential power output of the wind farm and implementing limitations of the wind farm are done using various data and assumptions. The offshore wind farm is assumed to consist of 83 GE Haliade-X 17 MW turbines, giving a total installed capacity of 1,411 MW and a similar size as the Södra Victoria farm, another project of RWE Renewables. To simulate the power output from the wind farm a given power curve for the chosen wind turbines is used. This is shown in eq.3.2:

$$P_{wt}(h) = f(v_{hub})N_{wt} \tag{3.2}$$

where f is the function of power generated at a certain wind speed for one GE Haliade-X 17 MW and N_{wt} is the number of wind turbines installed in the wind farm. To make the simulation more realistic, it is important to include the issues accompanied with the installation of a wind farm which decreases the total conversion efficiency of the park. Losses included when calculating the wind farm performance are total turbine interaction effect included here are wake losses, availability (turbine, balance of plant, grid, electrical (operational electrical efficiency), performance (generic power curve adjustments, hysteresis, site specific power curve, curve adjustment) and environmental (icing, temperature shutdown, site access). These losses are accounted for in a collected document of power generated from Södra Victoria wind farm (similar size as Neptuni), resulting in a maximum power output of 1,360.8 MW and therefore an overall efficiency of 96.4% with the installed capacity of 1,411 MW. Also, all machinery experiences an unrecoverable loss in performance over time. Falling availability and overall performance of the wind turbines are common with age, and is assumed to be 0.6% per year, according to a research made in 2014.[98] Therefore, the power production over time is described in eq.3.3 below:

$$P_{wt,N_{year}} = \sum_{n=1}^{N_{year}} P_{wt,1}(1 - 0.006)^{n-1} \tag{3.3}$$

3.2.3 Floating Solar PV model

The hourly power output from the floating solar PV system is calculated with a given solar irradiance of the site together with an assumed panel area, panel efficiency and performance ratio to assume for system loss. The panels used in this analysis are assumed to be 1.76 m^2 monocrystalline silicon panels with a maximum power rating of 400 W_p and panel efficiency of 22.6%. The panel efficiency is a function of ambient temperature, extracted from experts from JA Solar and RWE. Other losses include electrical losses (2.71%), temperature losses (2.3%), irradiance losses (2.03%) and soiling losses (2%). Losses including conversion by inverters are accounted for in the performance ratio. The hourly energy generated from a solar panel is calculated with eq.3.4:

$$P_{PV}(h) = PR\eta_{PV}A_{PV}G(h) \tag{3.4}$$

where P_{PV} is the hourly generated power of one solar panel, η_{PV} is the panel efficiency, PR is the performance ratio, A_{PV} is the panel area and $G(h)$ is the solar irradiance per hour. In order to calculate the power output from the solar farm of a certain capacity the hourly generated power should be multiplied with a total number of solar panels. Therefore, hourly floating solar PV farm power outputs are calculated with eq.3.5:

$$P_{PV_{tot}}(h) = N_{PV}P_{PV}(h) \tag{3.5}$$

where N_{PV} is the number of solar panels.

Similar to wind turbines, the efficiency of a solar panel decreases over its lifespan, and a precise quantification of this decline, also known as the degradation rate, is crucial for all stakeholders, including utility companies and researchers. On average, according to a study made [99], the efficiency of solar panels decreases by 0.5% per year. Using eq.3.6, the total energy production of the solar farm over its lifetime can be calculated:

$$P_{PV,N_{year}} = \sum_{n=1}^{N_{year}} P_{PV,1}(1-0.005)^{n-1} \tag{3.6}$$

3.2.4 Wave Energy Converter System model

Wave heights and periods are collected as open source data from SMHI, providing a basis for every hour of the year of 2021. In the context of WECs operating in irregular seas, it is common practice to use a power matrix to represent their power generation performance. The power matrix is typically obtained by modeling a specific WEC, such as the Reference Model 5 (RM5) OSWC, for a range of sea states and calculating the average power output for each bin. The power matrix is gathered from official documentation from the National Renewable Energy Laboratory (NREL) on the RM5. To derive the electrical power matrix, NREL multiplied the mechanical power matrix by a power conversion efficiency factor, such as the power conversion chain efficiency (PCC), and constrained the maximum electrical power output to the rated power of the WEC. The PCC efficiency was assumed to 82.5% and the capacity factor to 30%.[57] The power matrix in kW for a RM5 OSWC is displayed in fig.5.1 below.

Significant Wave Height, Hs [m]	Energy Period, Te [sec]													
	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5
0.75	12	17	19	21	23	22	21	19	19	17	16	14	13	12
1.25	32	41	45	48	52	49	45	42	40	36	35	32	29	27
1.75	58	72	77	82	87	81	74	70	67	60	58	53	49	45
2.25	91	110	116	119	127	117	108	102	97	86	83	76	71	65
2.75	131	155	160	163	172	159	145	138	130	116	110	101	95	87
3.25	175	204	209	210	221	203	186	176	166	148	140	130	121	110
3.75	224	259	262	262	272	250	228	215	205	183	173	160	148	135
4.25	277	317	319	316	327	299	272	257	246	220	207	192	177	162
4.75	335	360	360	360	360	349	317	302	288	259	243	225	209	190
5.25	360	360	360	360	360	360	360	349	333	299	280	261	242	220
5.75	360	360	360	360	360	360	360	360	360	340	319	299	276	251
	5.2	6.4	7.5	8.7	9.9	11.0	12.2	13.3	14.5	15.7	16.8	18.0	19.1	20.3
	Peak Period, Tp [sec]													

Figure 3.2: Electrical power matrix (in kW) for a RM5 OSWC.[100]

In order to calculate the power output from the wave farm of a certain capacity the hourly generated power should be multiplied with a total number of wave converters. Therefore, hourly wave farm power outputs are calculated with eq.3.7:

$$P_{WEC_{tot}}(h) = P_{WEC}(h)N_{WEC} \tag{3.7}$$

where $P_{WEC}(h)$ is the power generated every hour for one RM5 OSWC and N_{WEC} is the amount of wave energy converters installed in the wave farm.

3.2.5 Battery Energy Storage System model

One of the most discussed and used applications of a utility-scale BESS is energy arbitrage, where the BESS charges energy when the energy prices are low and discharge the energy when the energy prices are high. This allows the system to obtain an economic benefit. To develop a suitable energy arbitrage strategy, it is crucial to determine the behavior of energy prices for the following day. Several models for price forecasting have been proposed throughout the years. These include multi-agent models, which simulate the offers of participating agents to obtain price forecasts; seasonal models, which consider the periodicity of the market and the impact of significant events on its behavior; statistical models, which are based on econometric analysis of the market; and models based on computational intelligence, such as neural network architectures and artificial intelligence, which incorporate elements of learning, evolution, and adaptation. In this study, we will use a statistical based operating strategy, where charge and discharge hours are defined seeking that the BESS operate one cycle per day. These hours are defined by a statistical analysis using the historical prices of each hour for the previous 7 days. For each of the hours (1-24) the hours with the lower and higher prices are determined and used to establish the charge and discharge hours for the next day.

Energy arbitrage plans to maximize the cash flow throughout the planning horizon, as presented in eq.3.8 below:

$$Max \sum_{t \in T} EP_t \cdot (P_t^{dc} - P_t^{ch}) \cdot \Delta t \tag{3.8}$$

where t refers to the time period, T refers to the entire simulation horizon, Δt is the absolute time between time periods, EP_t is the energy price at the time period t and P_t^{dc} and P_t^{ch} is the discharge and charge power to either the grid or from the wind farm.

In order to simulate a realistic operation of a BESS, restrictions are needed to be established. The BESS can't charge more power than the difference between the system's energy storage capacity E_{cap} times the maximum state of charge SOC_{max} and energy level E_{level} at the previous time period, divided by the BESS round trip efficiency η_{rt} as presented in eq.3.9:

$$\Delta t \cdot P_t^{ch} \leq (E_{t-1}^{cap} \cdot SOC_{max} - E_{t-1})/\eta_{rt} \tag{3.9}$$

Important to clarify is that the battery capacity isn't constant over time, because of the degradation due to its use. This is modeled later in this section. By the same premises, the BESS cant discharge more energy than the difference between the energy level and the energy storage capacity times the minimum state of charge SOC_{min}, divided by the round trip efficiency, presented in eq.3.10 below:

$$\Delta t \cdot P_t^{dc} \leq (E_{t-1} - E_0^{cap} \cdot SOC_{min})/\eta_{rt} \tag{3.10}$$

The SOC_{max} and SOC_{min} are defined to prevent the integrity of the BESS. Values of these are assumed later in the thesis. Another important factor to take into account is the degradation of the BESS as they are used, which mainly is caused by wear of the electrolyte due to the stress generated by the charge/discharge cycles. In eq.3.11, a new capacity after degradation is calculated together with a degradation rate β:

$$E_t^{cap} = E_{t-1}^{cap} - \beta \cdot E_0^{cap} \tag{3.11}$$

Figure 3.3 display a flow chart of the BESS operation, where t is the specific hour of the year, $\overline{EP}_{low}$ and $\overline{EP}_{high}$ are the hours with the lowest and the highest prices respectively.

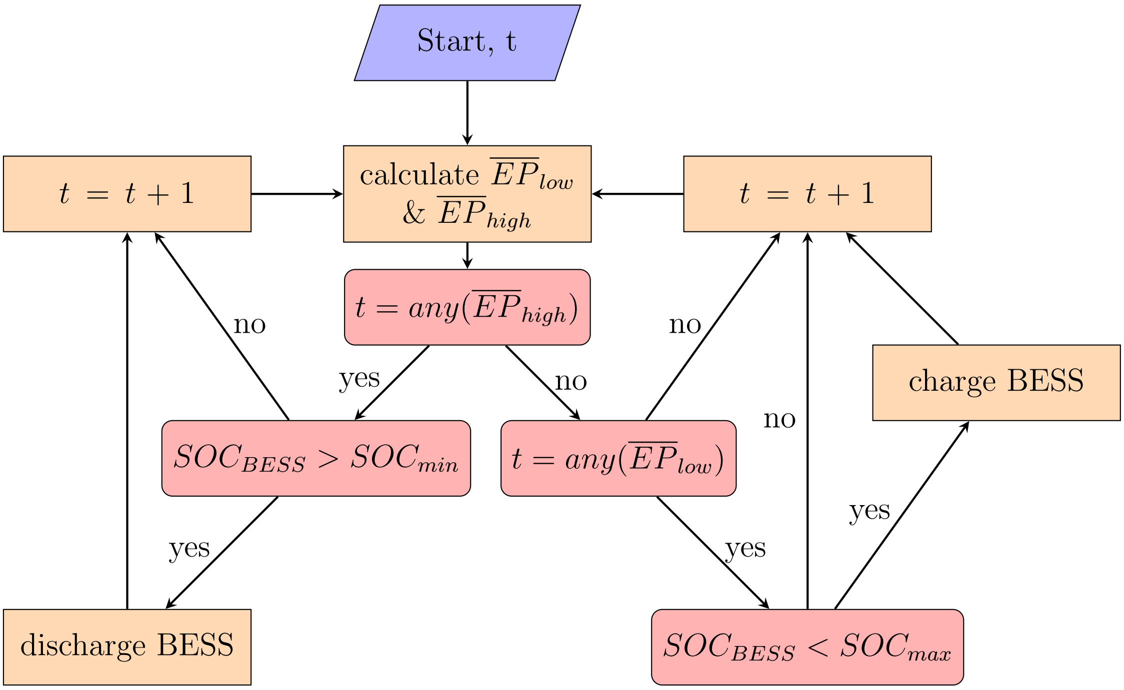

Figure 3.3: Flow chart of the BESS system model.

3.2.6 Optimizing the hybrid systems

The primary technical limitation of this case is the maximum capacity of the power transmission cable, which can handle a maximum of 1,400 MW of power, thereby restricting the total power output of the hybrid power system to prevent congestion in the transmission cable. The assumption made in this investigation is that if the combined power production of the generation systems exceeds 1,400 MW, the additional generation or storage output must be curtailed, meaning that the system will not deliver full power to the grid during that period. The maximum cable capacity of 1,400 MW is assumed according to limitations from Svenska Kraftnät, where energy producers are limited to connect maximum 1,400 MW to the grid at a single offshore connection point.[101] Therefore, a larger cable or wind farm capacity would require two separate connection points to the grid, and that is not what RWE expects to implement. Therefore, the total power production of the combined energy system can be calculated using the following 3.12:

$$P_{tot}(h) = P_{wt}(h) + P_{other}(h) \leq 1400 \quad \text{for} \quad h \in [1, 8760] \tag{3.12}$$

where P_{other} is the power generated to the grid from the additional generation or storage output examined.

3.3 Economic analysis

The technical analysis results provide an understanding of the potential energy output achievable by integrating power or storage systems with offshore wind farms. The economic analysis objective is to assess the economic worth of the generated energy and to offer insight into the potential costs of such an energy system. Consequently, the initial step of the economic analysis involved determining the economic value of the energy produced.

3.3.1 Market price

In order to calculate the economic value of generated electricity by the complementing generation system or the storage system the market price needs to be forecast. This subsection considers the market price and the value of renewable energy (subsidies).

The market system is complex and influenced by many factors, leading to a fluctuating price and uncertain prediction of the future prices. This study uses the hourly prices from the year 2021, scaled up to the price levels of 2022, together with Svenska Kraftnäts short and long-term market analyses to somewhat accurately forecast the market prices for the next 25 years. This is done by using Svenska Kraftnäts price forecast for the years 2023-2027 together with the average annual price of 2021 from NordPool to calculate the decrease in annual average electricity price over the years, which amounted to a decrease every year by 7.87%, the decrease was estimated by looking at the “normal” years; 2016-2019, before the energy crisis. This decrease every year is used together with the prices for 2021 from NordPool to forecast the prices for 2027, the forecast prices is used together with Svenska Kraftnäts long-term market analysis and two of its scenarios, who had to be scaled up.[1] Two extreme scenarios were also created which represents an extreme increase of prices and an extreme decrease in price. The two price scenarios together with the two extreme scenarios are later used as a guideline in the calculation of the increase or decrease of the resulting 2027 prices until the years 2035 and 2047. The forecast prices over the next 25 years will later be used in the NPV analysis.

3.3.2 Price scenarios

Svenska Kraftnät regularly conducts energy grid market analyses where they try to forecast the future of electricity prices and the electrical grid in Sweden from the view of four different scenarios. Svenska Kraftnäts most recent long-term market analysis was made in 2021 and forecast the period up until 2045. However this analysis does not take into account the recent energy crisis in 2022. To get a better understanding of how the recent energy crisis will affect the energy prices of the near future Svenska Kraftnät conducted a short-term market analysis which ranges from 2023-2027. In this study we will use both the long-term market analysis from 2021 with two of its four scenarios and the short-term market analysis to make somewhat accurate forecasts of the future energy prices.

Scenario 1: Extreme increase

In Scenario 1 the use of electricity is the highest out of all the scenarios, the prices stagnate at 2022 levels until the electrification of the industry and transport sector starts in the year 2027 according to SVKs short-term analysis. During the electrification the prices increase drastically up until the year 2035, after that there is a slight decrease every year until 2047 due to the fact that the production has had time to catch up to the demand. The prices over 25 years are displayed in figure 3.4 below.

[1]Scenario price forecasts had to be up scaled due to the fact that the market price of 2022 was very high.

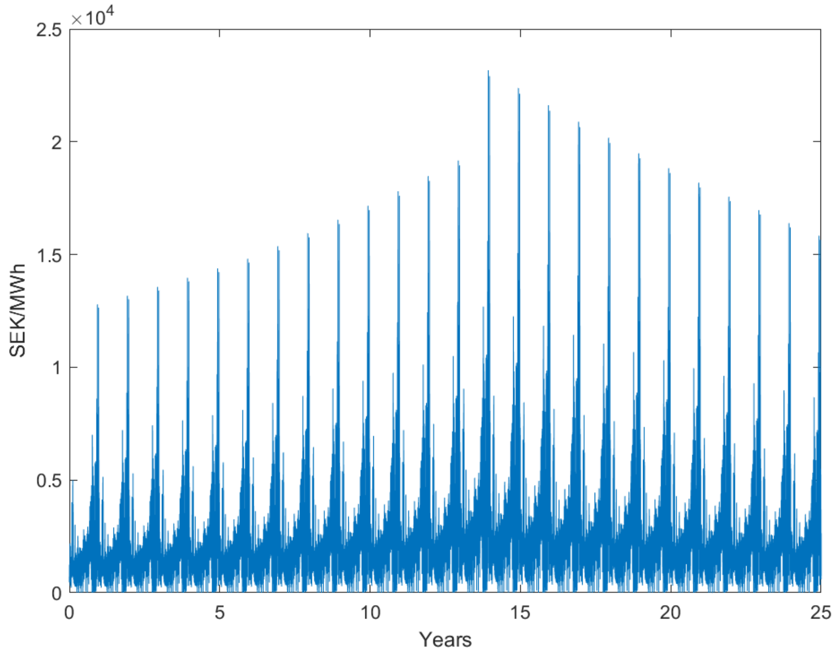

Figure 3.4: 25 year hourly price forecast of price scenario 1.

The average price for each of the 25 years together with the standard deviation for every day of the 25 years are displayed in figure 3.5 below:

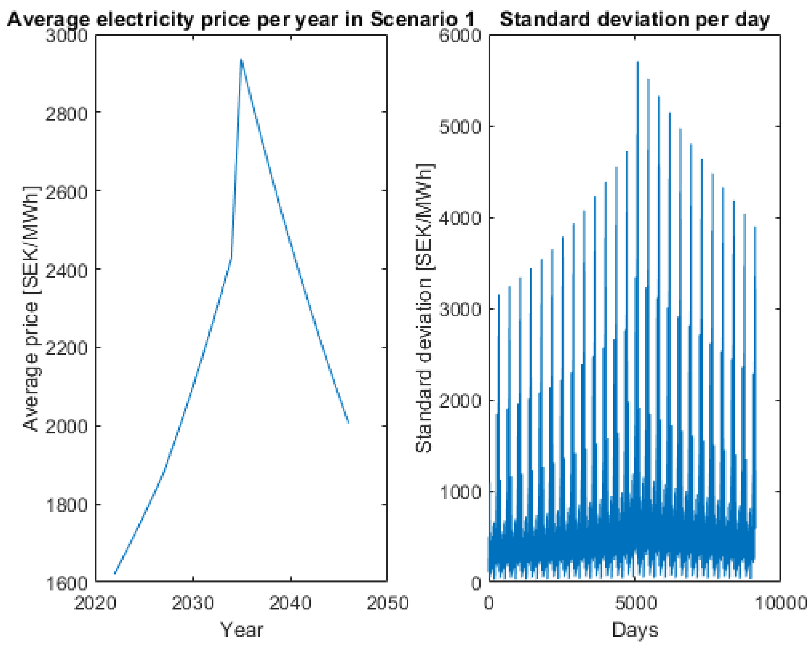

Figure 3.5: Average price each year and standard deviation each day scenario 1.

Scenario 2: "Färdplaner Mixat" Itineraries Mixed (FM)

In Scenario 2 energy consumption is increased compared to today. Wind and solar power is expanding while thermal production is decreasing. Two nuclear reactors gets extended lifetime and are continued to be operated after their 60 year lifetime. The hydrogen economy and sector integration does not get a major breakthrough. The prices over 25 years are displayed in figure 3.6 below.

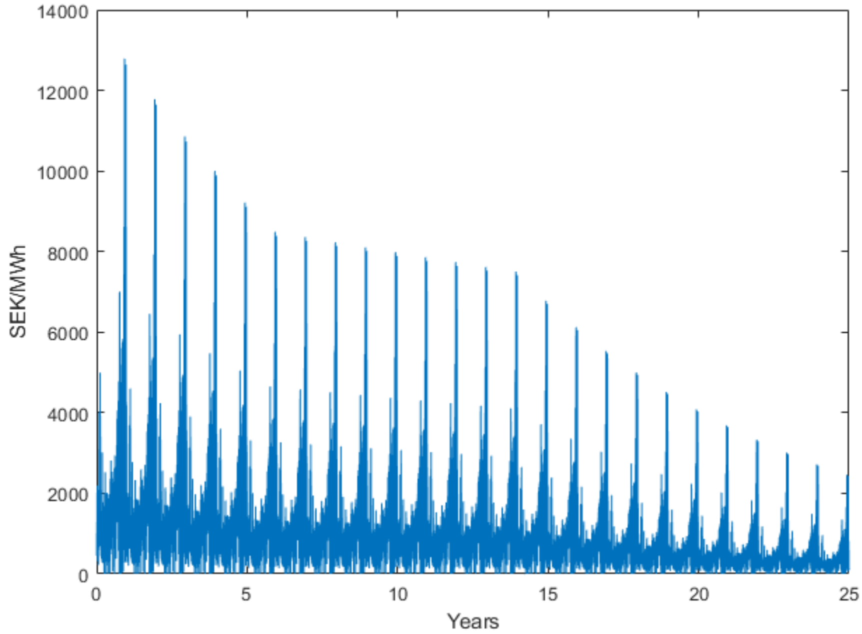

Figure 3.6: 25 year hourly price forecast of price scenario 2.

The average price for each of the 25 years together with the standard deviation for every day of the 25 years are displayed in figure 3.7 below:

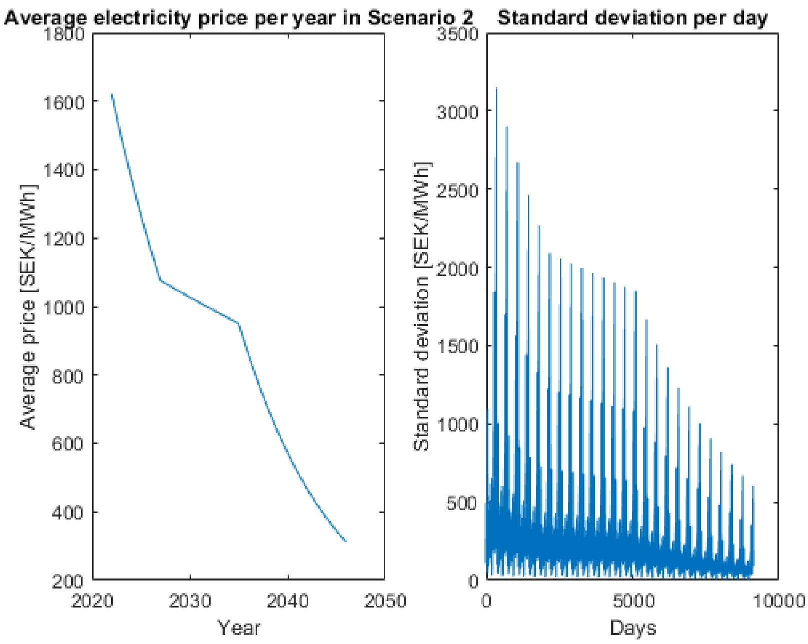

Figure 3.7: Average price each year and standard deviation each day scenario 2.

Scenario 3: "Elektrifiering Planerbart" Electrification Plannable (EP)
Scenario 3 is characterized by a major increase of energy consumption due to the electrification of the industry and transport sector. Renewable energy is further expanded and nuclear power gets continued or increased support. Sweden's primary energy car-

rier is electricity in the transition to a net zero emission society by 2045. Electricity is used in the chemistry industry to produce green fuel for aircrafts and heavy duty vehicles. However, the electrification of the industry sector is not as vast as that for Scenario 1. The prices over 25 years are displayed in figure 3.8 below.

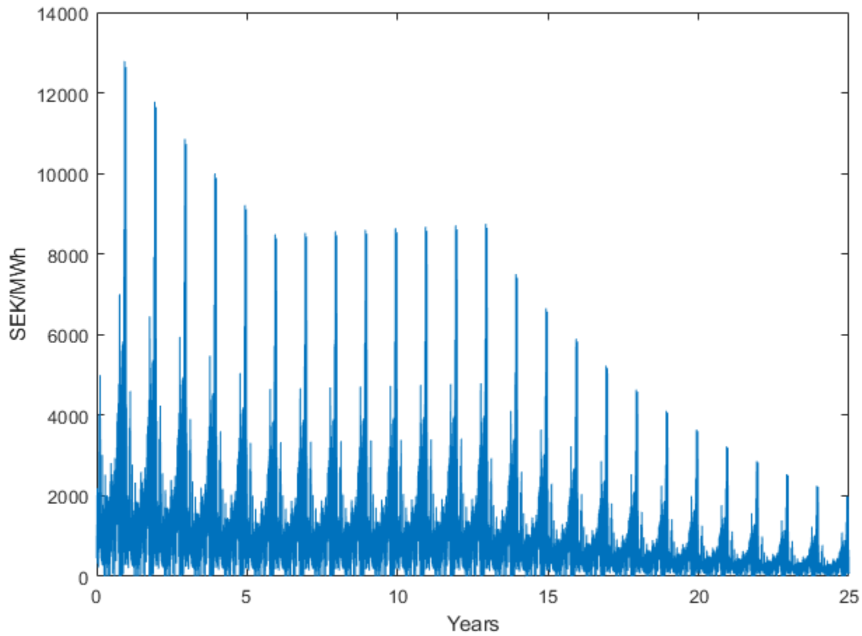

Figure 3.8: 25 year hourly price forecast of price scenario 3.

The average price for each of the 25 years together with the standard deviation for every day of the 25 years are displayed in figure 3.9 below:

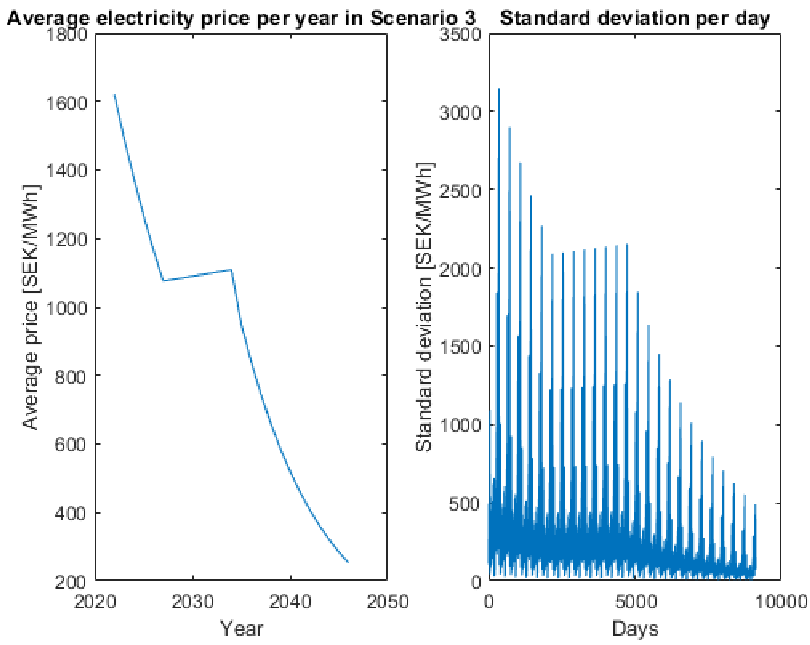

Figure 3.9: Average price each year and standard deviation each day scenario 3.

Scenario 4: Extreme decrease

In Scenario 4 the electricity prices returns to the "normal" levels of 2016-2019 and the electrification of the industry and transport sector is delayed until 2030. The increase in price during the electrification is not as high as that of the other scenarios due to it not having a real breakthrough. Past 2035 prices slightly decrease until 2047 where they stagnate. The prices over 25 years are displayed in figure 3.10 below.

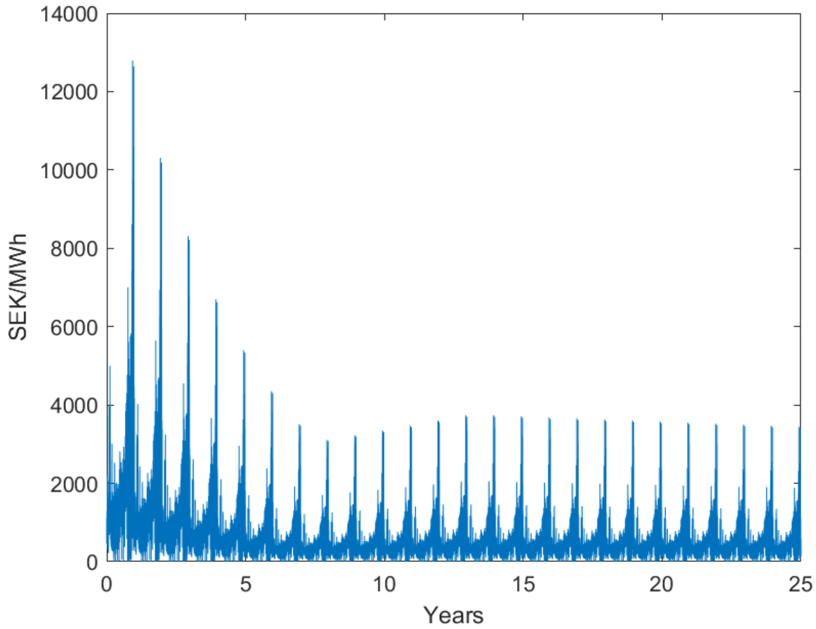

Figure 3.10: 25 year hourly price forecast of price scenario 4.

The average price for each of the 25 years together with the standard deviation for every day of the 25 years are displayed in figure 3.11 below:

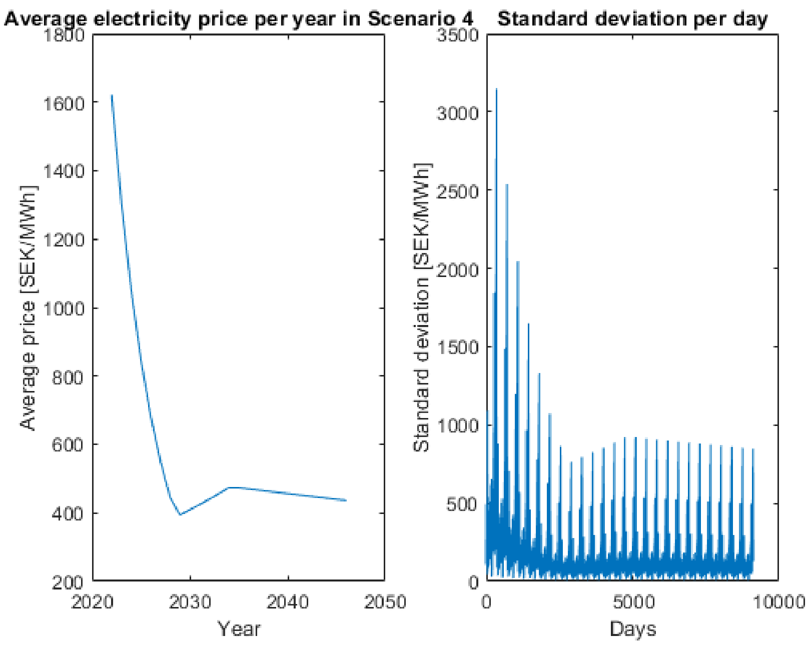

Figure 3.11: Average price each year and standard deviation each day scenario 4.

3.3.3 Value of renewable energy (subsidies)

Energimydigheten offers grants for R&D projects in the energy sector, the grant ranges from SEK 0.09-6 million and can be valuable for projects developing new technology that helps Sweden reach their energy and climate goals. All of the different methods for generation and energy storage are deemed eligible in small scale for this grant.[102]

The EU Innovation Fund offers a grant to projects which have an innovative renewable energy generation solution or projects which incorporate an energy storage system. The grant covers up to 60% of the capital and operational costs and up to 40% of the grant can be payed based on pre-defined milestones before the project is operational. The WEC system and the battery energy storage system are both deemed eligible for this grant. However, the selection is based on factors such as scalability, maturity and cost efficiency.[103]

Although the grants can be utilized to ease the development of new projects this study will not take the grants into consideration due to the fact that the focus lies on the commercialization of the different systems and not just as demonstrators and R&D projects.

3.3.4 Lifetime benefits

The total value for the generated and stored energy were determined previously. The analysis calculates the total revenue of the hybrid systems over their lifetimes. The total revenue for each year is calculated with eq.3.13:

$$\Pi_a = \sum_h E_{tot}(h)\pi_i(h) \tag{3.13}$$

where E_{tot} is total energy transmitted to the grid from the hybrid system, π is the price of energy in €/MWh and $i \in [Scenario1, Scenario2, Scenario3, Scenario4]$. Since the potential risks of investment in the different additional generation or storage systems, interest rates of different values is given by RWE experts. The net present value of the benefits over the energy system's lifetime is calculated with eq.3.14:

$$NPV = F_0 + \sum_{n=1}^{N_{year}} \frac{F_n}{(1+r)^n} \tag{3.14}$$

where F_n is the cash flow of n:th year, r is the WACC, n is the summation index and N_{year} is the total lifetime. The term F_0 is the initial investment and is important. This the capital cost in $€/W_p$ resulting in a large negative value, which a typical investment project involves. Then, a combination of revenues and the expenses which are expected to return the initial investment is F_n considered as below in eq.3.15:

$$F_n = \Pi_{a,n} - Opex \tag{3.15}$$

where $Opex$ is the operation and maintenance expenditures of the additional generation or storage system as a fraction. This leads to eq.3.16 as followed:

$$NPV = \sum_{n=1}^{N_{year}} \frac{\Pi_{a,n}}{(1+r)^n} - F_0 \cdot (1 + Opex \cdot N_{year}) \tag{3.16}$$

The NPV is an indicator of how much value an investment adds to the firm, in this case RWE.

3.4 Power fluctuation analysis

3.4.1 Offshore energy resource calculation

The wind energy resource is estimated in terms of the common metric Wind Power Density (WPD). It is an efficient metric when comparing seasonal resources of energy. The metric of power density considers the resource available in the atmosphere, and allows efficient comparison between different sites or in this case different energy resources. The wind power density is calculated with eq.3.17:

$$WPD(h) = \frac{1}{2}\rho_a W_H^3(h) \tag{3.17}$$

where $W_H(h)$ is the wind speed of the Neptuni site for every hour of the year at the hub height and ρ_a is the air density. WPD is calculated with given measured data from RWE at the Neptuni site.

The given data of solar irradiance is the direct metric given from open source data to compare the wind resource with the solar resource. For the wave energy resource the power density of irregular waves MW/m can be defined based on the linear wave theory, using eq.3.18 below:

$$PD_{wave}(h) = \frac{\rho_w g^2}{64\pi} H_s^2(h) T_e(h) \tag{3.18}$$

where H_s and T_e are the significant wave height and wave energy period. ρ_w and g are the water density and the gravity acceleration constant respectively. The BESS is not generating energy itself but does rely on the wind power density.

Diversity of wind and solar power or wind and wave power is a key determinant for combined hybrid exploitation. Due to the inherent time lag and lack of correspondence between the two analyzed resources, the power output variability can be minimized through the implementation of a hybrid system, as compared to the exploitation of a single resource. The correlation between the power systems can be measured on an hourly basis through Pearson cross-correlation analysis, as defined by eq.3.19:

$$C(\tau) = \frac{1}{N} \sum_{k=1}^{N-\tau} \frac{[x(k) - \mu_x] \cdot [y(k+\tau) - \mu_y]}{\sigma_x \sigma_y} \tag{3.19}$$

In this equation, $C(\tau)$ represents the correlation coefficient at a time lag of τ between wind power density x and the complementary power density y. N denotes the length of the sample data, and μ_x, μ_y, σ_x and σ_y are the mean value and standard deviation of wind and complementing power densities, respectively. A value of $C(\tau) = 0$ indicates no correspondence and a value of $C(\tau) = 1$ indicates a strong correlation. Cross-correlation can also be used to analyze the correlation between the energy generation and the demand from the grid. The standard deviation is calculated according to eq.3.20:

$$\sigma = \frac{\sqrt{\sum_{t=1}^{N} |A_i - \overline{A}|^2}}{(N-1)} \tag{3.20}$$

where A_i is each value of either the wind speed, solar irradiance or wave height series, $\overline{A}$ the mean value of A and N the total number of elements of the series.

Two indices are considered to evaluate the richness of the offshore energy resource. The Effective Resource Occurrence (ERO) quantifies the frequency of resource data values between the typical cut in and cut out value for the power system. The Rich Level Occurrence (RLO) index considers the frequency of occurrence of the power densities above a "rich" value. For example, the RLO threshold for WPD is 200 W/m^2 The threshold value is decided based on previous analyses. The ERO and RLO thresholds are either gathered from open sources or collected from RWE.

3.4.2 Variability analysis

To evaluate the power variability from the wind farm alone and the proposed hybrid systems, several distinctive indices are used. Coefficient of variability is used to evaluate the smoothing effect for the combined energy exploration, where C_V is defined by the standard deviation normalized by the mean power production. Eq.3.21 below is used:

$$C_V = \frac{\sigma_x}{\mu_x} \tag{3.21}$$

where $x \in [FPV, WEC, BESS]$.

The absolute value of variability is quantified as the accumulated sum of variation. This value is then divided by the hours of the data sample to calculate an hourly mean ramp rate as represented by eq.3.22:

$$\overline{\Delta} = \frac{\sum_{k=1}^{N-1} |p_{k+1} - p_k|}{N} \tag{3.22}$$

where p_k denotes the evaluated power output from the analyzed system at hour k, while N refers to the overall hours included in the data sample.

Numerous research studies endeavor to establish a precise characterization of the ramp rate based on its duration, rate, and magnitude. In general, the term ramp rate denotes a substantial alteration in power generation occurring over a brief period. Within researched literature, the authors in [104] identify a ramp rate occurrence as an augmentation in power exceeding 50% of the maximum capacity of the combined hybrid power system transpiring over a time horizon of less than 4 hours. Additionally, [105] specifies the definition of ramp event magnitude, where any power ramp event causing an increase or decrease exceeding 30% of the wind farm's capacity is considered significant, as outlined by the following eq.3.23:

$$\frac{|P_{t+\Delta t} - P_t|}{\Delta t} > P_{threshold} \tag{3.23}$$

where P_t is the power output from the system at time t, $P_{t+\Delta t}$ is the power output after a fixed time duration Δt. Furthermore, the authors in [105] also considered the magnitude Δt of the initial and final points of the time interval where the ramp change rate occurs and consider that a ramp event occurs when the ratio between the absolute value of the difference between the powers referring to two moments Δt are far from each other and Δt is greater than the threshold power value. $P_{threshold}$ represents the maximum change rate power. For example, in [106], exceeding the limit of ramp rate is assumed to be an event when the change in power is greater than 50% of the wind plant capacity in an interval of time equal to 4 hours. In this thesis, exceeding the limit of ramp rate is assumed to be an event when the change of power is greater than 30% of the installed capacity.

3.5 Sensitivity analysis

The introduction of the targeted applications of FPV, OSWC and BESS each represents a rather new area of research with significant uncertainty regarding input assumptions. The benchmark scenarios fail to encompass the vast variability in terms of project-specific structural design and other factors. With a sensitivity analysis the robustness of the results are examined and it aims to investigate the effects of changes in certain parameters on the system. In this case, the effects on the NPV of the additional generation or storage method are analyzed. Parameters are selected based on their relevance and significance in this study.

The first parameter examined is the capital expenditures, more specifically the capital cost, which is selected due to the rapid price development observed in the last decade for all of the complementary methods, and cost projections indicating continued price reduction over the next decade. The dynamic nature of this parameter makes it an interesting variable to investigate its impact on NPV. Operational expenditures will also be examined for further analysis of the cash flow.

Another great uncertainty with this analysis are the future scenarios and the spot prices, which affect the revenues from energy transmitted to the grid by using the different methods on the spot market. Due to the fact that it is impossible to correctly predict the energy market this long in advance, this parameter is selected to enable the analysis of the impact of arbitrage revenues on the economic prospects of a FPV, OSWC or BESS investment.

The degradation rate of FPV, WEC and BESS is expected to result in large impacts on the NPV calculations. As previously mentioned, all machinery experience unrecoverable loss in performance over time, but the rate is difficult to conclude. As for all energy generation and storage methods, falling performance is very common with age, especially in harsh offshore conditions. These rates are therefore included in the analysis.

A key driver for all investors of determining the fair value of renewable energy is the WACC. However, the data is hard to gather and investors often rely on their own experiences or advice from evaluation experts. In recent years the renewable energy market is becoming more established and investors are looking to diversify into new and innovative technologies in search for greater returns. This parameter is therefore also examined.

3.6 Clarification of assumptions

It is assumed for this study that the BESS is installed onshore close to the connection to the grid. Installing the BESS offshore, either centralized or non-centralized, would have included costs of another substation for the BESS to be placed upon or more expensive foundations for the wind turbines in non-centralized scenario. Installing the BESS onshore also includes costs off land acquisition near the connection point, but since the onshore substation power equipment requires land as well the BESS is assumed to be placed at the same location. This leads to a negligible land acquisition cost.

This model assumes that the BESS exclusively charges from the wind farm and not from the grid, utilizing an energy arbitrage operational method. By disregarding the option of grid charging, the analysis omits considerations of grid subscription fees. This assumption has implications for the economic analysis as it results in periods when the wind farm's insufficient energy production prevents the BESS from generating profits. If the BESS were capable of charging directly from the grid, it would have been profitable every day of the year. This impacts the NPV calculations, influencing the required size of the BESS installation, which consequently affects power fluctuations to the grid.

Energy arbitrage is a strategic approach employed to optimize profitability through energy trading. The selection of this method is motivated by the recognized challenges associated with achieving a profitable return on investment in BESS. Given RWE Renewables commercial nature, the imperative to generate positive NPV from all investments underscores the preference for energy arbitrage. It is crucial to remember the divergent outcomes that would have arisen from adopting an alternative operational approach. For instance, employing a load leveling method would likely yield lower profitability but potentially greater mitigation of grid fluctuations.

Historical data is not a perfect template for future estimations. In this case, historical data from 2021 have been used as a basis for future estimations of the power resources. It is very unsure how the wind, wave and solar irradiance characteristics will change in the future, and all we can rely on is recent available data. Since data on solar radiation, significant wave heights and periods were not available for the Neptuni site in particular, this case was forced to rely on near locations with accessible data. It is clear that the results would differ if data were available on site, but unsure in what way. Since the Swedish power system nowadays is heavily influenced by renewable intermittent power this also affects the spot prices on the market, further affecting this study. Since this data is the foundation of the case study these facts increase the uncertainty of the results provided.

It is of importance to mention that this site is not optimized for the complementary technologies examined. It has not been of RWE Renewables intentions to later install either FPV, OSWC or BESS to this site. The meteorologic conditions for these immature technologies is one of the reasons why it mostly is not technically (nor economically) favorable. More favorable conditions for FPV would be further south on the continent where the solar radiation is higher and more consistent throughout the year, and more favorable for OSWC would be at more open sea where the occurrence of increased wave heights and periods is more frequent. This is displayed through the RLO and particularly the ERO, where the wind turbines are able to effectively operate during 8,186 hours a year, while the FPV and OSWC only operates effectively during 2,763 hours and 4,872 hours respectively. Noticeable is that the wind turbines and the OSWC can not generate power outside of their ERO thresholds, while the FPV is able to convert solar irradiance outside 100-1,000 W/m^2 yet still very inefficiently especially above the higher boundary. Solar panels are usually rated from a Standard Test Condition (STC) of 1,000 W/m^2 irradiance and 25°C cell temperature, and higher values may effect the efficiency of the PV panel.[107] This inefficiency has not been taking into account in this model which decreases the credibility of the FPV power output. The model could have included an efficiency vs. cell temperature curve, but was not due to difficulties in finding concrete sources with relevant data. Luckily, according to table 5.2 the maximum solar irradiance of the year of 2021 never exceeds 862.15 W/m^2 and ambient temperatures over 25°C are rare in Sweden, substantially reducing this uncertainty.

The FPV power assessment does not include the effects of angling nor shading in the system model. It is assumed that the FPV panels are able to convert all of the solar irradiance to power even though this is not realistic. A FPV panel is likely able to tilt approximately 10°, but will not be able to capture all of the solar irradiance. It is also assumed that shading offshore could be neglected, even though the FPV is installed close to the wind turbines which could cast shade and marine life such as algae could grow on the panels. This leads to an exaggeration of produced power from the FPV panels.

The wind and wave power assessments use a power curve for the calculation of the generated power, leading to an assumption that a certain product is used in the study. No specific commercial product is considered for the study on the FPV panels nor the BESS, which has led to assumed values of the specifications for the systems. By using an existing product the uncertainty from the assumptions regarding the specifications could have been decreased. Many of the values collected from the various sources are closely knit to the manufacturer in their respective cases and therefore very specific for the specific study regarded. Therefore it is not very realistic to use the mean values as a point of departure. However, this uncertainty is reduced through consultation with experts in the field, directing these assumed values in the right direction.

There are many types of WECs and BESS to choose from. This study considers specifically OSWC and Li-Ion batteries displaying these particular potentials of profitability and mitigation of power fluctuations in a hybrid system with wind power. This does not necessarily mean that every type of WEC or BESS should not be considered for system integration. It surely should give a good indication of where the different technologies positions themselves at the market as of now, but there are plenty of different WEC and BESS technologies yet to be examined.

There are also plenty of assumptions regarding the economic analysis. In the background merging costs was introduced as a synergy effect of hybrid systems. Even though there is a great potential of this, relevant data on this were hard to collect. This led to zero assumed merging costs of the various hybrid systems. The change of spot prices when connecting the Neptuni wind farm to the grid is not considered in the price scenarios. It is also not considered how the spot prices are affected by the installation of a BESS operating for energy arbitrage. An estimation of this would have implied further uncertainty to the study and is therefore not included in the price scenario formulation. However, the price scenarios used in the study are, depending on which scenario considered, does regard the green energy transition and thus the installation of more renewable energy. Therefore, the scenarios should provide a good overall picture of how the installation of renewable energy affect the spot prices.

Another clarification is that these hybrid systems are assumed to be installed instantly. Since the study are based on data from 2021, this means that the systems are installed the year after in 2022. The price scenarios are customized from the data of 2021 to reflect the reality the year after in 2022 by analyzing data. This is not a realistic approach, since the wind farm is not planned to be installed until approximately 2030. Assumptions regarding an installation in 2030 would have meant different costs, more mature technologies, and a more advanced prediction of the spot prices later in the future to name a few. This is avoided by analyzing the effects of installing the systems directly instead. Though, according to some of the scenarios presented the spot prices are predicted to generally decrease in the future, meaning that the highest prices are predicted to be in the next few years. If the hybrid systems are installed further in the future they would miss out on large revenues. It can therefore be stated that the result from the economic analysis would probably look very different if the model had assumed a later installation.

4 Data

This section describes the collection of the datasets used to execute the simulations which produce the results, the section is divided into subsections for each dataset and are there explained further.

4.1 Collection of datasets

All datasets are between the time period 2021-01-01 00:00 and 2021-12-31 23:00, and are downloaded as Excel files which are imported to Matlab where the simulations and calculations take place.

- **Prices:** The prices are collected from NordPools database for the SE4 region between the period 2021-2022. The data contains the hourly spot prices in SEK/MWh for every hour of the period and are used to forecast the spot prices 25 years into the future in conjunction with Svenska Kraftnäts market analyses. The forecast prices are later used in the economic analysis.
- **Load:** Data is collected from Mimers database and covers the SE4 region over the 2021-2022 period. The data contains the hourly load demand in kW and is used to see how well the wind farm and the hybrid systems correlate with the load demand.
- **Wind speed:** Wind data was provided by RWE for the exact site of the Neptuni project and contains the hourly wind speeds in m/s for each year from 1979 to 2022. The used time period is 2021-2022 to correspond with the price and load data. The data is used to simulate the power density in W/m^2 and power generation for different time scales; hourly, daily, and monthly. It is also used to calculate variability indices. The data serves as a base of many calculations.
- **Solar irradiance:** Data was collected from the database of SMHI for a location just northeast of the Neptuni site called Visby Sol. The data is given in W/m^2 for every hour of the time period 2021-2022. The data is used to calculate the power density of the solar irradiance in W/m^2 and power generation of one solar panel for different time scales; hourly, daily, and monthly. It is also used to calculate the variability indices and its correlation with the wind power. The data is later used in the simulations of the hybrid system and in the economic analysis.
- **Wave:** Wave data was collected from the database of SMHI for a location around 5 km northwest of the Neptuni site called Knolls Grund. The data contains the significant wave height and wave period for every hour of the time period 2021-2022. The data is used to calculate the power density of the wave resource in W/m and power generation of one oscillating surge wave converter for different time scales; hourly, daily, and monthly. The data is also used to calculate the variability indices and the correlation with the wind power. It is also a base in the simulations of the hybrid system and in the economic analysis.

- **Wind turbine power curve:** The power curve of the chosen wind turbines is given from RWE, where a 19 MW turbine is scaled down to the chosen rated power of 17 MW. This data is considered to be very sensitive and is only shared between RWE and their contractors. For the purpose of modelling we are given a model from one of RWE Renewables previous projects. This model is very similar to the real power curve and is approximately 97% accurate.
- **Wave power matrix:** The wave power matrix of the chosen OSWC was collected from NRELs technical report on the RM5 OSWC which corresponds to the chosen OSWC.[108] At the moment of this master thesis, RWE where unable to provide any information about wave power projects, which is why other sources were used.

4.2 Choice of parameters

Due to the FPV, OSWC and Li-ion BESS not being technologies that yet met maturity, several assumptions have to be made. These parameters are compared between different sources and are later chosen after their plausibility. Mostly previous research and projects on offshore wind power, FPV, OSWC and Li-Ion BESS form the basis of our assumed values to this study. For the parts where we have been able to interview RWE Renewables experts for more reliable statements and confirmations of our assumptions, this information have been weighted more heavily than the online sources. Due to confidentiality, experts have not been able to provide precise values of the parameters but they could point out values from the online sources that seemed most reasonable.

4.2.1 Floating PV system

Golroodbari et al. (2021) performed a techno-economic feasibility study on the integration of floating offshore solar power into an already established offshore wind farm at the coast of the Netherlands. They assume that the solar panel used is a crystalline silicon panel with a rated maximum power point of 300 W_p, an efficiency of 18.8%, an area of 1.6 m^2 and a performance ratio of around 0.95. In their NPV calculations they also assume an initial investment of 0.6-1.85 €/W_p for each panel.[109]

Ramasamy and Margolis published a system cost benchmark for floating photovoltaics in 2021. The assumption of a module efficiency of 19.9% was made, based on median values from different PV installers and developers. The base scenario of 1.29 \$/W_p is calculated, based on 10 MW_p installed capacity. However, the capital cost decreases with increasing installed capacity, approximating the values 1.68 \$/W_p for 2 MW, 1.46 \$/W_p for 5 MW, 1.29 \$/W_p for 10 MW, and 1.05 \$/W_p for 50 MW. The cost benchmark include O&M costs of 0.016 \$/W_p per year.[48]

Dizier (2018) performed a techno-economic feasibility study on floating PV-systems and assumes a rated maximum power of 270 W_p, an efficiency of 16.4%, a performance ratio of 0.84 and a panel area of 1.65 m^2. The capital costs are estimated as 1.27 \$/W_p including cooling, decreasing to 1.21 \$/W_p excluding cooling. The prices are assumed as a standard from the electronics corporation AUO panel prices in Taiwan.[110]

Ghigo et al. (2022) did a design and analysis of a floating photovoltaic system for an offshore installation. In their analysis they used the solar panel SunPower Maxeon 3 which has the main dimensions of: Nominal power of 400 W_p, performance ratio of 75%, efficiency of 22.6%, and area of 1.76 m^2. The capital cost of one solar panel was calculated to 2.04 €/W_p. The O&M cost per panel was calculated to 0.015 €/W_p.[111]

Source	**Lifetime** [years]	**Efficiency** [%]	**Area** [m^2]	**PR** [%]	**Nominal power** [W_p]	**Cap. cost** [€/W_p]	**O&M cost** [€/W_p-year]
Golroodbari et.al (2021)	20	18.8	1.6	95	300	0.6-1.85	-
Ramasamy & Margolis (2021)	30	19.9	-	-	-	1.56-0.98	0.016
Dizier (2018)	25	16.4	1.65	84	270	1.13	-
Ghigo et.al (2022)	20	22.6	1.76	75	400	2.04	0.015

Table 4.1: Parameter choices for different sources.

4.2.2 Choice of FPV parameter values

The selection of parameters utilized for the computations is based on the reports presented in table 4.1 above. The significant decrease in the price of PV-panels highlights the importance of employing the most current values available. The selection process involves determining certain values by computing the mean of various values reported. Additionally, certain values are selected by means of a weighted approach that takes into consideration the various values and their corresponding descriptions. Chosen parameters are compiled in table 4.2 below.

- **PV-panel lifetime:** The value presented to an expert was 23.75 years and is the mean value of the sources presented. The expert from RWE Renewables indicated that the value from Dizier (2018), 25 years, is a more reasonable value.
- **PV-panel area:** The panel area is crucial for the energy capture of a PV-system. This is closely tied to the manufacturer. The collected information about cell area from previous research seemed small to the expert. Therefore, the largest value collected was chosen.
- **PV-panel efficiency:** The same goes for the efficiency which is knit to the manufacturer. The efficiency presented to the expert was 19.425 and was a mean value of all sources. The expert preferred a higher value, thus the efficiency was chosen to the largest value collected.
- **Performance Ratio:** The performance ratio is closely tied with temperature. The PV-panels of this case is offshore and together with the cool climate of Sweden there is an enhanced cooling effect. This will result in an overall higher performance ratio. The value presented was the mean value 84.67% but should

be higher according to the expert. Once again, the largest value is chosen.

- **Nominal Power:** The nominal power is the maximum output of one solar panel. This is also closely tied to the manufacturer. After consolidation with the expert the largest value collected was chosen which amounted to 400 W_p.
- **Capital cost:** The solar power market has seen a rapid decline in capital costs over the past years which makes it quite surprising that the latest value is the highest of all the values presented. This can be explained by the shortage of semiconductors around the world which has halted the decline in investment cost of PV-panels. The values Ramasamy & Margolis presented is based on the fact that the cost per watt will decrease with the increase of installed capacity and the lowest of the values corresponds to a farm of 50 MW_p which is more inline with this case study than any other value. However according to the expert the value should be higher. A mean value was calculated of all the sources which resulted in 1.41 €/W_p.
- **O&M cost:** The O&M costs are assumed in a similar way as the capital costs. The value chosen is the mean value of the sources; 0.015 €/W_p which was deemed reasonable by the expert.

Parameter	**Value**
Lifetime [years]	25
Efficiency [%]	22.6
Area [m^2]	1.76
PR [%]	95
Nominal power [W_p]	400
Cap. cost [€/W_p]	1.41
O&M cost [€/W_p-year]	0.015

Table 4.2: Chosen parameters FPV.

4.2.3 Wave

The type of wave energy converter chosen for this case study is an RM5 floating OSWC because of its predicted promising future.[58] The parameters could not be commented neither confirmed by RWE since they at the moment do not research in the area of WEC. This means that this thesis has to completely rely on external research and sources on the RM5 OSWC.

Mangela et al. (2022) recently published a report on the estimation of future costs of wave energy technologies. The RM5 is used as test model which is an OSWC. The RM5 is assumed to have a lifetime of 20 years, nominal power - 360 kW. A CAPEX and OPEX breakdown is later computed with these parameters considered, equaled the capital cost of 13.33 $\$/W$ and O&M cost of 0.33 $\$/W$.[58]

Yu et al. (2015) published a report on the RM5 which includes a cost breakdown of the model similar to the report of Mangela et al. This includes assumptions of different parameters such as the nominal power of 360 kW and an efficiency of 29.4%. With these parameters in mind a CAPEX and OPEX breakdown was computed which resulted in the capital cost of 32.58 $\$/W$ and the O&M costs of 3.2 $\$/W$. However, the installation of one unit is not applicable for this thesis and therefore the capital costs and O&M costs of 100 installed units will be considered. The capital costs of 100 installed units resulted in 11.2 $\$/W$ and O&M costs of 0.25 $\$/W$.[57]

Chang et al. (2018) performed a study of the factors affecting the levelized cost of wave energy conversion projects. The report investigates different types of wave energy converters one of which being an OSWC named F-3OF. The parameters assumed in the report are: Lifetime - 20 years, capital cost - 11.56 $\$/W$ and O&M cost - 0.62 $\$/W$. Worth noting is that this type of OSWC uses three flaps instead of one (RM5).[112]

The team of Innovation and R&D at RWE Renewables have not performed analyses on any type of WEC, meaning that no data has been collected or considered from the company. This forces this thesis to rely on open source data and recent research published online.

Source	**Lifetime** [years]	**Nominal Power** $[kW]$	**Cap. cost** [€$/W$]	**O&M cost** [€$/W$-year]
Mangela et.al (2022)	20	360	12.66	0.31
Yu et.al (2015)	-	360	10.64	0.24
Chang et.al (2018)	20	-	10.98	0.59

Table 4.3: Parameter choices for different sources.

4.2.4 Choice of OSWC parameters

The parameters for the calculations are chosen from the reports presented in table 4.3 above. Chosen parameters are compiled in table 4.4 below.

- **Lifetime:** Since all sources use the same value of lifetime, this thesis will not differ. The lifetime chosen for the calculations will be 20 years.
- **Nominal power:** The sources with a given nominal power assume the same value of 360 kW. The RM5 is a prototype developed by NREL which has a nominal power 360 kW, and therefore there is no need to differ from this value.
- **Capital cost:** The importance of number of units is the key driver for this value, where Mangela et al. uses a 50 unit farm while Yu et al. uses a 100 unit farm for their studies. Chang et al. based their capital costs on the initial array values of stakeholder responses and reference model studies presented by Ocean Energy Systems. This thesis will use the mean value of the sources which amounts to a capital cost of 11.43 €$/W$.
- **O&M cost:** The same can be said for the O&M cost as for the capital cost. The mean value of the different sources is used which is calculated to an O&M cost of 0.38 €$/W$.

Parameter	Value
Lifetime [years]	20
Nominal power [kW]	360
Cap. cost [€/W]	11.43
O&M cost[€/W-year]	0.38

Table 4.4: Chosen parameters OSWC.

4.2.5 BESS

Liu et al. (2020) published a report on the uses, cost benefit analysis, and markets of energy storage systems for electric grid applications. One of the BESS investigated was the Li-ion BESS where the following parameters were assumed: Efficiency - 92-95%, the lifetime - 5-20 years, lifetime in cycles - 0.5-20k cycles and the capital cost of 200-1,260$/kWh$.[94]

Augustine and Blair (2021) published their report on the energy storage future, where the Li-ion battery is one of their main subjects. Some parameters used for a 4-hour duration Li-ion battery were: Capital cost - 320$/kWh$, Efficiency - 86%, Depth of Discharge (DoD) - 80%, cycles at 80% DoD - 3,500 cycles, cycles per year - 330, lifetime - 10 years. However, the capital costs change depending on the size and the duration of the Li-ion battery. For example, 60 MW_{DC} 2-hour duration battery had the capital cost of 443 $/kWh$, 60 MW_{DC} 4-hour duration battery with storage had the capital cost of 382 $/kWh$ and 60 MW_{DC} 10-hour duration battery had the capital cost of 345 $/kWh$.[89]

Cole et al. (2021) did a report on the cost projections for utility-scale battery storage, the main subject of the report were the 4-hour Li-ion battery with storage, the authors gave recommendations and projections for parameters such as cost, lifetime and efficiencies based on the publications that they surveyed. The values of the parameters for the year 2020 were: CAPEX - 350 $/kWh$ with a steady decrease to around 150 $/kWh$ in 2050, the authors strongly advise not to cycle more than once a day which leads to 365 cycles/year, the lifetime chosen was 15 years, and the efficiency was set to 85%.[90]

Lazards (2021) latest report on the levelized cost of storage includes in-front-of-the-meter values for utility scale Li-ion BESS with parameters such as lifetime, cycles, cost, DoD, duration and size. The values of the parameters are assumed as: Lifetime - 20 years, Cycles/year - 350 cycles, DoD - 90%, duration varies between 1, 2 and 4 hour with corresponding costs for the different durations resulting in the 4-hour duration battery with the cost ranges between 147-231 $/kWh$, the mean cost of 189 $/kWh$, and the efficiency ranges between 91-84% for all discharge times.[113]

Thunder Said Energy performed a study of what causes degradation in Li-ion batteries. The result showed that a Li-ion battery degrades in optimal conditions by 2% every 1000 cycles which equates to around 0.667% every year.[114]

Gräf et al. (2022) performed a study on what drives capacity degradation in utility-scale BESS. The results showed that an average degradation rate in a BESS with a lifetime of 20 years was 1,55% annually.[115]

Source	LT [y]	Cy. [c/y]	Cap. [€/kWh]	DT [h]	Eff. [%]	DoD [%]	O&M [€/kWh-year]	Size [MW_{DC}]	DR [%]
Liu et al. (2020)	5-20	100-1,000	188-1,184.4	-	-	-	-	-	-
Blair et al. (2021)	10	330	359	4	86	80	9.05	60	-
Blair et al. (2021)	-	-	416.4	2	-	-	9.05	60	-
Blair et al. (2021)	-	-	339.3	6	-	-	9.05	60	-
Blair et al. (2021)	-	-	329.9	8	-	-	9.05	60	-
Blair et al. (2021)	-	-	324.3	10	-	-	9.05	60	-
Cole et al. (2021)	15	365	329	4	85	-	2,5% of Cap.	-	0
Lazard (2021)	20	350	138.2-217.1	4	91-84	90	1.4-2.3	100	2.6
Lazard (2021)	20	350	161.7-235	1	91-84	90	1,6-3.6	100	2.6
Lazard (2021)	20	350	138.2-224.7	2	91-84	90	1.4-3.6	100	2.6
TSE (2023)	-	-	-	-	-	-	-	-	0.67
Gräf et al. (2022)	20	-	-	-	-	-	-	-	1.55

Table 4.5: Parameter choices for different sources.

4.2.6 Choice of BESS parameters

The values of the parameters for the calculations are chosen from the values in table 4.5 above. Chosen parameters are compiled in table 4.6 below.

- **Cycles:** The method used in this case study for the BESS model will perform one full cycle a day. Charging is executed at off-peak hours and the discharge is executed at peak-hours to increase the revenue. This method is said to not increase O&M costs nor decrease the lifetime according to Cole et al.[90] This results in 365 full cycles each year.

- **Lifetime:** The lifetime of the BESS is said not to decrease in lifetime by doing one full cycle each day every year. Therefore the lifetime is set to the most frequent occurring value of the collected data, 20 years. This is a reasonable value according to the RWE Renewables expert interviewed.
- **Discharge time:** The discharge time chosen will be 4 hours (C-ratio = 0.25) since it is the most recurring value from the sources.
- **Capital cost:** Since the discharge time was chosen to 4 hours, the collected capital costs of the sources with the same discharge time should be considered. The mean value of these, 288.55 €$/kWh$, was considered to low by the expert, and therefore the largest value of these sources was chosen.
- **O&M cost:** The O&M cost calculation corresponds with the capital cost. The mean value calculated from the collected data from 4 hours discharge time batteries is equated and chosen to 6.38 €$/kWh$.
- **Efficiency:** In general the efficiency depends on the cooling system and "secondary" equipment like inverters, transformers etc. The efficiency chosen will be a mean value of the sources. This resulted in an efficiency of 86.17%.
- **Depth of Discharge:** The depth of discharge chosen is a mean value of the different values from the sources, this resulted in a value of 85%. The expert mentioned that a discharge below 20% would for sure impact the degradation rate of the battery. This is considered in the next point.
- **Degradation rate:** This is according to the expert closely knit to the battery system assumed and the manufacturer. In many sources the degradation rate was left out and therefore more resources were considered for the calculation of this value. The mean value was calculated to 1.61% annually since it is not reasonable that the BESS operates under optimal conditions for eternity. Note that the O&M costs of Cole et al.(2021) includes a compensation cost of the degradation rate. This means that the degradation rate has been considered twice in our assumptions, compensating for the discharge of the battery below 20%.

Parameter	Value
Lifetime [years]	20
Cycles [cycles/year]	365
Efficiency [%]	86.17
Discharge time [h]	4
Depth of Discharge [%]	85
Degradation rate [%]	1.61
Cap. cost [€$/kWh$]	359
O&M cost [€$/kWh$-year]	6.38

Table 4.6: Chosen parameters BESS.

5 Results

This section assesses the wind, solar, wave and battery power generation potential on the Neptuni site and investigates their variability. The correlation and time lag between the wind and complementary power are analysed to study the synergy between the renewable sources, but also to analyze the correlation between the hybrid systems and the system load. In addition, an economic analysis is presented to decide the optimal sizing of the complementary power systems in order to maximize the NPV. Furthermore, the variability of these hybrid power systems are compared to the stand alone offshore wind farm. The power fluctuation analysis will provide information on how the power supplied to the grid changes as we connect more renewable and volatile power. Shown in table 5.1 is a short review of the indices and abbreviations that are used in the analysis.

Abbreviation	Meaning	Unit
V	Wind Speed	m/s
G	Solar Irradiance	W/m^2
H_s	Significant Wave Height	m
T_e	Significant Wave Period	s
WPD	Wind Power Density	W/m^2
PD_{WEC}	Wave Power Density	kW/m^2
σ	Standard Deviation	MW
C_V	Coefficient of Variability	-
$\overline{\Delta}$	Mean Ramp Rate	MW
Δ_{limit}	Hours exceeding 30% of the installed capacity	h
$C(\tau)$	Cross-correlation coefficient	-
τ	Time Lag	h
NPV	Net Present Value	€
$WACC$	Weighted Average Cost of Capital	%

Table 5.1: Abbreviations and their meanings respectively.

5.1 Technical results

5.1.1 Resource data

The hourly wind speeds, solar irradiance and wave heights of 2021 at the Neptuni site are shown in figure 5.1 below. The figure is presenting the distinctive characteristics of each renewable power source. Thereafter, the raw resource data of the Neptuni site is presented in table 5.2 where the max and mean wind speeds, max and mean solar irradiance, and the mean wave height and wave period are collected and calculated. The ERO is also presented in hours. The wind speed thresholds are between 3.5 and 28 m/s, the solar irradiance are between 100 and 900 W/m^2 and the wave heights between 0.75 and 5.75 meters.

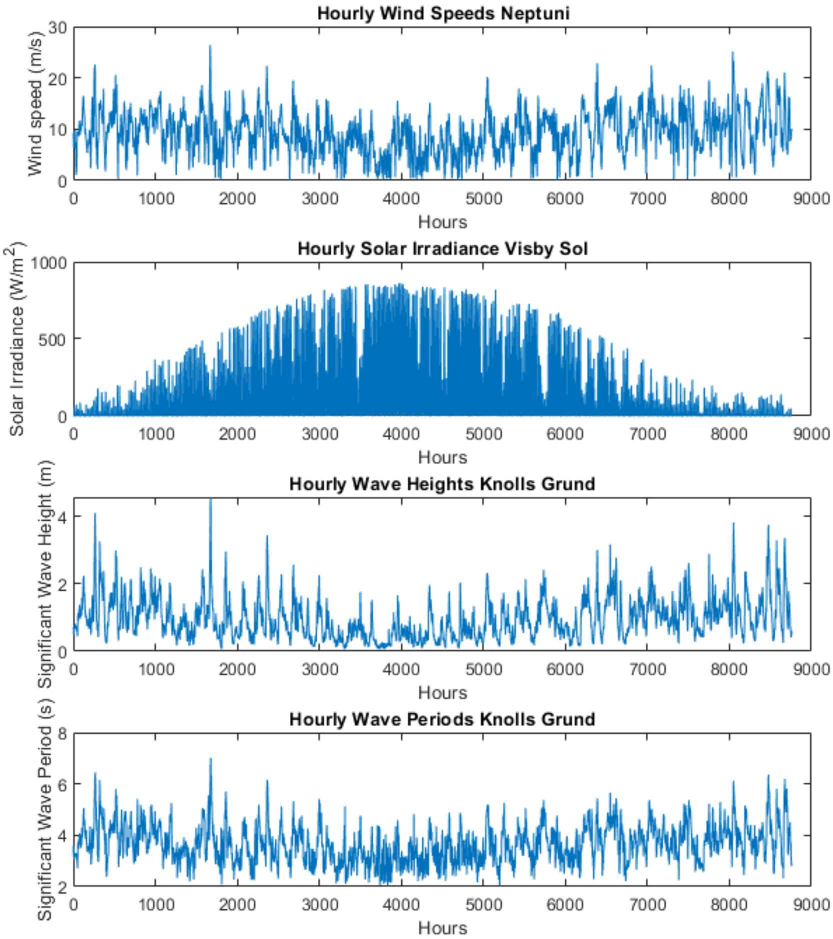

Figure 5.1: Power resources over the year of 2021.

The correlation between wind speeds and wave height or wave period is clearly evident from the data in figure 5.1. Additionally, both the wind and wave characteristics display a seasonal pattern, with their peaks occurring in the fall or winter months. Similarly, the solar irradiance also exhibits a seasonal trend, with the highest values observed during the summer months.

	Wind (m/s)		Solar (W/m^2)		Wave (m & s)	
	V_{max}	$\overline{V}$	G_{max}	$\overline{G}$	$\overline{H_s}$	$\overline{T_e}$
	26.39	9.28	862.15	129.29	0.97	3.65
$ERO(h)$	8186		2763		4872	

Table 5.2: Raw resource data.

5.1.2 Power density

The hourly average power density for wind and solar in W/m^2 and wave in W/m are shown in figure 5.2 below. The wind power density is from the Neptuni site while the solar and wave power densities are collected from measurement points Visby Sol and Knolls Grund respectively. A comparison between the three different monthly average power densities are displayed in figure 5.3 to give a better comparison between the different power densities. The comparison of the power density for wind and wave indicate higher values from fall to spring while the power density for solar is at its highest in the summer. This is very much inline with the resource data results, since the power density is dependent on its resource. Table 5.3 displays the mean and maximum power densities collected from the data, clearly displaying wind and wave as the largest power resources. The RLO is also displayed in the same table as an indication of how many hours of the year that are assumed to be "rich of power". The threshold for wind is above 200 W/m^2, above 400 W/m^2 for solar and above 25 kW/m for wave.

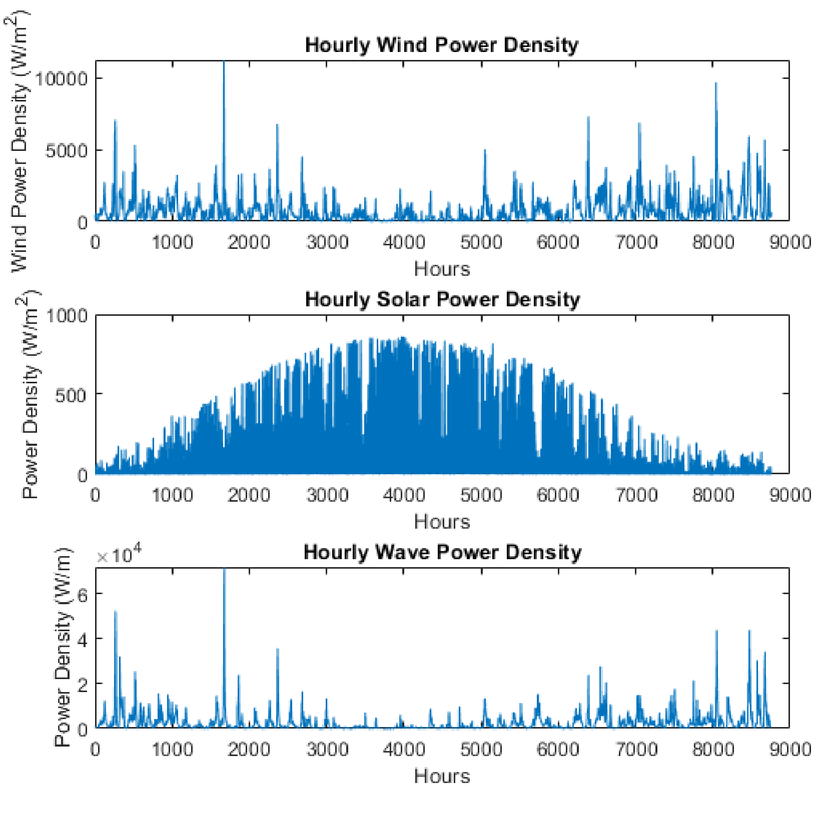

Figure 5.2: Hourly power densities.

Figure 5.3: Monthly power densities.

Figure 5.2 and 5.3 clearly demonstrate significant differences between the resources, with solar irradiance lagging behind wind and wave power density. This observation can be attributed to the geographical location of the project not being favorable for solar power in comparison to other places on the continent.

	Wind (W/m^2)		Solar (W/m^2)		Wave (kW/m)	
	WPD_{max}	$\overline{WPD}$	G_{max}	$\overline{G}$	$PD_{WEC,max}$	$\overline{PD_{WEC}}$
	11 251.10	790.91	862.15	129.29	71.93	2.83
$RLO(h)$	6194		1146		75	

Table 5.3: Power densities of the different resources.

5.1.3 Power generation

Figure 5.4 below shows the hourly power generation of 17 MW installed capacity of wind power, FPV and OSWC. Also power supplied from and to an onshore Li-Ion BESS is displayed with a capacity of 20 MWh (4h-duration). Important to remember is that the BESS can not operate without the wind farm, and therefore the wind power curve will change in combination with the BESS. It is clear that the wind, solar and wave power generation is fluctuating heavily throughout the year while the BESS operates steadily without any larger gaps with zero power to the battery nor to the grid.

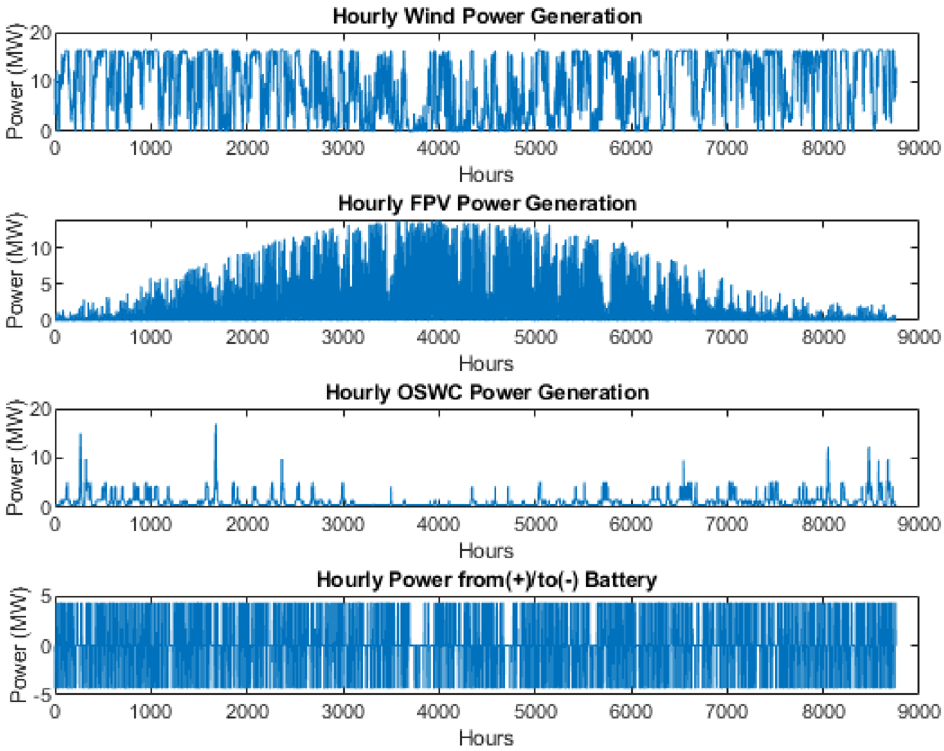

Figure 5.4: Hourly power generation 2021.

Figure 5.4 also confirms that wind turbine power generation is the most mature of the presented technologies, generating the most power to the grid. The OSWC experiences only a few hours generating more power than a half of its installed capacity. This is because of technology immaturity and bad site conditions for wave power conversion. In this case the BESS is strongly tied with wind power generation as it is dependent on the wind to complete one full cycle each day when there is wind power available for charging. The BESS always charge and discharge approximately a quarter of its capacity when the wind turbines are generating power at the low price (charging) hours.

Figure 5.5 demonstrates the monthly average power generation of a 17 MW installed capacity across various technologies. The data clearly indicates that the OSWC is not efficiently utilized, falling short in its power harnessing capabilities. Surprisingly, solar power technology, despite having a lower power density, outperforms the OSWC by generating power more effectively. Additionally, the figure highlights the site's suitability for wind power production and emphasizes the significant technological advantages that wind power holds over the other technologies mentioned. In June, the monthly average power generation of FPV reaches its peak, while wind power experiences its lowest average power generation. Despite this, wind power manages to maintain a power output comparable to that of FPV.

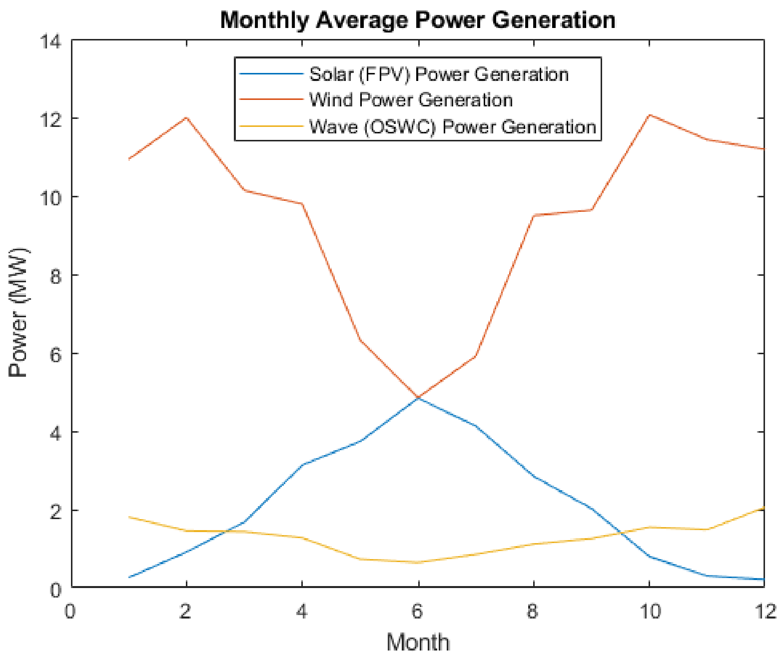

Figure 5.5: Monthly average power generation 2021.

From the power generation calculations the variability indices mentioned in Section 3.4.2 for each system can be computed and are compiled in table 5.4 below. Included is the standard deviation, hourly coefficient of variability, mean ramp rate, amount of hours the ramp rate exceeds 30% of the installed capacity, cross-correlation between the power generation and load with time lag for wind power, cross-correlation between wind power generation and complementary power generation method with time lag for solar and wave.

	Nr. of Units	*Capacity*	σ	C_V	$\overline{\Delta}$	Δ_{limit}	$C_{max}(\tau)$	$\tau(h)$
	[Unit]	[MW]	[MW]	[frac]	[MW]	[h]	[frac]	[h]
Wind	1	17	6.15	0.65	0.78	54	0.84	47
FPV	42 500	17	3.39	1.63	0.61	17	0.44	-2528
OSWC	47	16.92	1.41	1.08	0.14	25	0.77	2

Table 5.4: Variability indices of the different power generation methods.

5.2 Economic analysis results

5.2.1 NPV analysis

The results of the technical analysis indicate that the integration of floating PV panels and OSWCs within the Neptuni wind farm holds considerable promise, albeit with some restrictions on the additional energy generation achievable through the incorporation of more capacity. The economic advantages of this fusion must be evaluated for us to be able to propose a possible way forward for RWE Renewables with well-founded arguments.

The NPV analysis is based on the price scenarios from section 3.3.2. The results are displayed in figure 5.6 below and it demonstrates that the correlation between the NPV and complementary installed capacity is non-linear, owing to the reduction in marginal power production with the inclusion of each additional MW. A marginal change in the value of energy can yield an NPV inferior to zero, as the different curves for the scenarios indicates. Furthermore, table 5.5 sums up the different additional capacities in MW for the integrated technologies depending on the scenario considered. Clearly Scenario 1 resulted in largest capacities to be installed because of the scenario assuming electricity price increases in the next few years.

Noticeable is that for all scenarios for OSWC and BESS there were no capacities generating positive NPV in the economic analysis. This results in assumptions having to be made on the magnitude of installed capacity of both technologies. This to be able to complete an analysis of the power fluctuations their respective hybrid systems when integrated with the Neptuni wind farm. The installed capacity of OSWC is assumed to be 1 GW, 100 MW, 500 MW and 20 MW in scenario order 1-4. The same is assumed for the BESS but the capacity is represented by the unit MWh. The outcome was the same for all scenarios except Scenario 1 for FPV. This forced us to assume values for this technology for the remaining scenarios. For FPV scenarios 2-4 installed capacities are assumed to 100 MW, 500 MW and 20 MW, the same as for the OSWC.

Unit	(MW)	(MW)	(MWh)
Scenario	FPV	$OSWC$	$BESS$
1	1,540	1,000	1,000
2	100	100	100
3	500	500	500
4	20	20	20

Table 5.5: Capacities assumed to be installed for the integrated technologies.

Figure 5.6 indicates that the FPV technology is on the brink of commercial availability as it has the only positive NPV. On the other hand, the OSWC technology is far from being financially viable. The scenarios for OSWC technology are all close and steadily declining with negligible changes with increased capacity. The BESS technology falls somewhere in between the other technologies.

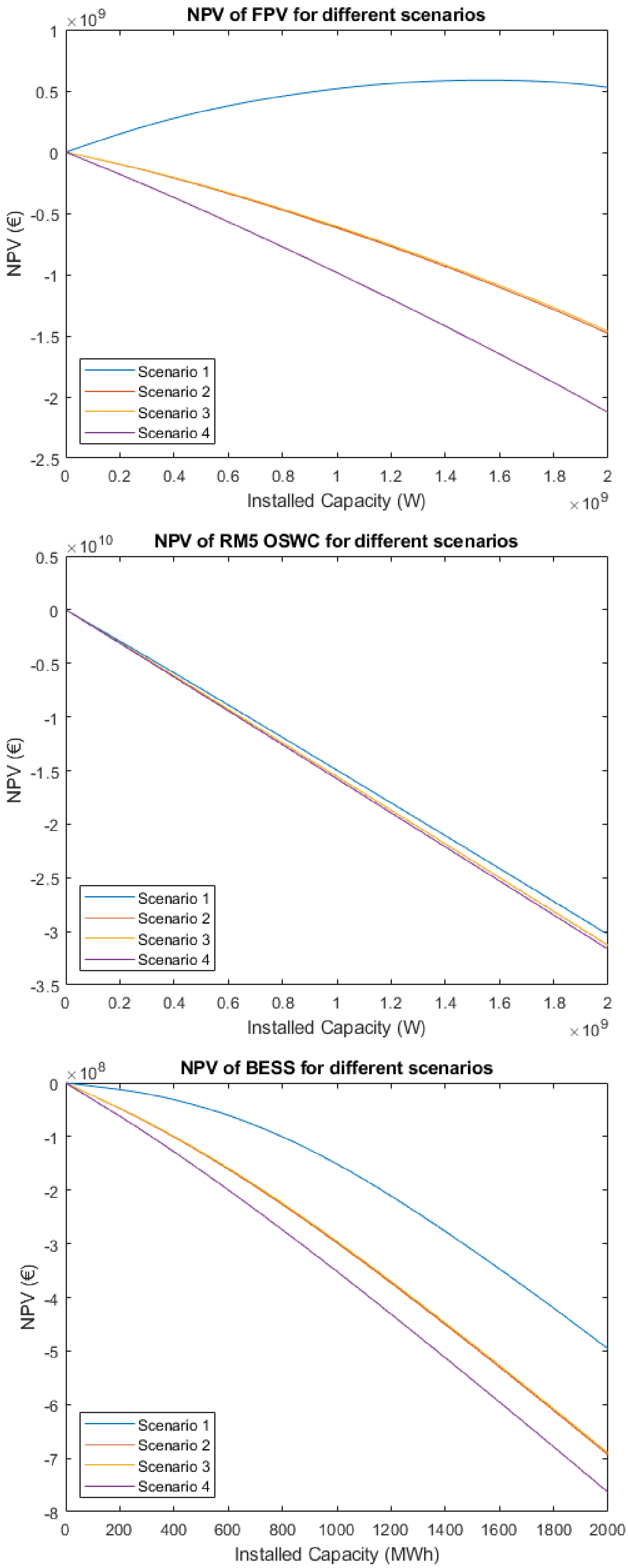

Figure 5.6: NPV graphs for the different scenarios for FPV, OSWC and BESS.

5.3 Power fluctuation analysis

The results of the economical analysis an indication of which capacity is most suitable for every system and each price scenario. This together with the technical results gives solid ground for the power fluctuation analysis where FPV, OSWC and BESS are combined with the wind farm in a hybrid system. Table 5.6 display the comparison of the variability indices for each scenario between the hybrid systems and the standalone wind farm. The power variation reduction or increase, and also the alignment of the the different hybrid systems with consumption is displayed with a change ratio in table 5.7. The change ratio is the percentage decrease or increase of the index in comparison to the standalone wind farm. The green values displayed indicates an improved value, while the red values indicate a deteriorated value. These results clearly displays the efficient power fluctuations reduction pattern for FPV and wind power hybrid systems. For OSWC and BESS combined with wind power the reductions are fewer. What does in fact improve is the cross-correlation to the load, indicating a better balance between production and consumption.

System	*Scenario*	σ	C_V	$\overline{\Delta}$	Δ_{limit}	$C_{max}(\tau)$	$\tau(h)$
Unit	-	(MW)	(frac)	(MW)	(h)	(frac)	(h)
Wind farm	Wind	510.19	0.65	64.51	54	0.84	47
FPV & Wind	1	470.39	0.51	77.37	0	0.90	48
	2	506.16	0.63	65.24	30	0.85	48
	3	489.33	0.58	67.77	8	0.87	48
	4	509.24	0.65	64.62	43	0.84	48
OSWC & Wind	1	517.64	0.62	63.89	1	0.85	48
	2	514.08	0.65	65.06	31	0.84	47
	3	519.14	0.64	64.85	10	0.85	48
	4	511.00	0.65	64.62	44	0.84	47
BESS & Wind	1	507.87	0.65	85.80	38	0.84	47
	2	510.14	0.65	65.81	39	0.84	47
	3	509.09	0.65	73.96	34	0.84	48
	4	510.16	0.65	64.66	44	0.84	47

Table 5.6: Variability indices of the different power generation methods.

Hybrid system	*Scenario*	σ	C_V	$\overline{\Delta}$	Δ_{limit}	$C_{max}(\tau)$	$\tau(h)$
Wind farm	Wind	0	0	0	0	0	0
FPV & Wind	1	-7.80	-21.87	+19.93	-100	+6.41	+2.13
	2	-0.79	-2.30	+1.13	-44.44	+0.71	+2.13
	3	-4.09	-10.26	+5.05	-85.19	+3.12	+2.13
	4	-0.19	-0.46	+0.17	-20.37	+0.15	+2.13
OSWC & Wind	1	+1.46	-4.25	-0.96	-98.15	+1.17	+2.13
	2	+0.76	-0.18	+0.85	-42.59	+0.07	0
	3	+1.75	-1.77	+0.53	-81.48	+0.51	+2.13
	4	+0.16	-0.03	+0.17	-18.52	+0.01	0
BESS & Wind	1	-0.45	+0.40	+33.76	-29.63	+0.29	0
	2	-0.01	0	+2.59	-27.78	+0.06	0
	3	-0.22	+0.06	+15.29	-37.04	+0.20	+2.13
	4	-0.01	0	+0.80	-18.52	+0.01	0

Table 5.7: Change ratios (%) in comparison with the stand alone wind farm.

The results shows a greater reduction of the coefficient of variability when the cross-correlations between the power resources are low. The mean ramp rate is reduced for increased installed capacities for wind-solar and wind-BESS hybrid systems. The wind-wave hybrid system do not follow the same trend. It is also shown that the amount of hours when the ramp rate exceeds 30% of the installed capacity is reduced for all of the hybrid systems. This is due to the fact that the ramp rate is not increasing at the same rate as the installed capacity. Also, all hybrid systems correlate more with power consumption for increased installed capacities, and a wind-solar hybrid system show great potential of matching power generation with power consumption.

The installation of capacity within a cable network is a viable method to enhance its energy transport efficiency. Nonetheless, the cable's established capacity of 1,400 MW is periodically surpassed during certain hours of the year. The amplification of capacity, though feasible, may engender more frequent breaches of the cable's maximum capacity threshold. By combining wind with FPV, OSWC and BESS maximum cable capacity usage can occur more often, but the curtailed power of the system could also increase. Table 5.8 shows the effect on adding capacity to the wind farm as well as the increase in curtailed energy of the hybrid systems.

System	Scenario	Installed cap.	Gen. energy	Curtailed power	Frac.
Unit	-	[MW]	[GWh]	[GWh]	[%]
FPV & Wind	1	1,540	8,124.69	406.84	5.01
	2	100	6,990.14	0.69	0.01
	3	500	7,358.17	60.63	0.82
	4	20	6,905.24	0	0
OSWC & Wind	1	1,000	7,295.31	264.38	3.62
	2	100	6,949.82	1.60	0.02
	3	500	7,131.87	89.90	1.26
	4	20	6,897.36	0	0
BESS & Wind	1	250	6,826.08	0	0
	2	25	6,883.14	0	0
	3	125	6,865.40	0	0
	4	5	6,883.70	0	0

Table 5.8: Yearly data from the hybrid systems displaying the effect of adding capacity on energy curtailment.

5.4 Sensitivity analysis

The novelty of the technologies investigated adds uncertainty to our input assumptions, and our case study does not capture all the variability among projects. Figure 5.7 present the results of a sensitivity analysis conducted to determine the NPV associated with the different technologies for the scenarios. The analysis involved adjusting the parameters of capital cost, O&M cost, spot market prices (scenarios), degradation rate and WACC individually to obtain varying NPV. The sensitivity analysis will not consider all of the different price scenarios presented to you in section 3.3.2. Chosen is price scenario 3 since it to the authors seems like a reasonable outcome for the future. The NPV model used for the economic analysis in this study is the same for all of the different technologies. Therefore, this sensitivity analysis can be linked to all technologies. This sensitivity analysis will primarily focus on the economic parameters and how they affect the NPV. Their impact on the power fluctuations will be discussed in the next chapter.

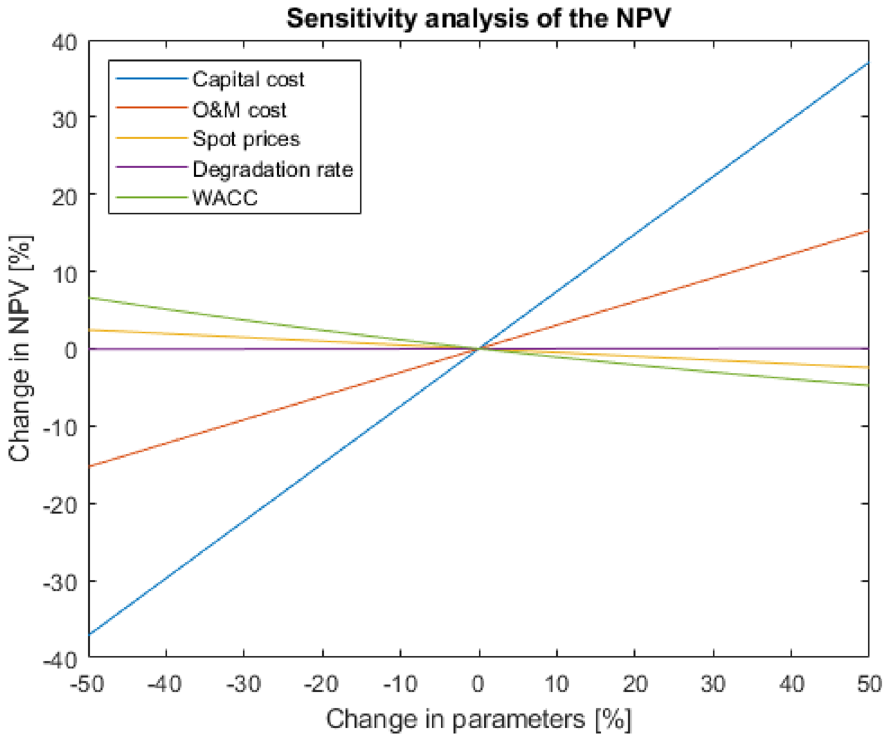

Figure 5.7: Sensitivity analysis of the NPV model for different parameters.

The sensitivity analysis of the different technologies and wind hybrid system clearly displays that the NPV is very sensitive to capital costs and O&M costs. This indicates that any cost reduction or savings in the initial investment can have a significant impact on the total cost of ownership of the systems. Therefore, it is crucial to carefully evaluate the capital costs of the hybrid systems during the design and planning phase to ensure that the systems are cost-effective and efficient. Furthermore, the NPV is sensitive to the WACC. This means that it is important to carefully evaluate the financing options for the systems during the planning and design phase. By analyzing the potential changes in the WACC, the system's financial viability can be assessed, and appropriate financing options can be identified to minimize the overall cost of the systems while ensuring that the systems meets its performance goals.

6 Discussion

This section analyses the results by discussing different perspectives of the executed simulations. Results are discussed according to the technical, economic, and power fluctuation results in the previous sections presented in chapter 4.

6.1 Technical analysis

From the technical results it is clear that the wind and wave power densities are superior to the solar power density. This can be attributed to the geographical location of the project being in the Nordics where solar irradiance is scarce throughout the winter and fall. However, OSWC technology is not able to convert the wave resource in an efficient way. This is evident in the power generation graphs where the OSWC does not live up to its potential by only being able to average a very small portion of its installed capacity, while the FPV are able to average a greater portion of its installed capacity.

The Li-Ion BESS does not contribute additional power to the grid; instead, it depends on wind power for charging. Figure 5.4 illustrates that the BESS is either fully charging or discharging throughout the year, or it shows the remaining capacity to be fully charged or discharged. The graph depicting hourly wind power generation in the figure reveals a gap around the 4,000-hour mark. This gap indicates a lack of power supplied to the grid, which is also evident in the BESS graph. The absence of wind power prevents the battery from being charged, resulting in the inability to provide power to the grid.

Especially table 5.4 helps us answer research question number two on how the power generating technologies differ individually. Wind power has the lowest coefficient of variability, followed by the OSWC which generated a lower value than FPV indicating it to be more consistent and less volatile. A low value could imply a greater possibility of prediction, and more consistent power supply could be engendering enhanced confidence and reliability in long-term planning and investment strategies. The improved predictability of power supply is a critical consideration for energy providers, grid operators, and policymakers in their deliberations concerning infrastructure development, capacity planning, and resource allocation. A higher value implies more challenges with predictability leading to balancing problems for the electrical grid. Nevertheless, it is crucial to bear in mind that a low variability does not necessarily imply a positive effect on the balancing of the grid. Considering that demand fluctuates over time and does not follow a constant pattern, it becomes imperative for power production to align with consumption in order to achieve a state of balance. This is considered in the power fluctuation analysis.

The coefficient of variability and standard deviation values suggest that the FPV system have a higher mean power production compared to the OSWC system. Additionally, the OSWC exhibits the lowest mean ramp rate, potentially due to its lower mean power production. When it comes to exceeding the ramp rate limit, FPV has a lower value, indicating less frequent and unpredictable fluctuations in energy generation. This lower value is beneficial as it reduces the risk of grid overload when energy generation surpasses the limit. Conversely, higher values can lead to more frequent fluctuations, increasing the likelihood of grid overloading. Moreover, a decrease in energy generation without proper management can result in energy shortages and blackouts.

Based on the provided indices, it is clear that the OSWC exhibits lower variability compared to FPV when considering them individually. Although FPV has the lowest number of hours exceeding the ramp rate limit, it still has a higher mean ramp rate. It's important to note that exceeding the ramp rate limit is not always detrimental to grid balancing. In certain situations, such as during periods of high demand or unforeseen weather fluctuations, it may be necessary to rapidly adjust energy generation to meet demand and maintain grid stability.

Figure 5.3 display a strong cross-correlation between the wind and wave power densities, indicating their similarity and the wave dependency of wind. On the other hand, the solar-wind correlation is weak, implying that solar power can compensate for the absence of wind, resulting in a more consistent power production throughout the year as shown in figure 2.11. OSWC also has the lower time lag when compared with FPV. A short time lag with a high correlation between wind and wave indicates a developing sea that is dominated by wind-waves generated by the local wind. Conversely, a large time lag with a high correlation indicates a fully developed sea, where the ocean wave is produced by the wind and continuously increases in size due to sustained wind. The extended time lag highlights that the wind speed is greater than the wave speed, resulting in a prolonged wave propagation time. Typically, a low correlation and long time lag between both renewable sources, as between FPV and wind power, are considered desirable indicators for power smoothing and combined exploration. In contrast, a high correlation with a short time lag is not preferable. As the wind and wave are highly synchronized, this causes the power peaks and valleys to occur simultaneously and not leveling the generation.

Reviewing the results of the technical analysis the variability indices are implying OSWC to be the most consistent individually but the cross-correlation is implying FPV to be more suitable for system integration with wind power.

6.2 Economic analysis

Figure 5.6 is revealing that currently neither of the considered technologies have an installed capacity yielding a positive NPV over the next 25 years, except for scenario 1 of FPV. This means that only one scenario of one of the technologies are economically tenable at the moment. In the case of the OSWC there are no indications of an NPV increase for either scenario. An investment in a BESS is not generating as much losses over the lifetime as for the OSWC, but is still too expensive to yield a positive NPV for any installed capacity. The NPV of the different scenarios for FPV is indicating that it is the most mature technology when comparing the three considered. It is important to recognize that the lack of economic feasibility does not exclude the possibility of investing in these technologies for other reasons. For instance, investing in renewable energy projects can contribute to gaining valuable experience, fosters innovation and research, paving the way for future advancements in the considered technologies, which may eventually make them economically viable in the future. Furthermore, such investments play a crucial role in reducing carbon emissions and addressing the adverse effects of climate change, which are issues that profoundly impact the environment, society, and the economy. Investing in renewable energy not only contributes to a more sustainable future but also promotes the development of a sustainable economy. Therefore, while a positive NPV is an essential consideration for investment decisions, it should not be the sole factor taken into account. The broader benefits of investing in renewable energy projects, such as environmental preservation, social welfare, and technological progress, should also be given due consideration.

The current state of the technologies suggests that they are not mature enough for immediate investment. However, these technologies hold significant potential for future development and are expected to become more cost-effective and prominent contributors to the power system. Since the wind farm is not scheduled for operation until 2030, there is ample time for further refinement and maturation. Nevertheless, it is worth considering the impact of the current economic conditions, characterized by high inflation, which may hinder the expectation of lower capital costs in the near future. However, rising inflation can also result in higher electricity prices, which can enhance the competitiveness of renewable energy sources. Consequently, investments in renewable energy become more appealing as they offer stable, long-term energy costs that are less susceptible to inflationary pressures compared to fossil fuel-based power generation. Moreover, the increasing deployment of renewable energy technologies is crucial to achieving the goals established by governments and institutions worldwide. While subsidies for renewable energy cannot be relied upon today, it is not unrealistic to anticipate the implementation of several subsidies in the coming years to expedite the development and installation of renewable energy. Also, recent events such as the conflict in Ukraine and disruptions in gas pipelines from Russia have highlighted the vulnerabilities associated with dependence on fossil fuels for energy production. In contrast, renewable energy production methods offer greater energy security and independence since they can be sourced domestically. Investing in renewable energy reduces reliance on fossil fuel imports and strengthens energy resilience in the face of price fluctuations and geopolitical tensions. Overall, despite the current immaturity, the potential of the considered technologies, the long-term cost stability they offer, and the enhanced energy security they provide make investments in renewable energy a viable and strategic choice for the future.

Predicting price scenarios for the energy market is an extremely challenging task due to the high level of uncertainty. The events of the past three years have clearly demonstrated this unpredictability. The global COVID-19 pandemic in 2020 had a profound impact on various aspects of people's lives worldwide, including energy markets. Additionally, the 2022 conflict between Ukraine and Russia significantly disrupted the European energy market, leading to a sharp increase in prices due to limitations on natural gas supply from Russia. These unforeseen events have had long-lasting effects on the energy market and highlight the inherent difficulties in accurately forecasting its future dynamics. To address these challenges, the developed price scenarios drew inspiration from Svenska Kraftnät's long and short-term energy market scenarios. This approach aimed to incorporate reliable background information into the price scenarios. However, it is important to note that despite the well-supported arguments behind these scenarios, they still remain uncertain and carry a significant impact on our analysis. The recognition of this uncertainty underscores the need for caution and flexibility when interpreting and utilizing these results as a basis for investment.

In the economically viable scenario, it is unreasonable that the installed capacity of FPV surpasses that of the Neptuni wind farm since FPV is intended to complement the wind farm's energy generation. This issue extends to other technologies as well, where an installed capacity of 1,000 MW or 1,000 MWh not only incurs high costs but also requires an impractically large area both onshore and offshore. For example, considering a FPV plant consisting only of panels with an installed capacity of 1,540 MW and an area of one solar panel measuring 1.76 m^2, the total surface area amounts to 6.776 km^2 . This area would be even larger if the structures and modules of the FPV plant were taken into account.

The sizes of the technologies were selected to roughly align with the calculated optimal FPV capacity for scenario 1, and to analyze four sizes that differ significantly. The remaining capacities for other scenarios were determined based on the prices outlined in the price scenarios. Lower prices in the scenarios correspond to lower assumed capacities to be installed. For example, among the two scenarios based on Svenska Kraftnät's predictions, scenario 3 encompasses a higher level of electrification and, consequently, predicts higher prices compared to scenario 2. An increasing energy demand from the electrification of the industry and transport sector leads to higher electricity prices, in turn leading to increased revenue and therefore larger installed capacities of the technologies considered. However, given that none of the technologies demonstrated a positive NPV, it is advisable for the Neptuni project to commence with a modest installed capacity as demonstrator projects which are seldom economically favorable. This approach rather allow for experience gain and a gradual advance of the technology, while also setting an example to the industry, and establishing RWE as early pioneers of the technologies.

The economic analysis help us answer research question three. From figure 5.6 it is clear that the FPV is on the brink of commerciality with the only positive NPV out of all the technologies. An investment in BESS or OSWC is not financially justifiable at the moment. However, the NPV analysis is based on the price scenarios which are unsure and impossible to accurately predict. Because of this the results are also unsure, nevertheless the FPV is the most economically feasible technology from the assumptions made in this analysis.

6.3 Power fluctuation analysis

By analyzing the variability indices for each technology, we can identify the most suitable technology to pair with a wind farm in order to achieve the maximum reduction in power fluctuations to the grid. Examining the standard deviation for each technology and scenario, particularly focusing on the wind-solar hybrid, reveals that increasing the capacity leads to a decrease in the standard deviation. This reduction can be attributed to the low cross-correlation between solar and wind, which results in power generation moving closer to the mean value. This effect is particularly pronounced during the summer months when wind power production is lower, and solar power generation is higher. Turning our attention to the wind-wave hybrid, we observe the opposite effect, whereby an increase in installed capacity leads to a rise in the standard deviation. This occurrence is attributed to the high cross-correlation between wind and wave energy sources. In this case, when there is wind, the wave power merely supplements the existing power generation from the wind farm, rather than compensating for the periods when wind power generation is lower. Consequently, this exacerbates the deviation of power generation from the mean value. The BESS also demonstrates a decrease in the standard deviation as the installed capacity increases. This phenomenon can be attributed to the charging of the battery during periods of low electricity prices and discharging during periods of high prices. High prices often occur when wind power generation is low, leading to a reduction in the difference between two data points when the BESS discharges at these periods.

A significant reduction in C_V is observed in table 5.7 for the wind-solar hybrid system as the installed capacity increases. As the standard deviation decreases with increased capacity while the mean value increases, the C_V subsequently decreases. This implies that the variability in the hybrid system diminishes due to a decrease in relative dispersion compared to the mean value. The wind-wave hybrid also witness a decrease in C_V compared to the standalone wind farm, despite an increase in the standard deviation with higher installed capacity. This phenomenon is attributed to the mean value increasing at a higher rate than the standard deviation during the same period. As a result, the overall C_V decreases since the standard deviation is outpaced by the growth in the mean value. This indicates a reduction in relative variability, even though the absolute variability (standard deviation) may have increased. The BESS is operated using a revenue-maximizing approach that focuses on energy trading. It follows a strategy of charging during low price periods and discharging during high price periods. Spot prices are primarily dependent on demand during specific times of the day but in regions where wind power has seen significant growth in recent years, like southern Sweden, spot prices also tend to be low when wind power conditions are favorable. As a result, the BESS frequently charges during these periods. When large capacities of BESS are installed, it imposes a limitation on the total power supply to the grid, which cannot exceed 1,400 MW due to the cable. This means that a substantial amount of energy can be stored in the battery but may not always be supplied to the grid. Consequently, this arrangement leads to a decrease in the mean power delivered to the grid and an increase in the coefficient of variability. Considering the definition of the coefficient of variability, the use of this operational method results in increased variability in power generation from the hybrid system compared to the wind farm alone. If an alternative operational method such as load leveling had been chosen, it could have reduced the variability of power generation to a greater extent than the wind farm operating alone. However, this alternative approach would have generated less revenue compared to the energy arbitrage model used in this thesis. Consequently, for a company seeking profitable investments, operational methods other than energy arbitrage may be considered less feasible in the near term.

As seen in table 5.7, the mean ramp rates is increased for every technology and every scenario except one. Increasing the installed capacity of a hybrid system results in a greater power generation potential, allowing for a higher output of electricity. This increase in capacity leads to higher ramp rates due to the larger difference in power generated between consecutive data points. In an ideal scenario where the power systems perfectly complement each other, the ramp rate would decrease. As mentioned before, it is indeed desirable to have a low correlation and a long time lag between the complementary technology and wind power to compensate for the variability of wind power. The FPV, with its low correlation and long time lag, exhibits a smaller increase in the mean ramp rate compared to the BESS. The OSWC, on the other hand, behaves differently from the other technologies when it comes to increased installed capacity. It experiences the lowest increase (even a decrease for 1,000 MW installed capacity) and does not follow the same pattern as the other technologies. This can be attributed to its individual low mean ramp rate and its high cross-correlation and low time lag with wind power. When wind power generation is high, wave power generation is also high, indicating that a significant portion of wave power during these periods will be curtailed due to the maximum cable capacity being limited to 1,400 MW. Conversely, when wind power generation is low, wave power generation is also low. This, combined with the OSWC's low individual value of mean ramp rate, marginally influences the mean ramp rate of the hybrid system, neither increasing or decreasing it substantially. In summary, increasing the installed capacity of a hybrid system generally leads to higher mean ramp rates. However, the specific behavior of each technology within the hybrid system, including its correlation, time lag, and individual ramp rate, can result in variations in the overall mean ramp rate.

The number of hours surpassing the ramp rate limit is reduced across all technologies and scenarios. As additional complementary capacity is installed, the occurrence of hours exceeding the ramp rate limit decreases. This is due to the requirement that both wind power and the complementary technology must exceed their individual ramp rate limit, which is set at 30% of the installed capacity within one hour, or one technology experiences a significant generation drop or rise. Such instances are less frequent compared to when the wind farm alone surpasses its own individual limit. With larger installed capacities of GW-scale, it becomes even more challenging for a single technology to exceed the limit of ramp rates over 30% of the installed capacity of the hybrid system.

Table 5.7 also reveals that all hybrid systems and scenarios exhibit higher cross-correlation with energy consumption compared to the standalone wind farm. Additionally, as installed capacities increase, the hybrid systems demonstrate a greater cross-correlation. The wind-solar system exhibits the most significant increase, followed by the wind-wave system. Increased cross-correlation between load and power generation in a hybrid system is advantageous as it enhances stability, improves reliability, and optimizes resource utilization. This alignment ensures that power generation closely meets demand, reducing imbalances and fluctuations between production and consumption while promoting efficient integration of the renewable energy technology and a more reliable and sustainable operation of the hybrid system.

The analysis of power fluctuations helps address the fourth research question. As observed in Table 5.7 and supported by the previously discussed variability indices, the solar-wind hybrid demonstrates the most effective reduction of power fluctuations to the grid among all the technologies examined. It consistently exhibits the largest C_V reduction across all scenarios, ensuring compliance with the power ramp rate limit.

Additionally, the solar power component exhibits the lowest cross-correlation with wind power, compensating for periods when wind power generation is insufficient. The solar-wind hybrid also displays the highest increase in cross-correlation with the load compared to the standalone wind farm, leading to higher load matching for the hybrid system and ensuring better grid stability.

Analyzing the findings presented in Table 5.8, it becomes evident that the curtailed energy rises as the installed capacity increases for wind-solar and wind-wave hybrid systems. Within both hybrid systems in scenario 4, the combined output with the wind farm never exceeds 1,400 MW due to the wind farm generating only 1,360.8 MW out of its total installed capacity of 1,411 MW. Curtailment of energy is generally regarded as undesirable since it results in unutilized energy, leading to financial losses and missed opportunities to maximize the technology's return on investment. However, the BESS is not subject to energy curtailment. If the wind farm and BESS were to generate more than 1,400 MW within an hour, the BESS model takes this into account and discharges only the necessary energy to "fill" the cable, storing the excess energy in the battery for discharge at a later time, either later that day or the following day. This approach ensures no energy goes to waste. As a result, higher installed capacity in the BESS leads to less frequent discharges compared to lower installed capacity. Larger installed capacities are more likely to exceed the 1,400 MW discharge threshold more frequently than lower installed capacities. This observation is evident for the BESS-wind hybrid system in table 5.8, where a smaller installed BESS generates more energy throughout the year. In such systems, scheduled energy discharges occur more frequently.

6.4 Sensitivity analysis

The sensitivity analysis shown in Figure 5.7 provides clear evidence that the capital costs and O&M costs have the greatest influence on the NPV. By reducing the value chosen for these parameters, it becomes feasible to achieve a positive NPV for more technologies. Consequently, this leads to increased installed capacity for various technologies. With the previous section in mind; with more installed capacity follows reduction in power fluctuations for the complementary power generation technologies. The confirmation of capital costs as the primary influencing factor on power fluctuations suggests a promising future for the technologies involved. As the capital and O&M costs are anticipated to decrease as the technologies mature, new opportunities arise for expanding installed capacity. The NPV was found sensitive to the WACC as well. Inclusion of the WACC in the sensitivity analysis was motivated by the difficulty in obtaining precise information on the specific value for this type of project. Hence, we selected an assumed value of 5% and explored its variation within a range of -50% to +50% to assess its impact on the NPV. The chosen percentage may have been too conservative, particularly when considering the relatively less mature OSWC and BESS technologies. However, despite this, the negative NPV obtained for these technologies confirms their immaturity and unprofitable nature, thereby suggesting that the choice of percentage did not impact the outcome when examining the investment decisions.

7 Possible pathways for RWE Renewables

7.1 Pathway 1

The initial course of action we recommend for RWE is to make a large-scale investment in the solar-wind hybrid system. The results indicate that this technology not only exhibits the highest economic feasibility among all the technologies investigated but also demonstrates the most effective reduction of power fluctuations to the grid compared to the other technologies assessed. The solar power component has emerged as the optimal match for an offshore wind farm like Neptuni, primarily due to its low cross-correlation and significant time lag. This characteristic makes it an excellent complement to the wind farm, effectively compensating for periods of inadequate wind power generation and ensuring a balanced power supply that meets the demand. By making a large-scale investment in the solar-wind hybrid system, RWE can position itself as a leader in the hybrid system market. This investment not only sets an example for others but also contributes to the advancement of the technology itself. Therefore, investing in the solar-wind hybrid system presents a highly advantageous opportunity for RWE to demonstrate its commitment to innovation and drive the progress of this promising technology.

7.2 Pathway 2

In addition to making a large-scale investment in the solar-wind hybrid system, we recommend a second pathway for RWE, which involves making modest investments in demonstrator projects for research and experiential purposes. This approach, exemplified by collaborations like the SolarDuck project, allows RWE to gain valuable insights and knowledge without immediately pursuing full-scale commercial plants. This strategy applies to various technologies, including FPV, OSWC, and BESS. By focusing on demonstrator projects, RWE can explore the potential of these technologies on a smaller scale while assessing their feasibility, performance, and integration into existing infrastructure. This approach serves as an opportunity for RWE to gather valuable data, identify challenges, and fine-tune their strategies before committing to large-scale deployments. Moreover, such investments in research and experience have the potential to set RWE as a trailblazer in the industry, showcasing their commitment to innovation and pushing the boundaries of renewable energy development.

Furthermore, this pathway offers RWE a competitive advantage in the market. By accumulating early experience and expertise in hybrid systems, RWE can establish themselves as leaders and pioneers in the field. Having already gained practical insights and a deep understanding of hybrid technologies, RWE can navigate the complexities of deployment more efficiently than their industry peers. This positions them as a preferred partner for future projects and enhances their reputation as a company at the forefront of renewable energy innovation. By pursuing this pathway of investing in research and experiential demonstrator projects, RWE can capitalize on the benefits of early engagement, industry leadership, and market advantage. This strategic approach enables RWE to gain valuable experience, establish their position as an innovator, and shape the future of hybrid systems within the renewable energy sector.

7.3 Pathway 3

Another viable pathway for RWE is to refrain from investing altogether. This course of action finds support in several factors, including the limited number of scenarios and technologies that yielded a positive NPV over the 25-year projection period. Coupled with the relative immaturity of all the technologies under consideration, the investment prospects may not be lucrative enough to justify the allocation of resources. Furthermore, the geographical position of the wind farm could present challenges for the implementation of a solar-wind. The effectiveness of such hybrid systems heavily relies on the availability and suitability of the specific resources in the given location. If the wind farm's geographic position does not align favorably with the requirements of the proposed hybrid systems, it may further discourage RWE from pursuing investments in these technologies.

Considering the absence of a solid foundation or compelling justification for investment, RWE may be hesitant to take the leap into any of the technologies. The combination of limited positive NPV scenarios, technological immaturity, and potential limitations imposed by the wind farm's geographical position collectively contribute to a lack of a solid investment basis. By opting to forgo investment in these particular technologies, RWE can focus its resources and efforts on alternative avenues that offer more promising prospects. This strategic decision allows RWE to allocate its investments in areas with higher potential returns and greater alignment with its long-term objectives.

8 Conclusion

In conclusion, the technical and economic analysis of renewable energy technologies, specifically wind power, solar power, wave power, and BESS, provides valuable insights into their individual characteristics and their potential for integration with the Neptuni project.

Chapter 2 highlights the prominent expenses related to system integration, which primarily involve the FPV module, WEC, and the battery module. Additionally, substantial costs are associated with BoP and BOS, including foundations, floaters, module containers, piles, power management systems, and mooring lines. In Chapter 4, a detailed presentation of the CAPEX and OPEX for each technology is provided, showcasing specific values collected from various open sources.

From the technical results, it is evident that wind and wave power densities outperform solar power density in the Nordics due to limited solar irradiance during the winter, fall and nights. However, the OSWC technology struggles to efficiently convert wave resources, resulting in power generation well below its installed capacity. In contrast, PV-cell technology demonstrates better performance.

The analysis of the variability indices reveals that wave power exhibits a lower coefficient of variability than the FPV. This stability may enhance confidence and reliability in long-term planning and investment strategies. Additionally, FPV technology demonstrates lower ramp rate values, reducing the risk of grid overload and ensuring a more stable energy generation.

The cross-correlation analysis shows a strong correlation between wind and wave power densities, indicating their dependence on each other. However, the correlation between wind and solar power is weak, suggesting that solar power can compensate for the absence of wind, leading to more consistent power production throughout the year. These findings highlight the potential for system integration between wind power and FPV technology.

The economic analysis reveals that currently, none of the considered technologies have a positive NPV over the next 25 years, except for scenario 1 of FPV. This implies that none of the technologies are economically viable at the moment. However, the NPV analysis should not be the sole factor in investment decisions. Investing in these technologies can contribute to gaining experience, fostering innovation, reducing carbon emissions, and promoting a sustainable future.

Considering the potential for future development and cost-effectiveness, the technologies analyzed hold promise for becoming more economically viable and prominent contributors to the power system. It is crucial to acknowledge the impact of current economic conditions, such as high inflation, which may hinder expectations of lower capital costs. Nevertheless, rising inflation can also increase electricity prices and enhance the competitiveness of renewable energy sources, making them more appealing in the long run.

The power fluctuation analysis indicates that a wind-solar hybrid system can reduce power fluctuations to the grid by increased installed capacity. On the other hand, a wind-wave hybrid system exhibits increased power deviation due to the high cross-correlation between wind and wave sources. Battery energy storage systems show an increase of variability with higher installed capacity, thanks to their revenue-maximizing charging and discharging strategy.

While the results of the analysis provide valuable insights, it is important to acknowledge the challenges and uncertainties associated with predicting price scenarios and the future dynamics of the energy market. Unforeseen events and fluctuations can significantly impact the viability and profitability of investments in these technologies.

Overall, while the analyzed technologies may not be mature enough for immediate investment, their potential for future development, long-term cost stability, and enhanced energy security make investments in renewable energy a strategic choice for the future. It is advisable to start with modest installed capacities to gain experience and gradually advance the technologies. The broader benefits of investing in renewable energy, such as social welfare and technological progress, should also be considered alongside the economic feasibility when making investment decisions.

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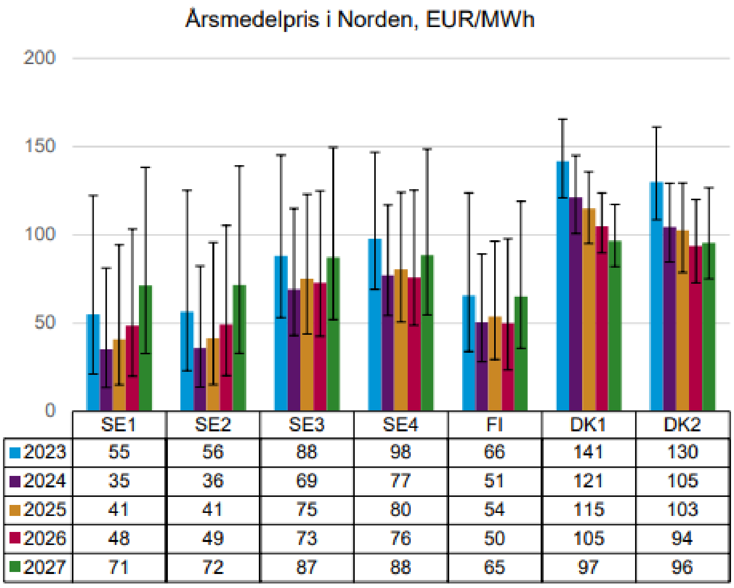
Appendix A

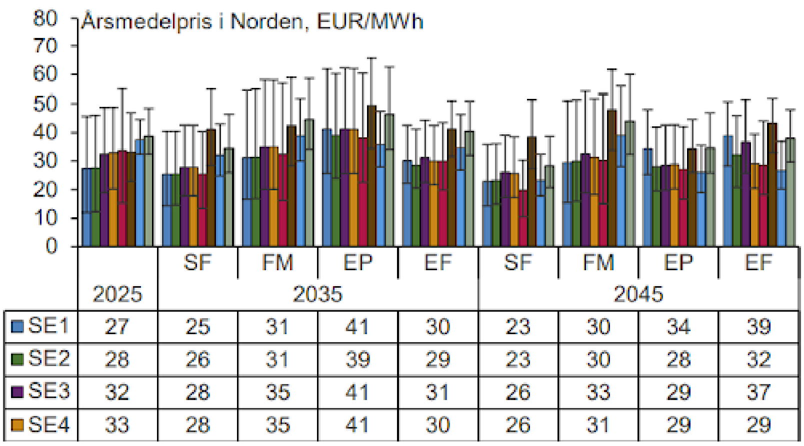
Svenska Kraftnät Scenarios

Below are the original price scenarios that were utilized to shape the price scenarios employed in the thesis. These scenarios, along with the progression of prices, served as a reference point during the creation of the final price scenarios employed in the economic analysis.



	SE1	SE2	SE3	SE4	FI	DK1	DK2
2023	55	56	88	98	66	141	130
2024	35	36	69	77	51	121	105
2025	41	41	75	80	54	115	103
2026	48	49	73	76	50	105	94
2027	71	72	87	88	65	97	96

Figure A.1: Short-term market analysis.[116]



	2025	2035 SF	2035 FM	2035 EP	2035 EF	2045 SF	2045 FM	2045 EP	2045 EF
SE1	27	25	31	41	30	23	30	34	39
SE2	28	26	31	39	29	23	30	28	32
SE3	32	28	35	41	31	26	33	29	37
SE4	33	28	35	41	30	26	31	29	29

Figure A.2: Long-term market analysis.[117]

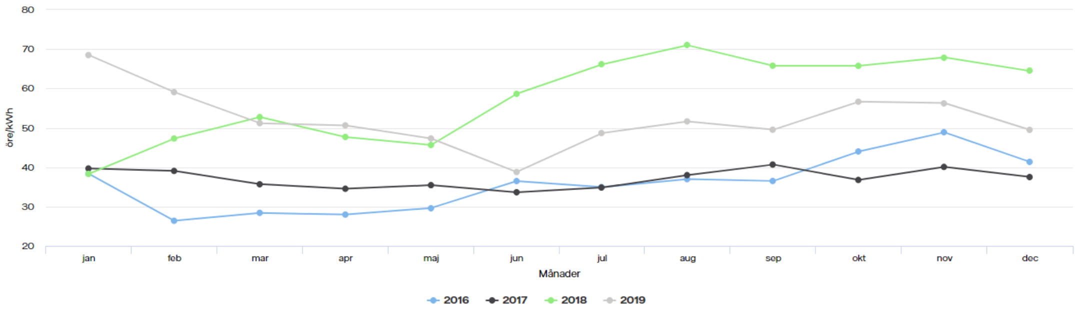


Figure A.3: Price evolution 2016-2019.[118]

Appendix B

Abbreviations

Table B.1: Abbreviations and their explanations respectively.

Abbreviation	Explanation
AC	Alternating Current
BESS	Battery Energy Storage System
BoP	Balance of Plant
BOS	Balance Of System
$C(\tau)$	Cross-correlation coefficient
CAPEX	Capital Expenditures
C_V	Coefficient of Variability
DC	Direct Current
Δ	Ramp Rate
DoD	Depth Of Discharge
EC	Energy Converter
EIB	European Investment Bank
EPC	Engineering, Procurement & Construction
ERO	Effective Resource Occurrence
EU	European Union
EV	Electric Vehicle
FIT	Feed-In Tariff
FOW	Floating Offshore Wind
FPV	Floating Photovoltaic
G	Solar Irradiance (W/m^2)
GDP	Gross Domestic Product
GWEC	Global Wind Energy Council
H_s	Significant Wave Height (m)
HAWT	Horizontal Axis Wind Turbine
HDPE	High-Density Polyethylene
HV	High Voltage
HVAC	High Voltage Alternating Current

Continued on next page

Table B.1: Abbreviations and their explanations respectively. (Continued)

Abbreviation	Explanation
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IPCEI	Important Projects of Common European Interest
IRA	Inflation Reduction Act
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost Of Electricity
Li-Ion	Lithium-Ion
LTH	Lunds Tekniska Högskola
MRE	Marine Renewable Energy
NDA	Non-uniformly Distributed Array
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
O&M	Operational & Maintenance
OPEX	Operational Expenditures
OSWC	Oscillating Surge Wave Converter
OWC	Oscillating Water Column
PCC	Power Conversion Chain
PDA	Peripherally Distributed Array
PTO	Power Take-Off
PV	Photovoltaics
R&D	Research & Development
RLO	Rich Level Occurrence
RWE	Rheinisch-Westfälisches Elektrizitätswerk
SBOS	Structural Balancing Of System
σ	Standard Deviation (MW)
SMHI	Swedish Meteorological Hydrological Institute
SPIC	State Power Investment Corporation
STC	Standard Test Conditions
SVK	Svenska Kraftnät
SWEA	Swedish Wind Energy Association
SWOT	Strengths, Weaknesses, Opportunities and Threats
τ	Time Lag (h)
T_e	Significant Wave Period (s)
TSO	Transmission System Operator

Continued on next page

Table B.1: Abbreviations and their explanations respectively. (Continued)

Abbreviation	**Explanation**
UDA	Uniformly Distributed Array
v	Wind Speed (m/s)
WACC	Weighted Average Cost of Capital
WEC	Wave Energy Converter
WPD	Wind Power Density

Appendix C

Figures

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Appendix D

Tables

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