Offshore Wind + Energy Storage

Selection and design of energy storage for the integration of offshore wind energy in the future Dutch electricity system

by

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Preface

This report concludes; my master's degree in Mechanical Engineering at Delft University of Technology, and my contribution to the understanding of the energy transition the world is facing. And to me, like the great artist Bob Dylan wrote many years ago,

The answer, my friend, is blowin' in the wind

Offshore wind energy is playing a key role in the energy transition in the Netherlands, but there are obstacles which have to be overcome to reach its full potential. With this thesis I contributed to the understanding of the challenges faced with integrating offshore wind energy into the Dutch electricity system, and where the key solutions lie for the obstacles. However, I could not have done it alone.

First, I would like to thank all the people at Eneco for the chance to get to know the company and the energy business during this internship. My direct supervisor René Bos of whom I learned a great deal about the offshore wind and conducting a scientific research in a work environment. My other supervisors Leon van der Meijden and Ferry Boerefijn for their enthusiasm in the topic and their critical view on my work. And a special thanks to Roald Arkensteijn for introducing me to Eneco and the continuous interest in my work. I have learned lots from all our conversations and your insights in the future energy markets.

I'm thankful for the great guidance from my TU Delft supervisors, Henk Polinder and Wiebren de Jong. From the moment that I introduced the topic of this report you have been enthusiastic and supportive. This has greatly boosted my enthusiasm and efforts into this research. In the hard times when this enthusiasm was a bit less, with your constructive feedback you put me on the right track again. Thank you for making the time to supervise me in the past 8 months, and a special thanks to Ruud Kortlever for making the time to complete the graduation committee.

On a more personal note, I would like to thank my family and friends; My fellow interns for the good company in the office. My friends for the help with my report and the sometimes well needed distraction from the research. And above all thanks to my parents for their help and support in this report, but moreover thanks for the continuous support during my time as a student, which has finally come to an end.

Coen Ponsioen
Delft, May 2019

Summary

The Dutch government has set out to largely reach reductions in carbon emissions in the electricity sector with the utilization of offshore wind energy. Due to the intermittency of wind energy this poses new problems and challenges for the future Dutch electricity system. The objective of this report is to identify the challenges for the electricity supply of offshore wind farms (OWFs) and to research how energy storage and alternative wind turbine design can aid in these challenges. For this objective a time horizon of 2025 to 2050 is chosen, as this is the period in which the now designed wind farms will be producing electricity. This has led to the research question:

> *”How does energy storage fit in the design of multi-hundred megawatt offshore wind farm systems in the Netherlands in 2025?”*

The literature review into wind turbine solutions identifies system friendly wind turbine design as a principle to reduce the integration issues of offshore wind. In the system friendly design, the rotor diameter of the turbine is increased without increasing the generator capacity. For large scale energy storage (ES) six storage techniques are identified as suited to be applied in combination with an offshore wind farm. For offshore storage, decentralized Li-ion storage in the monopile of the wind turbine is identified as technical most viable option. The six storage techniques further assessed in the report are:

- Compressed air ES
- Li-ion battery
- Sodium sulfur battery
- Flow battery
- Hydrogen ES
- Liquid air ES

To answer the research question, firstly measured and simulated data of offshore wind electricity production is analyzed to identify the key challenges. Secondly the data is used as entry in a Matlab model, that is constructed to simulate a storage facility. The discharging strategy of this model can be focused on two purposes; profile effect reduction or maximization of the revenue of the system. Thirdly the Matlab model is used to determine the optimal configuration of the storage facility in combination with an OWF. Fourthly, determine the optimal design of the turbines in an OWF combined with a storage system. Finally, the impact of the optimal design into the future Dutch electricity system is analyzed.

This research has led to the following conclusions: Of the challenges for future offshore wind farms do short-term profile effects have the most influence. These effects negatively affect: 1. the security of supply in the electricity system, 2. the stability of the load on the high voltage grid and 3. the market value of the produced electricity. The impact of these factors is intensified by the strong correlation in power production between the connected (future) onshore and offshore wind farms. To reduce short-term profile effects energy storage is added to the offshore wind farm. The optimal configuration of such a storage facility has a power capacity between 0.23 and 0.27 times the rated power of the wind farm. For this system an optimal energy capacity is not obtained, however it was determined that the most cost-efficient storage technique is; Li-ion batteries for small energy capacity, liquid air energy storage for medium energy capacity and hydrogen storage for large energy capacity.

The impact analysis of the optimal configuration of an OWF in combination with a storage facility, shows that the system is economical not feasible in the future Dutch electricity market. However, energy storage is essential in a future electricity system that is dominated by wind and solar power. The short-term profile effects of wind energy are correlated too much and will have a too high impact on the system if no energy storage is included in offshore wind electricity production.

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Nomenclature

List of Abbreviations

AEP	Annual Energy Production
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
COS	Cost of Storage
DAM	Day Ahead Market
DoD	Depth of Discharge
DSO	Distribution System Operator
EPEX	European Power Exchange
ESS	Energy Storage System
FCR	Frequency Containment Reserve
GS	Gravity Storage
HESS	Hybrid Energy Storage Systems
LAES	Liquid Air Energy Storage
LCOE	Levelized Cost of Energy
LCOS	Levelized Cost of Storage
LUD	Luchterduinen
MMC	Modular Multi-level Converter
NaS	Sodium Sulfur
NGCC	Natural Gas Combined Cycle
OPEX	Operational Expenditure
OWF	Offshore Wind Farm
PCR	Primary Control Reserve
PHS	Pumped Hydro Storage
PPA	Power Purchase Agreement
PTES	Pumped Thermal Energy Storage
PV	Photovoltaic
RTO	Regional Transmission Operator
SMES	Superconducting Magnetic Energy Storage
SNG	Synthetic Natural Gas
TES	Thermal Energy Storage
TSO	Transmission System Operator
VRB	Vanadium Redox Battery
WP	Wind Park

Greek Symbols

η_{rosd}	rate of self-discharge efficiency	$-$
$\eta_{roundtrip}$	round trip efficiency	$-$
ρ	density	$\frac{kg}{m^3}$

List of Symbols

a	induction factor	$-$
A_{swept}	area swept by turbine rotor	m^2
AEP	annual energy production	MWh
$C_{charging}$	charging cost	$\frac{euro}{MWh}$
C_{eff}	cost effectiveness	$\frac{euro}{ton\ CO_2}$
COS	cost of storage	$\frac{euro}{MWh}$
d_{rotor}	rotor diameter	m
$E_{capacity}$	energy capacity	MWh
$E_{discharged}$	electricity discharged	MWh
ef_{CO_2}	CO_2 emission factor	$\frac{ton\ CO_2}{MWh}$
$EPEX$	EPEX price	$\frac{euro}{MWh}$
$LCOE$	levelized cost of electricity	$\frac{euro}{MWh}$
$LCOS$	levelized cost of storage	$\frac{euro}{MWh}$
P	power	W
$P_{capacity}$	power capacity	MW
$P_{density}$	power density	$\frac{W}{m^2}$
P_{mean}	mean power produced	W
P_{rated}	rated power	W
r	discount rate	$-$
SoC	state of charge	$-$
t_{step}	time step	hr
U	wind speed	$\frac{m}{s}$
$U_{cut\ in}$	cut-in wind speed	$\frac{m}{s}$
$U_{cut\ out}$	cut-out wind speed	$\frac{m}{s}$
U_{rated}	rated wind speed	$\frac{m}{s}$

1

Introduction

Governments around the world have set out to prevent the global average temperature from rising more than 2°C in the Paris 2015 climate agreement [1]. A major role in preventing the global warming is the transition from a society that is fossil fuel based to a renewable energy-based society. This energy transition makes for the electricity sector in the Netherlands to switch from fossil fuels to harvesting wind and solar energy [2]. However, these are sources of energy that vary in availability and power. The so-called intermittency of these renewable energy sources results in a non-constant electricity production that is not available on demand. Due to the limited space available in the Netherlands, the Dutch government has planned to build offshore wind farms (OWFs) in the North Sea. Replacing the on demand available fossil fueled electricity sources with non-constant electricity production, that is located offshore, introduces new challenges. The objective of this report is to identify the challenges for the electricity supply of OWFs and to research how electricity storage in combination with alternative wind turbine design can aid to overcome these challenges. The scope for this research is limited to an offshore wind farm that is built in 2025 that uses power 2 power (P2P) electricity storage.

1.1. Offshore wind power

Electricity generated using wind turbines is unstable as the production is subjected to intermittent wind energy. This intermittency is caused by the profile effects of wind energy and is classified in three conditions; 1. annual fluctuations, 2. seasonal fluctuations and 3. short-term profile effects. The non-constant produced electricity is fed to the grid and needs to be predicted one day ahead, for the grid operator to be able to balance this supply with the demand. The deviation between this day ahead forecast, based on the weather forecast, and the realized electricity production is defined as imbalance. In appendix A the wind conditions together with the imbalance are elaborated more thoroughly.

In table 1.1 the different electricity markets on which it is possible to trade are shown. The majority of electricity produced by wind turbines is traded and sold on the European Power Exchange (EPEX) spot market [3], formerly known as the Amsterdam Power Exchange (APX) market. The price on this spot market is dependent on the available supply and demand, using the merit order the price is determined for every hour of the day. Wind and solar power generated electricity have low marginal cost and are in times of peak production pushing the higher order plants out of the merit order, steering the price down. In times of little wind or sunlight the wind turbines and photovoltaic (PV) panels are not able to produce electricity and the power from peak power plants is necessary, steering the price up. Adding intermittent renewable sources to the energy mix results in a highly volatile electricity price, as is further elaborated in appendix B.

Table 1.1: Wholesale electricity markets in the Netherlands [4]. The majority of the electricity produced by offshore wind is traded on the Day Ahead Market [3].

Market	Time frame	Bidding period	Description
Bilateral agreements	>1 month	1 yr	Non transparent bilateral trade agreements between large volume producers and consumers.
Day Ahead	**1 hr**	**1 day**	**Daily EPEX spot market explained in appendix B**
Intraday	5-15 min	15 min	Real time spot market for small volumes of electricity
Reserve capacity	Stand by	1 week	Primary, Secondary and Tertiary response to preserve the power quality on the grid.
Imbalance	15 min	Real Time	Market to balance the deviation between the DAM bid obligation and the produced electricity

Wind energy in Europe has seen major developments the past few years and is expected to keep growing in the coming years. The growth in the installed wind capacity is relative to the current capacity for a smaller part onshore and a large part offshore. In every scenario sketched wind energy will grow to large proportions both onshore and offshore, resulting in a high wind energy induced grid penetration [1].

An attractive location for the installation of wind power is the North Sea basin, due to its strong winds and relatively densely populated surrounding countries. This can be seen in the capacity growth expectations for this area where, until 2030, a growth of 300% up to 650% is expected in the divergent scenarios sketched by Wind Europe [5]. The larger concentration of offshore wind power in the North Sea results in a higher expected grid penetration for the North Sea neighbouring countries compared to the EU average. In the Netherlands a penetration of 40% to 50% is expected, with respect to the 30% for the EU overall. Appendix C provides a more detailed overview of the scenarios, wind penetration in the electricity markets and the expected growth numbers for the EU and the Netherlands.

A part of the success of wind power in Europe is related to government subsidies for the development of wind turbines and wind farms. For offshore wind energy in the Netherlands this subsidy comes in the form of a feed-in tariff. In this case the company operating the wind farm will get the electricity price as traded on the EPEX market. The condition holds that if the EPEX price is below an agreed-on price, the government will supplement this gap. Meanwhile the Dutch government sets out on a cost reduction for the construction of the wind farms. This is stimulated by simplifying the tender rules and requirements for bidding on an OWF tender. The government achieves this by providing the preliminary research, such as geological analysis, and arranging the high voltage connection from the OWF to shore. The transmission system operator (TSO) builds and operates the connection to the grid onshore in which the power is further distributed to the consumer. This arrangement has been a great success in the past year and a major cost reduction is achieved by technical development. Due to this success the new rounds of tenders is expected to be bid without the need for feed-in tariff subsidy [6].

1.2. Problem Description

Due to the success of this policy and subsidy programs of European governments, Offshore Wind Farms are being built rapidly in the North Sea. While this offshore wind energy becomes a growing share of the electricity market, it is also increasing the problems experienced with integrating this intermittent source of energy into the electricity market. The fact that the electricity production is not available on demand and sometimes stops completely poses a major problem. In order to make a clear analysis of this problem, it is split into multiple sub-problems elaborated in this section.

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[1] The share annual electricity production (AEP) of wind power with respect to the AEP of the whole electricity mix

1.2.1. Intermittency of Offshore Wind

As described in Appendix C the grid penetration of wind power for North Sea countries increases significantly in almost every scenario for the coming years. The effects of intermittency, described in Appendix A, will not disappear with this increasing penetration, but will in fact intensify.

Dispatchable generation is pushed out of the market by the low marginal cost intermittent sources of energy, as described in appendix B. In terms of carbon emission reduction this is a good effect, since renewable electricity generation is replacing carbon emitting electricity generation. The intermittency of wind energy results in moments where the ample installed capacity is not generating electricity and cannot meet the electricity demand. Due to the strong correlation of onshore and offshore wind energy the installed capacity will experience the same shortage in power production and create a shortage in electricity. Normally at such moments dispatchable generation would be deployed, but this capacity is expected to have been pushed out of the market and closed down. To prevent shortages and blackouts, other sources have to replace the conventional dispatchable generation.

The market value of electricity generated by offshore wind is decreased due to the extra measures necessary to counter the intermittency of wind energy. The reduction in market value[2] can be summarized in the integration cost of wind power. The integration cost consists of; profile cost [3], balancing cost [4], and grid-related cost [5] and decreases the market value of electricity produced by the intermittent wind power source [7]. This decrease in market value intensifies when the share of wind power in the electricity mix becomes significant [8] and can be considered identical to the societal impact or extend of technical difficulties [9]. Hirth et al. predict a drop in revenue from 100% to 50-80% of the market average, for a growth to 30% wind power grid penetration. The models used consider a divided installation of onshore and offshore wind power spread over countries that are lighter populated compared to the Netherlands. The fact that the Netherlands is limited in space for installation of onshore wind power, and the North Sea provides a hot spot location for offshore wind power, the market value of wind energy is expected to further decrease. This intensified decrease in market value for increasing market penetration is referred to as the self-cannibalization effect. It is caused by the strong correlation in power production between the wind farms. The majority of the Dutch offshore wind capacity in 2030 is modelled to be 92% correlated in power production as shown in appendix C.2.1.

In this report the market value of wind energy is used as a comprehensive tool that quantifies the: integration issues, self-cannibalization effect and inability to follow the electricity demand profile. The amplification of the first two mentioned is caused by the concentration and correlation of OWFs in the North Sea. A possible solution could be to use the electrical interconnection between countries in Europe to dampen out the short-term profile effects [10]. This, however, does not hold since the wind power supply and demand in these countries is also highly correlated [11]. As the electricity demand should be met at all times, it requires for significant back up power that could counter the short-term profile effects in times of little wind. Additional power for intercepting the imbalance is necessary as well.

Phasing out of the feed-in tariff subsidy plan and the decreasing market of the OWFs generated electricity is posing a threat on the ability to get a return of investment. The payback is highly dependent on the revenue from electricity, which is based on the annual yield, the electricity price and the market value. A decreasing market value could result in investors becoming more reluctant to invest and build OWFs. This can result in that the planned wind farms will not be built anymore as financing the project becomes much more difficult.

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[2] Market value can be described by the average revenue per kWh divided by the average market price for electricity

[3] The cost to counter the profile effects wind power production, described in section A.2

[4] The cost to counter the uncertainty, imbalance, of wind power production. Described in section A.3

[5] The cost for: Power quality control necessary, Transportation of power that is produced at locations where it is not consumed and Congestion

This poses a problem for Dutch government as this carbon neutral source of electricity is an essential part of the plan for 2030 to comply with the Paris Climate Agreements.

1.2.2. Offshore wind power opportunities

Although the integration issues and cost tend to form the main focus, there are also additional issues/opportunities faced in the shifting electricity market and the growing size of wind turbines. Two of these issues are highlighted in this research.

The power curve of wind turbines tend to be shifted by the manufacturer over the lifetime of the turbine. This is possible by increasing the generator power capacity and thus the rated wind speed over the wind turbine [12]. This has two effects on the electricity production; an increase in imbalance and a decrease in infrastructure load. The increased imbalance arises from the decreased time of the velocity of the wind being higher than the rated wind speed. This causes larger errors in the day ahead forecast of electricity production. The decreased load on the electrical infrastructure originates from the drop of the capacity factor [6]. If the capacity factor, and thus the total load over the infrastructure, decreases it will increase the levelized cost of energy (LCOE) of this component of the system. The infrastructure is a significant part of the total cost [13] and will become more significant over time, when OWFs are located further from shore [6].

Power quality of electricity generated by intermittent sources of energy puts an increasing load on the high voltage grid with increasing grid penetration. Conventional electricity generation, that is securing the power quality on the grid, is disappearing due to its polluting nature. Basically, power that is able to increase or maintain the power quality is taken out of the grid and replaced with generation that is reducing the power quality. Offshore wind is one of these renewable sources that is decreasing the power quality in multiple domains. To maintain the quality in the grid and prevent blackouts, a solution has to be found for these systems.

1.3. Research Objective

The subject of this research is the role of electricity storage in future offshore wind energy systems. The next generation offshore wind farms in the Netherlands that are tendered, are built in 2025 and have a lifetime of 25 years. Therefore, a time horizon of 2025 to 2050 is chosen for this research. The goal and objective of this report is to research the issues extracted from section 1.2 and resulted in the research question:

> *”How does energy storage fit in the design of multi-hundred megawatt offshore wind farm systems in the Netherlands in 2025?”*

In order to answer the main research question several sub-questions were identified:

- *What are the challenges for offshore wind energy in the future energy system in the Netherlands?*
- *What form and how much energy storage is necessary to solve these challenges faced with offshore wind?*
- *What is the techno-economic optimal configuration of an offshore wind + storage system in 2025?*
- *Can an offshore wind + storage system cost effectively eliminate the risks of self-cannibalization for North Sea wind farms in 2025?*

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[6] The capacity factor is the ratio of the realized electricity output over the maximum possible electricity output for the period of a year

1.4. Approach

In order to answer the questions identified in the research objective and make recommendations for future wind farm design an existing OWF will be analyzed, Luchterduinen Wind Park. This OWF is introduced below and its measured data serves as the basis of the data analysis and is used as input for the model simulations. The Matlab model is constructed to simulate a storage facility in combination with an offshore wind farm, in one system. Using the model, the optimal configuration for such a system is determined, after which its impact is assessed in the future Dutch electricity system. Finally, the results are discussed and a conclusions are drawn.

Luchterduinen Wind Park is a second generation OWF that is built in the Dutch North Sea as part of the strategy towards carbon free electricity production. After a two-year start-up period were all contracts signed in 2013, and in 2014 construction was started. In 2015 Luchterduinen Wind Park was fully operational has been operated by the Dutch energy company Eneco since. The location of the wind farm was chosen 23 kilometers of the coast of Noordwijk. The layout of this wind farm, consisting of 43 Vestas V112 wind turbines, is shown in figure 1.1. In this figure it is visible that the wind turbines are lined up perpendicular to the dominant wind direction.

Luchterduinen Wind Park		
Nr. of tubines	43	
Rated power	129	MW
Annual Energy Production	531	GWh
CO_2 emissions avoided	275	$\frac{Mton}{year}$
Vestas 3.0 V112		
Rated Power	3.0	MW
Cut-in wind speed	3.0	$\frac{m}{s}$
Cut-out wind speed	25	$\frac{m}{s}$
Rated wind speed	12	$\frac{m}{s}$
Rotor diameter	112	m
Hub Height	81	m

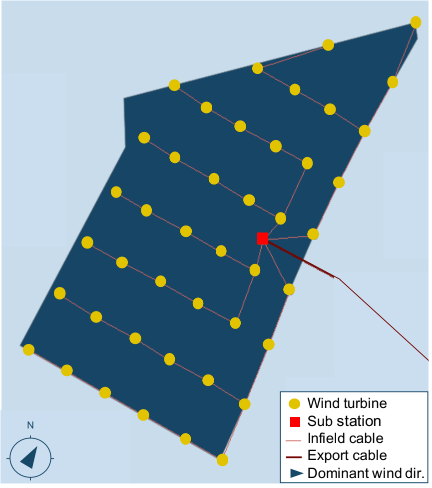

Figure 1.1: Layout of the Luchterduinen Wind Park located 23 kilometer of the coast of Noordwijk, the Netherlands.

1.4.1. Report Outline

The research is documented in a report consisting of six chapters. The outline of the report is as follows:

- Chapter 1 consists of the introduction, the problem description and the research objective.
- Chapter 2 presents the findings of a state-of-the-art literature review into large scale energy storage and wind turbine design.
- Chapter 3 provides the methodology, the model description and the background information of the research.
- Chapter 4 contains the results. Firstly, a data analysis is conducted to determine the major issues of offshore wind that can be solved with energy storage. Subsequently the model is used to determine the optimal configuration for an offshore wind + storage system that tackles the issues identified. Finally, the impact of the storage facility is determined, and the additional utilization are identified.
- Chapter 5 provides the discussion of the results presented in chapter 4.
- Chapter 6 presents the conclusions and recommendations made.

2

State of the Art

The issues described in section 1.2 are not new to the sector and much research has been conducted in this field. One of the key solutions would be to store the electricity generated by the OWFs to later access the electricity when it is demanded. In this literature review the state-of-the-art of large scale energy storage and the alternative designs for OWFs are researched. To get a clear overview of the previously conducted research at first the available storage techniques will be assessed, secondly the wind integration and wind turbine solutions will be evaluated and lastly the conclusion is drawn.

The scope of this research is a 129 MW offshore wind farm which is assessed in a system with energy storage. A system that combines an offshore wind farm and a storage facility in one system is identified as an offshore wind + storage system and defined by.

Offshore wind + storage system; *an offshore wind farm in combination with a storage facility, located offshore or onshore, that together as one system feeds electricity, through the high voltage connection, to the grid.*

2.1. Large scale energy storage system

In this section the state-of-the-art in energy storage is assessed. The precise dimensions of the energy storage system (ESS) used are still unknown, but large scale, or in literature referred to as grid scale, can be assumed. The options for efficient electricity storage applied on the scale of this research are classified into five groups which are represented in figure 2.1. In this section these different methods of energy storage will be explained in their working principles and at the hand of several examples. After the working principles a quantified overview of the storage characteristics is made in table 2.1. The examples given in this section are not the only method of energy storage in the category but in the light of the application the most relevant option.

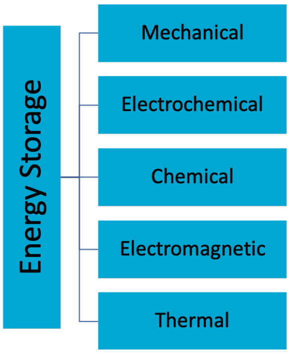

Figure 2.1: The classification of the different techniques for a large scale energy storage system

2.1.1. Mechanical storage

Using the application of the electric motor electricity seems to lend itself perfectly to be converted into a controlled rotational movement. This movement can be used to drive a machine that is able to store this momentum in some kind of form. In this research the techniques considered for the storage of electricity are; pumped hydro storage, gravity storage, CAES and flywheel storage.

Pumped hydro storage

The majority of the storage capacity installed today is in the form of pumped hydro storage (PHS) [14]. This technique uses the difference in potential energy by pumping water from a low altitude reservoir to an elevated reservoir in times of excess electricity. When the electricity is demanded the elevated water will run through a turbine driving a generator. The configuration of the system differs per location where in some cases the pump is acting as turbine. A schematic representation is given in figure 2.2.

PHS is able to achieve high round trip efficiencies in combination with a long lifetime and low cycle cost. However, is the large upfront investment together with the large environmental a barrier to overcome. Nevertheless, has PHS been commercially applied on a large scale since 1929 on geographical favorable locations where naturally elevated reservoirs occur [15]. In locations where there are no natural reservoirs available, it is possible to create artificial elevated reservoirs by constructing a dam or with the use of underground reservoirs. Many ideas have been proposed to create artificial reservoirs with artificial head, but none have been applied on large scale.

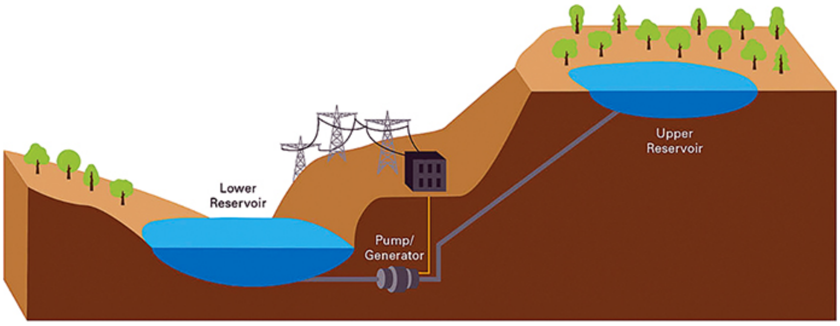

Figure 2.2: A schematic representation of a PHS system that uses natural reservoirs to store energy [16]

Gravity Storage

A different utilization of potential energy for the purpose of storing electricity is gravity storage. Gravity storage is working on the same principles as PHS where PHS is changing the potential energy of liquids (water), does GS store energy by changing the potential energy of solid materials. By lifting and releasing a solid, potential energy is stored and retrieved. A promising technique that uses this principle is the system developed by GravityPower [17]. This system (re)uses large cavities in the ground of which the walls are adjusted so that a piston can run up and down the cavity. The system stores energy by moving the piston, that supports a large mass, up with the use of hydraulic pressure induced by a pump. When the energy is necessary again, the pump acting as turbine connected to a generator will be able to supply electricity to the grid. A representation is given in 2.3. The system uses safe materials and mature technologies with a high achievable efficiency. The widespread use of large underground excavations in other appliances and the cheap materials available make the system able to easily scale to high power and energy capacity.

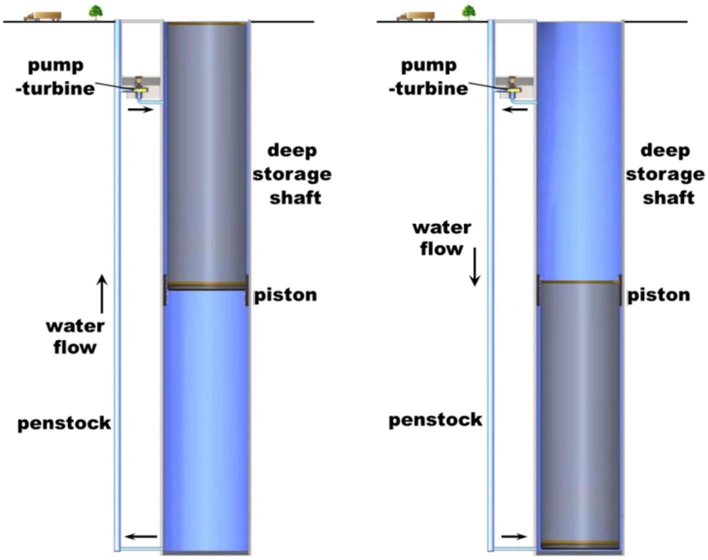

Figure 2.3: A representation of gravity storage underground by moving a piston up and down in a shaft, where the discharging is represented by the left image and the charging by the right [17]

Compressed Air Energy Storage

Energy can be stored in air mechanically by driving a compressor to compress air in an airtight environment. This energy can be then accessed in times of demand by expanding it over a turbine driving a generator. In theory every airtight space with a compressor and turbine can be classified as compressed air energy storage (CAES), but when this system is referred to in literature the system uses underground (salt) caverns as an environment to store the compressed air. The caverns are created by dissolving salt, that in some geographical locations lie relatively close ($\pm 500m$) to the surface, from the ground into water and extracting the liquid. An airtight environment with a size of around $0.5 - 1e^6 m^3$ can be created using this method.

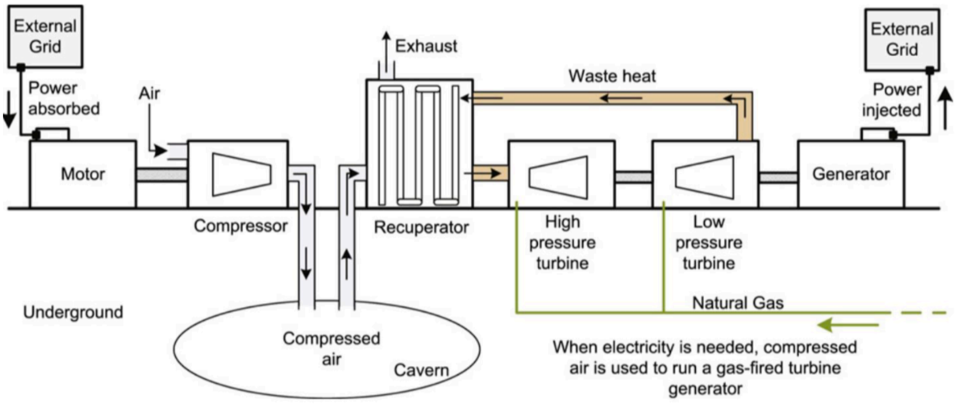

Figure 2.4: A representation of compressed energy storage in an underground salt cavern where this system uses a recuperator and a two-stage expansion process [18]

When the air is compressed into a cavern it will heat up the system and when expanded this air will cool down the system. In the applied CAES systems this heat will be released to the environment during compression, while during expansion natural gas is combusted to prevent the system from freezing. To efficiently do so recuperators are used and multiple stages of expansion are applied, schematically shown in figure 2.4. In order to improve efficiency, the use of advanced adiabatic CAES can be applied. In this case the system is designed in such a way that the heat created during compression is stored in a separate thermal storage, to be utilized during expansion of the air. The combustion of natural gas during expansion will become unnecessary. The efficiency is increased but the initial investment in the system is significantly higher and where CAES is commercialized on large scale is advanced adiabatic CAES still in the development phase. Generally, CAES can be considered as a high potential technique where a high power, high energy capacity can be reached. Maturity can be considered high as the technique has been applied for the storage of natural gas for many years.

Flywheel storage

In a flywheel the kinetic energy of a mass is increased and decreased in a controlled process to store energy. In times of excess electricity an electric motor will made to rotate a mass. When electricity is demanded this rotational energy can be converted back into electricity by using the electric motor as a generator. The mass is controlled by making it spin around an axis inside a secured housing. Flywheels come in many forms but are generally classified as low or high speed systems. Low speed flywheel will generally be able to reach 10,000 rpm where the high-speed flywheel systems can reach rotational speeds up to 100,000 rpm [19]. Due to these high rotational speeds it is possible to reach high efficiencies at high power ratings. However, the systems are prone to a high rate of self-discharge. This rate of self-discharge is minimized by reducing friction with for example; vacuuming the housing eliminating drag force and with the use magnetic levitation bearings. In high speed flywheel systems lightweight composite materials results for the system to have a high specific power, but a low energy density [20]. A principle view of a flywheel system is shown in figure 2.5

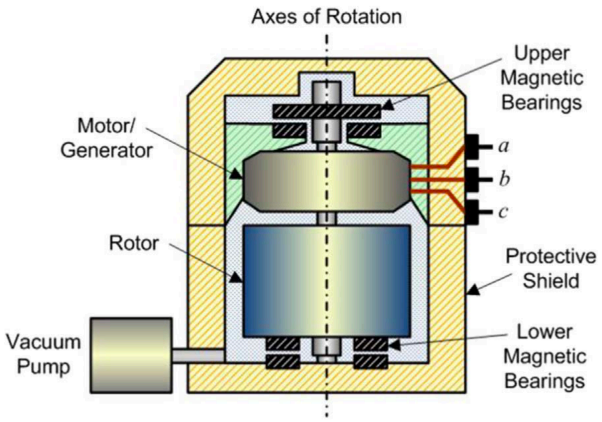

Figure 2.5: A principle view of a flywheel system to store energy [20]

2.1.2. Electrochemical storage

Electrochemical storage uses the principle where electricity is stored in the form of molecules by inducing a chemical reaction that will run under a potential. The most conventional technique of reversible electrochemical conversion, a dual cell battery, stores energy by creating electrically charged ions through chemical reaction between positive and negative plates. During times where electricity is demanded the reaction is reversed and the ions discharge their energy back to the grid. In this section three technique of electrochemical storage with the highest potential for our application are elaborated; Li-ion, NaS and flow batteries.

Li-ion batteries

Li-ion batteries have made a huge leap in technological advancement in the past years and, due to the intensive research, are expected to improve more. These lightweight and compact batteries have made numerous technological advancements possible such as the small mobile phones and the deployment of electric cars, where large scale energy storage is the next deployment [21]. This electrochemical storage system uses lithium-based components in the cathode and carbon graphite materials in the anode. In between the cathode and anode, the cells are filled with a non-aqueous liquid organic solvent electrolyte in which lithium salts are dissolved. A representation of the Li-ion battery is given in figure 2.6. Large scale capacity for a Li-ion battery is reached by numbering up the cells to the desired power and capacity. Applying the battery on large scale provides little scale advantages, in contrary to the mechanical storage methods.

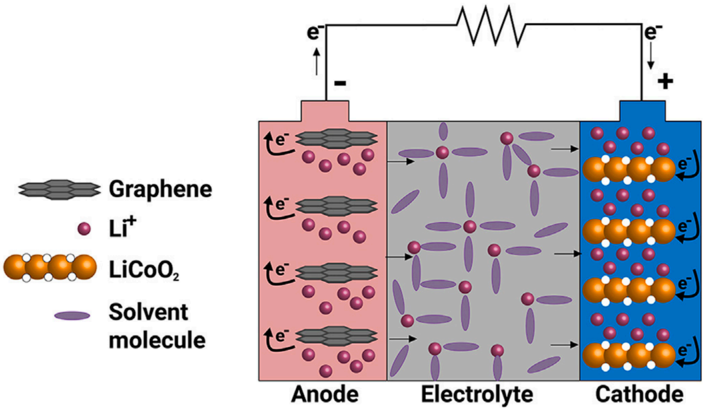

Figure 2.6: Schematic view of a Li-ion battery [14]

Sodium Sulfur batteries

Sodium Sulfur (NaS) batteries have been around for over half a century and are one of the candidates sticking out to be utilized for large scale stationary electrical energy storage. This battery contains tubular cells that have to be kept at a temperature of approximately 325°C to ensure that the electrodes are in a liquid state, leading to a high reactive activity [22]. The high reactivity of the molten Sulfur cathode and Sodium anode together with the solid electrolyte provide a high energy density. This while having a small self-discharge rate while avoiding dangerous and toxic materials. Due to the high operating temperatures the NaS battery system has high operational and maintenance cost. Like the Li-ion batteries, grid scale appliances for NaS batteries are reached by numbering up the single cell units to the desired scale.

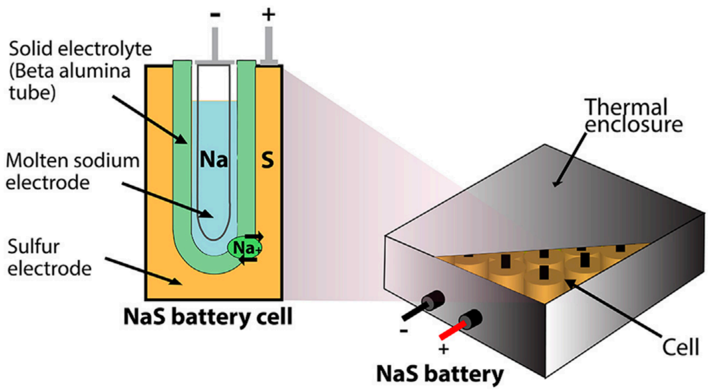

Figure 2.7: Schematic view of a NaS battery [23]

Flow batteries

Flow batteries are a relatively new technique designed as an improvement to the secondary cell batteries, like Li-ion and NaS, for application on large scale. The flow battery uses the same principles where excess electricity is converted into a chemical reaction which is based on a redox reaction. During charging the electrolyte at the anode is oxidized, while the electrolyte at the cathode is reduced. During discharging the opposite happens, and electricity is fed back to the grid. By pumping the electrolytes through the cell and storing them separately, a main disadvantage that the secondary cell batteries have is overcome. In the secondary cell batteries, the electrochemically created components store directly on the electrodes causing a limited energy capacity [24, 25]. A schematic representation of this process is shown in figure 2.8. The most widely applied flow battery is the vanadium redox flow battery (VRB), which will be considered in this research.

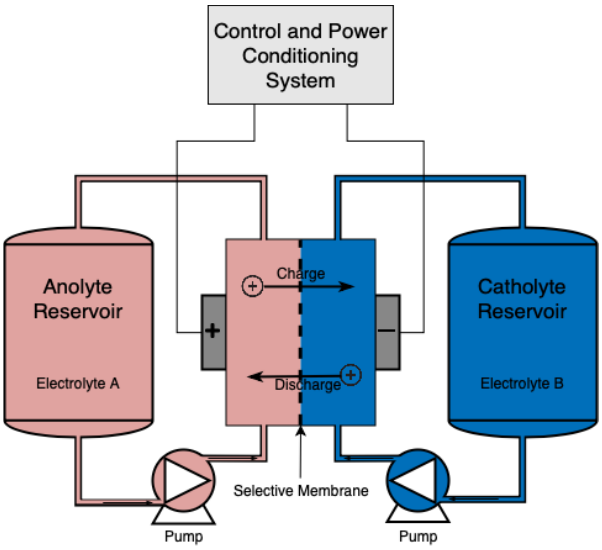

Figure 2.8: Schematic view of a flow battery

2.1.3. Chemical storage

Energy is stored in the chemical bonds between atoms, if these atoms are subjected to a chemical reaction, they can absorb energy. If these atoms are kept stable, they can be made to release the energy in a chemical reaction, at a desired moment. Electricity can be used to induce such a reaction and convert electrons into atoms. Many options are possible to store energy into atoms where in the scope of this research two most relevant candidates have been selected and are elaborated.

Hydrogen storage

Hydrogen has been widely used as a feedstock in industry for centuries. Recently hydrogen has gained attention in the form of green hydrogen [1], which has been introduced as a tool in the energy transition to transport and store energy. To store the electricity hydrogen is obtained through electrolysis, of which the reaction is shown below.

$$2\,H_2O \xrightarrow{\text{power}} 4\,H_2 + O_2$$

---

[1] Hydrogen produced using electricity from renewable energy sources and/or waste heat via an electrolysis process

This electrolysis has an efficiency of approximately 75% where after conversion a gas is formed with a high energy density of $142\frac{kJ}{kg}$ [26], based on the higher heating value. When the electricity is stored in the energy carrier this carrier should be stored. Due to the low density and the volatile nature of hydrogen it is not possible to stably store it without special measure, generally applied techniques are:

- In the gas phase under a pressure of 350 to 700 bar
- In the liquid phase below the boiling point of hydrogen, $-252.8°C$, with the use of cryogenic cooling methods [27].
- In material-based storage where metal hydrides are used to absorb the hydrogen into the material. This technique is safe to use at low pressure and room temperature. [23, 28]
- Mixing in the gaseous hydrogen in the existing natural gas grid, which is without complication allowed up to 0.5 vol% [29]. In future applications this infrastructure could (partly) be converted to 100% hydrogen infrastructure.

The energy stored in hydrogen can be accessed when it is demanded in different forms or immediately be used as a feedstock for chemical process. If electricity is demanded the hydrogen can be combusted in a fuel cell, this electrochemical cell converts the hydrogen into electricity by feeding it to the anode, where oxygen is fed to the cathode. This creates a potential difference between the electrodes making the electrons run, between the anode and cathode. The H+ atoms are transported through electrolyte or a membrane separating the anode and cathode. A representation of the fuel cell integrated in a system is shown in figure 2.9. The efficiency of the fuel cell can go up to 50%, but together with the efficiency of the electrolyzer makes the round trip efficiency low. The energy stored in hydrogen can also be utilized for other purposes such as feedstock in industry or heat.

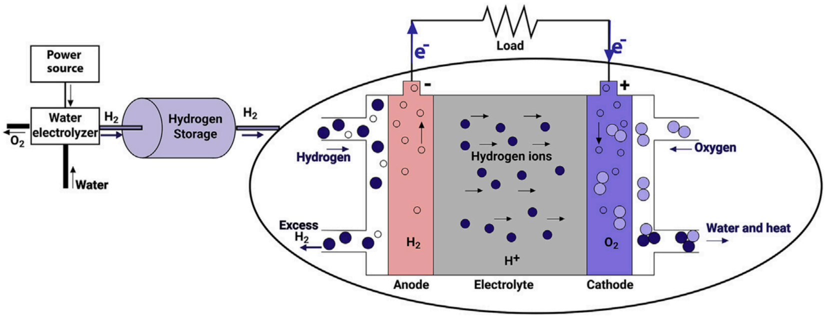

Figure 2.9: A schematic representation of a hydrogen fuel cell and storage, where the anode and cathode a separated by electrolyte [14]

Synthetic Natural Gas

Using hydrogen and CO_2 as a feedstock it is possible to create synthetic natural gas (SNG) through a methanization process, which is expressed in the chemical reaction below. Several methods are available to perform this process in creating a gas which is widely used nowadays. This is beneficial due to the numerous applications available to store the gas in existing buffers and to utilize this gas for electricity production again. An important additional benefit is the fact that this gas can be fed into the existing grid without limitations. The natural gas grid in Europe has connection with every country and due to its size, it can be assumed to be the largest energy storage facility in the world. The estimated energy capacity of the natural gas stored in this grid is $220TWh$ [30]. Generally, if natural gas is utilized or combusted CO_2 is emitted into the atmosphere. However, in the synthesis of the gas CO_2 was taken out of the atmosphere and this process can be assumed carbon neutral.

$$\mathrm{CO_2 + 4\,H_2 \rightleftharpoons CH_4 + 2\,H_2O}$$

2.1.4. Electromagnetic storage

Storage of energy in a magnetic field or a current can be classified as electromagnetic storage. These applications of storage can deliver high currents of electricity for a short period of time. In this research two types of storage are of relevance; the supercapacitor and SMES. As both techniques are characterized by high power and low capacity, they are mainly applied in the stabilization of power output or for peaks shaving in the demand in electricity on industrial scale.

Superconducting Magnetic Energy Storage

The workings of a Superconducting Magnetic Energy Storage (SMES) system is based on the working of electrodynamics [31], where the electricity is stored in the magnetic field by directing a direct current flow into a superconducting coil. This coil becomes a superconductor when the right materials are chosen together with operating conditions below the critical temperature of the material. The critical temperature is at such low levels that cryogenic cooling is necessary to be able reach it. The electricity in the coil can be released by discharging the coil and feeding it to the grid. A schematic of a SMES system is shown in figure 2.10.

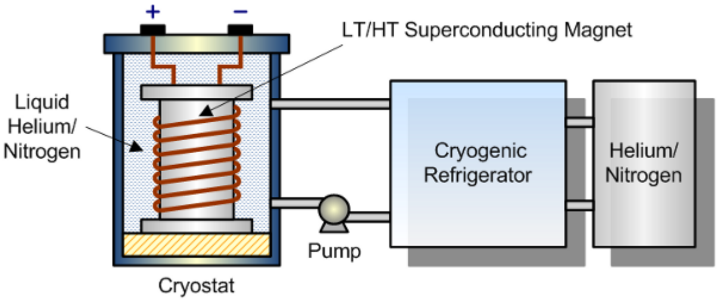

Figure 2.10: A schematic representation of a SMES system [32]

Supercapacitor

Where capacitors have been applied as an ESS for a longer period of time, supercapacitors are a fairly new technique that is introduced to the market. A supercapacitor contains electrolyte but works without the principle of chemical reactions where the energy is stored in an electric field between two electrodes as a static charge. The layers of electrolyte are nearly to a molecule thin and have very large surfaces of activated carbon [33]. During charging the ions that are electrically charged move towards the opposite polarity electrodes under the influence of an electric field that is imposed [23]. Compared to capacitors and other energy storage techniques do supercapacitors have; a high power density, high round trip efficiency, fast response time and a high lifetime. Where it is of importance to denote that the electrolyte is, in retrospect to batteries that use electrolyte, not degrading over the lifetime due to the absence of chemical reactions [15, 23, 34]. Due to the limited energy capacity and the fast reaction time the supercapacitor is often used for power quality control in the grid.

2.1.5. Thermal energy storage

Thermal energy storage (TES) is achieved by using electricity to heat or to cool down a substance and storing it in an insulated environment. This is done to create a temperature gradient between two sources or between a source and the environment. This principle of storage has been applied for centuries in many forms within residential and industrial purposes. When TES is used for power to power appliances a large number of techniques will not be useful. The ones that are can be classified in three groups; 1. sensible heat, 2. latent heat and 3. adsorption/absorption. In this section several techniques are described which are proven by literature to be most promising for the purpose sought after. Since no large scale applications are available for adsorption/absorption storage this classification is left out of the description.

Pumped Thermal Electrical Storage

Pumped Thermal Electrical Storage (PTES) systems, that are classified as sensible heat techniques, use the excess electricity to drive a heat pump to transfer heat from a cold storage tank to a warm storage tank. During times in need of electricity, the warm storage is used to evaporate the working fluid in the heat pump that is expanded over a turbine driving a generator. The cold and warm storage tanks usually contain solids with high thermal capacity that can absorb heat from the working fluid and are able to withstand low to high temperatures (-160 to $+500°C$).

An alternative form of this storage technique is the SiFES system developed by Siemens [35] that uses excess electricity from wind turbines to heat rocks in an insulated underground storage. When the demand in electricity is high, water is fed through the rocks, acting as an evaporator, and steam is created that is expanded over a steam turbine connected to a generator. This relatively simple technique uses proven technologies and can be applied for high power and large energy capacity storage due to the scalability that is possible. In the 30 MW pilot plant that is to be installed in Germany it is to be expected that moderate efficiencies can be achieved.

Liquid Air Energy Storage

Liquid Air Energy Storage (LAES) makes use of the latent heat storage where air is cryogenically cooled down to the point where it condenses and can easily be stored in an insulated vacuumed tank. The air is liquified because the density drop of the air during this phase change with a factor ±700, making it more convenient to store. When electricity is needed again the air is evaporated using environmental heat and expanded in a turbine that is, through a generator, connected to the grid. A schematic representation of the process is shown in 2.11. LAES is a technique that uses relatively safe processes that is not using harming chemicals to obtain a high power and energy storage facility. If a LAES facility is combined with industrial low temperature waste heat the efficiency of the expansion phase can be increased significantly.

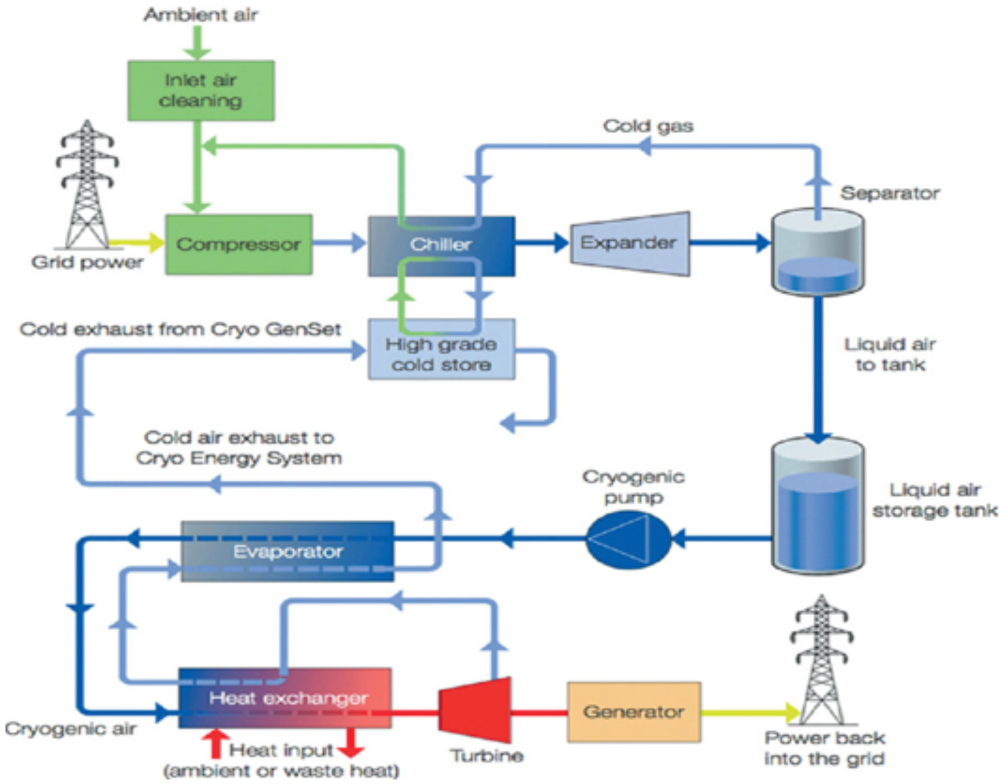

Figure 2.11: A schematic representation of the process in a LAES system [36]

2.1.6. Offshore utilization & North Sea appliances

Offshore and onshore energy storage is compared in this research, in this section offshore appliances are reviewed where no new principles/methods of energy storage will be introduced. The deviating characteristics due to the offshore utilization will be highlighted. The reason for separating the offshore utilization of energy storage with the conventional types is due to the impact it will have on the system that will be realized. In general, the offshore application does significantly influence the overall cost due to the high cost for offshore equipment, installation and operation.

Offshore utilization of storage techniques does bring along extra costs it still is a subject that cannot be ignored and where several chances lie for energy storage. As the North Sea has been a place of activity in the oil and gas industry for the past centuries, there are all sorts of facilities to accommodate advanced technical facilities. There is a large infrastructure of oil & gas pipelines available that can be used for transportation of (carbon free) liquids and gasses. Attached to the infrastructure is a large number of platforms that are/have been used to extract oil and gas. These platforms have to be decommissioned as they go out of operation. This is an expensive undertaking for the oil and gas companies and if there are ways for these platforms to somehow remain in operation, they are willing to pay the users for it [37].

Offshore PHS

Offshore PHS is not possible since there is not naturally occurring difference in elevation between two reservoirs. However, it is possible to artificially create this potential energy difference by building an enclosure in the sea, creating a potential energy gradient by having the water level of the lake below or above sea level. This concept of artificially creating head to store energy offshore has been the field of research. The idea to build an artificial lake which is enclosed by a dam that is built in the sea, where the water level in the lake is below the sea level [38]. A different way is to use the facilities that are already present offshore. The monopile of the wind turbine can be used as an enclosure where water can be pumped in the turbine to later discharge. However, the energy density of water is limited and for the current state-of-the-art monopiles is the possible amount of energy stored not sufficient to make an impact.

Offshore CAES

Offshore the application of CAES is possible in the form that is applied onshore, in caverns below the seabed. In the North Sea there are many salt layers in underneath the seabed occur which could potentially be converted to caverns to store compressed air. The gas fields in the North Sea are often being trapped underneath the seabed due to these salt layers in the earth, the existing platform above the depleted gas fields can be repurposed as location for the CAES system [39].

Energy storage in the form of compressed air is not limited to land on locations where salt caverns occur. Manufacturers and researchers have realized this as well and have come up with a system that uses compressed air to store the energy. Several of the techniques fall out of the scope of the research since the North Sea is not deep enough to apply the deep-sea concrete ball storage [40]. The company Flasc however has taken a more generic approach. A CAES facility is placed on the seabed to make the storage facility more applicable in places where offshore wind turbines are installed. The aim is to connect every turbine to a $6MW$-$8MWh$ CAES and tank combination that is able to respond quickly to power fluctuations [41].

Offshore Batteries

To store the electricity close to the source where it is produced can have numerous advantages. The installation of batteries would be a good to consider option since they require low maintenance after they have been installed. The batteries could be installed offshore on a separate platform. However, the space needed is quite significant this is an expensive operation due to the high cost offshore platforms. Another option is to use the open space inside the monopile of the wind turbine. The amount of battery cells will be limited but it will save the installation of a new platform, while the batteries are protected from the harsh conditions offshore. The high energy density of Li-ion batteries is the best candidate since there is limited space available offshore.

Offshore electrolysers

The plans for OWFs that are being tendered in 2025 all have locations further off the coast than the current OWFs. Due to the high costs for electrical infrastructure to transport the electricity immediately to shore, plans have been opted to directly feed the electricity generated by the wind turbines into electrolysers offshore. These electrolysers will feed the hydrogen that is created directly into the infrastructure to transport gas. The hydrogen can be transported to shore with more flexibility than electricity and be buffered or fed further into the grid. The Dutch TSO and GTSO together investigated the options to apply such a system for a wind farm that is planned far out the coast. The conclusion here was that offshore operation of electrolysers was too expensive to apply to the Ijmuiden Ver Wind Farm [37]. However, this research is using assumptions that are speculations on future developments, these developments can turn out differently making offshore power-to-hydrogen feasible.

2.1.7. Overview of storage systems

As the relevant storage techniques are elaborated separately in the previous section, this section will focus on comparing the different techniques to each other in a quantified manner. As for storage many factors are of relevance depending on the design requirements of the storage facility. In table 2.1 all the characteristics of the storage techniques are included, to constructively compare the different techniques on the relevant basis.

A Ragone diagram is drawn from the information provided in table 2.1 to easily identify the appropriate storage technique for the application. This diagram, shown in figure 2.12, can be used to quickly identify the appropriate storage technique for the application necessary.

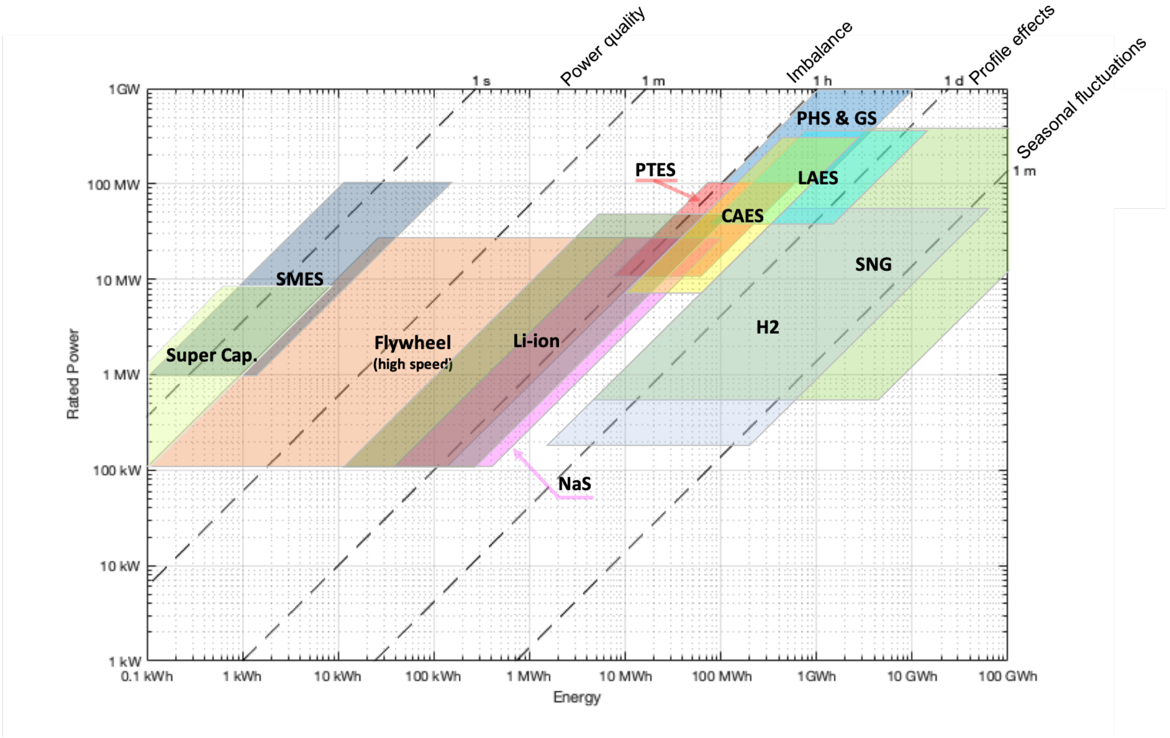

Figure 2.12: A Ragone diagram of the large scale energy storage techniques listed in table 2.1

Table 2.1: Properties and characteristics of the storage techniques described in chapter 2.1

Technology	Power rating	Energy Rating	Specific Power	Specific Energy	Efficiency	Response time	Cycle life	Rate of self discharge	Cost		Maturity
	MW	MWh	$\frac{W}{kg}$	$\frac{Wh}{kg}$	%			$\frac{\%}{day}$	$\frac{€}{kW}$	$\frac{€}{kWh}$	
PHS	100-5000 [15]	100-10000 [42]	-	1-2 [43]	65-85 [34]	min	10,000-30,000 [44]	0.01 [31]	440-4000 74 [45]	5-380 [46]	Commercialized
Gravity Storage	10-1600 [17]	20-2400 [17, 47]		1-2 [47]	70-86 [47]	sec-min			-	5 [48]	Developing
CAES	5-300 [49]	20-1200 [42]	-	30-60 [15]	38-80 [50]	sec-min	8000-12000 [15]	0.5 [31]	350-700 [34]	35-70 [51]	Commercialized
Flywheel (high speed)	0.1-20 [46]	0.01-25 [46]	400-1500 [52]	100 [15]	90-95 [34]	sec	10,000-100,000 [34]	55-100 [34]	100-300 [15]	900-4500 [24]	Commercialized
Li-ion	0.1-50 [18]	0.01 - 100 [18]	500-2000 [23]	80-150 [23]	90-97 [24]	5 ms	4500 [53]	0.1-0.3 [15]	1050-3500 [15]	500-3500 [54, 55]	Commercialized
NaS	0.15-10 [56]	0.5-200 [42]	115-240 [34]	150-240 [15]	75-90 [34]	5 ms	2500-4500 [34]	0.05 [31]	900-2700 [56]	270-450 [49]	Commercialized
Flow battery (VRB)	0.3-15 [28]		166 [24]	10-50 [57]	75-85 [34]	5 ms	12,000-14,000 [58]	0.15 [31]	530-1300 [56]	130-1300 [54, 59]	Developed
Hydrogen (fuel cell)	0.001-50 [60]		500+ [15]	300-1200 [61]	20-50 [15]	5 ms	20,000+ [24]	0.1 [15]	450- 9000 [34]	3-130 [62]	Commercialized
SNG	0.5-500 [63]	-		15,000	36-40 [63]	min					Commercialized
SMES	1.1-100 [46]	0.1-100 [64]	500-2000 [15]	0.5-5 [15]	90-95 [45]	5 ms	100,000+ [65]	10-15 [34]	180-270 [15]	900-9000 [15]	Developing
Supercapacitor	0.01-10 [64]	0-1	500-5000 [15]	2.5-15 [15]	85-98 [23]	5 ms	100,000+ [15]	0.5 [23]	90-270 [15]	270-1800 [66]	Developing
PTES	10-100 [47]	10-600 [47]	-	80-200 [15]	53-66 [47]	min	10,000+ [47]	0.05-0.1 [15]	900-2700 [59]	10-180 [47, 59]	Developing
LAES	50-250 [36, 67]	100-3000 [36, 67]	-	97-210 [59]	45-70 [36]	5 min		0.05-0.1 [15]	800 - 1800 [36]	100-450 [36]	Pilot

2.1.8. Hybrid energy storage systems

The energy storage systems listed in section 2.1.7 have their characteristics in strengths and weaknesses. These energy storage solutions are aimed to be counter multiple effects that all have their own appliances and characteristics. In figure 2.12 it can be observed that none of the techniques cover the whole range of the diagram, resulting in the disability of one storage technique being able to counter all issues faced integrating wind power in the grid [68]. The possibility for a storage solution should not be limited to a single energy storage technique. In this section several Hybrid Energy Storage Systems (HESS) are assessed which show, according to literature, the greatest potential.

CAES-TES

By combining adiabatic CAES and TES a higher round trip efficiency (±70%) can be obtained while avoiding the burning of fossil fuels in the process. This system has the potential to smooth the interaction between intermittent energy sources, where projects of significant size are planned on being built in Germany. [69, 70]

CAES-Flywheel

In the research of Zhao et al. [71] the combination of an adiabatic CAES and Flywheel energy storage system is evaluated to dampen out the effects of the intermittent nature of wind turbines. This system that combines fast reaction time and a large energy capacity has great potential to eliminate the power fluctuations that are fed to the grid. The slower reaction time of the CAES system is smoothed out by the flywheel storage.

Fuel Cell-Battery

Combining fuel cells and batteries in a hybrid system to integrate electricity generated by intermittent energy sources into the grid is a large field of research where many configurations are proposed. In this case the batteries are used to compensate the short-term fluctuations in the power production where the chemical conversion of hydrogen is then utilized for seasonal storage of energy. The hydrogen could be synthesized in other energy carriers or be stored in the several options given in section 2.1.3 [72–74]. An advantage of the fuel cell battery combination is the fact that the system could be integrated. An example is ”*the Battolyser*” where the anode and cathode of a alkaline battery act as hydrogen electrolysers when the battery is fully charged [75].

Battery-Flywheel

The combination of batteries and flywheel in one system can provide several advantages that come from the flywheels high power and efficiency for short periods, to keep the charging and discharging of the battery within the rated levels. This while preventing unnecessary cycles of the battery in the short-term operations. Additionally, this HESS results in the opportunity for a system to be used for; load management, peak shaving, primary control reserve and power quality management [14, 76].

2.2. Wind Turbines

The integration of wind energy into the grid on large scale is posing issues regarding the matching between the supply and demand of electricity. The extent of the integration issues depends on the layout of the wind farm and the characteristics of the wind turbines that compose this wind farm. This entails that aligning the design of the wind turbines to the site could reduce the integration issues. To get a better understanding of the issues at first some background information is given to which subsequently the relevant design solutions regarding wind farm and turbine design are elaborated.

2.2.1. Wind Turbine characteristics

The power production of a wind turbine is characterized by the power curve which together with the wind energy over a year results in the yield, or annual energy production (AEP). The power curve depends on the layout of turbine and is defined by; cut-in speed, rated wind speed and a cut-out speed. Between the cut in speed and the rated wind speed the curve will have a shape described by equation 2.1. In figure 2.13 an example of a power curve is shown, where it is notable to see that between the cut in speed and the rated wind speed the power produced by the wind turbine scales with the third power. A fluctuation in wind speed in this region results in a more amplified fluctuation in power output of the wind turbine. Besides the power curve in figure 2.13 there is a representation of an average wind profile on the North Sea. In this figure an offshore wind turbine is shown to display the scale of the shear profile that is formed. It can also be seen that at higher altitudes the wind will be stronger due to the lesser influence of the friction of the water and the waves. Increasing the height of the hub or the rotor diameter will provide more access to these stronger winds.

$$P = \frac{1}{2}\rho U^3 A_{swept} 4a(1-a)^2 \tag{2.1}$$

$$c_f = \frac{AEP}{P_{rated} t_{year}} \tag{2.2}$$

The wind speed throughout the year is not always at or above the rated wind speed of the wind turbine which means that the turbine cannot run at rated power throughout the year. The ratio between AEP and energy production at constant rated power throughout the year is termed as the capacity factor, equation 2.2. The capacity factor depends on the wind characteristics of the location and the power curve of the turbine. An important design parameter for the wind turbine to influence the capacity factor is the specific energy rating of the turbine, which is the rated power per area swept by rotor. A lower specific energy rating is generally defined by a higher capacity factor and a lower rated and cut out wind speed.

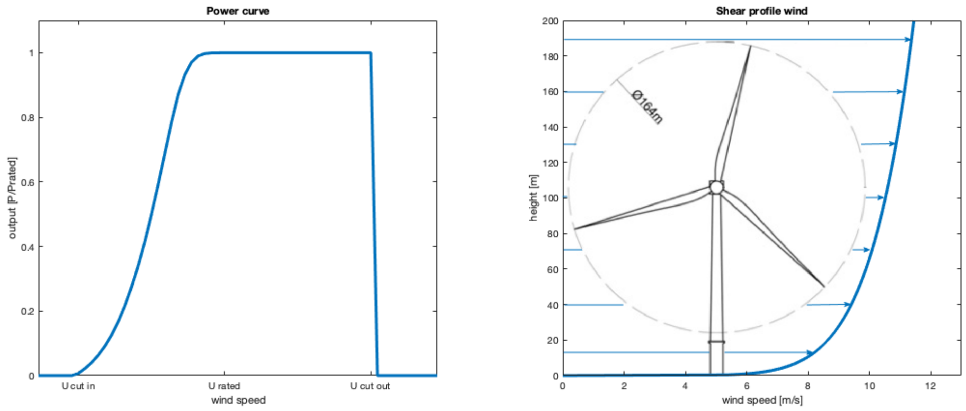

Figure 2.13: A representation of a power curve (on the left) and a wind shear profile on the North Sea with a 164 m rotor wind turbine as scale (on the right)

2.2.2. System friendly wind turbine design

The decreasing market value or self-cannibalization of wind turbines is posing an increasing threat to wind energy as it is being implemented as source of clean electricity on a large scale. A method to reduce the impact is to apply an altered design of the wind turbines, referred to in literature as system friendly wind turbine design [77]. This system friendly design, that has been already adopted in some sites, entails that the capacity factor of a wind turbine should be increased while having the production profile shape more towards a base load like profile [2]. This is possible due to the ability of the turbine to a higher extend produce electricity at times of little wind and having less extreme production peaks for strong winds.

If the design principles of system friendly wind turbines are applied the production of electricity will be steadier throughout the year and result in a higher capacity factor. For the design to be better suited for low wind speed the hub height and the rotor diameter are

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[2] A full base load profile will never be possible due to intermittency of the wind

increased, while keeping the generator the same dimensions. At higher altitudes there is more wind, as shown in figure 2.13, and the larger surface swept by the rotors decreases the specific energy while increasing the ability to harvest wind energy at low wind speeds. The system friendly wind turbine design is of significant value for reducing integration costs at high wind penetration levels in the grid. However, this advantage is marginal for low wind penetration levels [77]. Additionally, system friendly wind turbine design has the advantages of: reduced forecast errors, reduced grid costs and higher capability of auxiliary services.

If strong wind sites are considered, the choice for system friendly wind turbine is not as distinct as it would be for low to medium wind sites. The system friendly wind turbines can result in a higher LCOE when a strong wind site is considered. In this case of high wind load on the rotors connected to a small generator would result in lost yield. The lost yield does not weigh against the savings in CAPEX and integration cost. The consideration in the optimal size of turbine and generator is highly dependent on the wind speed of the site and the influence of the generator and the infrastructure on the CAPEX. For this consideration are the system friendly wind turbines better suited to produce higher value electricity in low to medium wind sites. Scarcity in space and feed-in tariffs do support the incentive to maximize the energy output of the specific site as this is more beneficial [77]. A cost benefit analysis over the whole chain can decide the outcome for the most preferable design. However, the choice of design is highly dependent on market projections of the future wind farms, the electricity price and daily fluctuations in this price.

2.2.3. Wind turbine frequency control reserve

When the rotors of the wind turbine are running in normal operation at constant speed, they have kinetic energy stored in the rotation, like a flywheel. Due to the size and mass of the rotors this results in a significant amount of energy that is readily available and already connected to a generator. Frequency control reserve (FCR) is standby capacity to absorb or deliver power to the grid to restore the frequency. If the grid operator desires power the energy stored in the rotor can be accessed by slowing down the rotors with the generator and feeding this produced electricity to the grid. This could be made available by keeping the wind turbines below the maximum available capacity so that a margin remains in the generator capacity [78]. This is not desired as this would entail the wind turbine not operating at maximum capacity.

After harvesting the kinetic energy from the rotor, the rotational velocity has to be restored to be able to extract power again. During this charging period the turbine will have a decreased power production in the generator [79]. Using additional control technology wind turbines will be able to provide frequency control support at high power for about 30 seconds with the energy stored in the rotors [80]. If a wind farm is considered the wind turbines can operate in cascade to be able to provide instant frequency support for a longer period of time, reducing the impact of the charging time of the turbines. If a storage system is considered that has a too slow reaction time for certain power quality services, the fast reaction time of kinetic energy in the rotors could be used as an instant power. When this kinetic energy in the rotors has to be charged again, the power gap can be covered with the slower reacting storage facility.

2.2.4. Offshore Wind Turbine trends

Onshore turbines often are restricted in size by transportation limitations of the turbine parts. Offshore wind turbines have less restrictions due to the sea vessel-based transportation, the offshore industry has outgrown their land-based counterparts. This can be observed in the trends in state-of-the-art wind turbines where offshore applications keep growing in power and size. The projections for the growth from 2014 to 2024 state that the average power rating installed will grow from 4 MW to over 12 MW per turbine, with an average installed rotor size that increases from 95 m to 220 m diameter. Staggering numbers for the fact that no disruptive innovations in the offshore wind industry are expected to achieve these numbers [12]. With the 12 MW, 220 m diameter rotor, GE Haliade X that is currently under development the company hopes to set a new benchmark for the proportions of the turbines. The unique component of this turbine is that it combines a high capacity factor together with a high power capacity, making it suitable for low wind regions too.

In the wind turbine business, it often happens as soon as the manufacturer has developed and certified its new wind turbine it starts upgrading the power rating. This enables the manufacturer to better serve the markets where the capacity factor is not one of the main issues due to the high cost per site or when certain schemes for subsidies are available. These factors do not encourage the production of high value electricity and in some way promote the self-cannibalization effect of wind energy. This is seen for the Vestas V164 turbine, which was introduced in 2012 as an 8 MW turbine, but has since been upgraded in several versions, where recently the 10 MW version has been introduced to the market [81]. This is to be expected to be happening for the other soon to be introduced turbines from GE and Siemens as well.

A wind turbine is, like other electrical power suppliers, obliged by the TSO to be able to supply or absorb reactive power to control the voltage on the electricity grid. When the generator of a turbine is upgraded this will decrease the reactive power capacity [81]. In some situations, this could entail additional costly installations to be built next to the (upgraded) wind turbines to comply with the reactive power regulations. Currently the TSO and the wind sector are in conflict on the fact if the wind farms should be able to supply and absorb reactive power at all times [82]. If it would turn out that this should be possible for future wind farms it will be necessary for the wind energy suppliers to have extra installation to provide this service when there is no wind. These extra installations could cost up to several tens of millions of euros for future OWF.

2.2.5. Synergy solutions with other turbines

The sites of OWFs cover a vast surface of the sea they are located, but that actual surface is used by the turbine foundations is very limited. With the developments where turbines will only increase in size the space used will decrease further. These parts of the sea that are being allocated to harvest wind energy could potentially be used for other purposes as well to further reduce the costs and integration issues. The infrastructure and points of access are already present and the space between the wind turbines can potentially be used for; wave energy converters, algae farms, the extraction of rare metals from the seawater, floating PV farms and nearly every offshore application possible [83]. This symbiotic approach to the design of offshore wind farms has great potential for future applications. However, it has as disadvantage that it highly complicates the system in construction and maintenance. As construction and maintenance are already complicated for offshore appliances this can easily become breaking point for the implementation of these kind of systems.

2.3. Infrastructure

The electrical infrastructure of an OWF, consisting of the (inter)connections to the grid, the back-up equipment and the transformers, is a significant part of the total CAPEX [13]. In the recent years the costs for the turbines and installations have decreased rapidly [6], but in this development the cost in the infrastructure has lacked behind [84]. To keep innovating and reduce the costs of offshore wind energy reductions in the infrastructure cost should be achieved as well. Up to recently the focus in literature has been on the optimal layout of the wind turbines to save costs on the infrastructure. Algorithms determine the optimal layout per location taking wake models, power losses and initial cost into account [84].

Besides an optimal layout it should be assessed if costs can be saved on other components of the infrastructure. The export cables connecting the offshore transformer to the grid are designed on the installed capacity of the wind farm and not the energy capacity. Alternative design of the wind farm could achieve a better use of the capacity of the cable. By increasing the capacity factor of the wind farm, the total energy transported over the cable can be increased [77], resulting in a reduction in the LCOE of the cable. As an alternative to maximize the use of the cable, synergy solutions are researched as well. In one of these multipurpose solutions the OWF is not only connected to the grid of one country but serves as an interconnector between multiple North Sea. The first studies seem to be promising and the desired cost reduction due to synergy is expected to be achieved [85].

2.4. Currently applied wind farm storage combination systems

The expected mismatch between the electricity supply and demand in a renewable dominated energy system has resulted in lots of research and publications. However, is this research quite superficial and generic. Every area has its own geographical characteristics and thus its own tailor-made solution with regards to an offshore wind + storage system. Nevertheless, the research in a few cases has resulted in realized pilot projects. These realized projects, however, are limited to the stand-alone systems and not the completely integrated network systems.

A joint venture of Mitsubishi, NGK Insulators and Japan Wind Development has resulted in an early development of a large scale energy storage wind farm on land. This $51MW$ wind farm and $34MW$ - $245MWh$ NaS battery storage facility is designed as a system to better be able to follow the electricity demand. The operation consists of countering fluctuations in power production by the wind turbines and increasing the power quality. The project integrates wind turbines on a relatively small electricity grid in order to gain knowledge in the development and operations of wind farm and energy storage systems. The results were promising, the NaS batteries were able to achieve the desired; cut-off operation, fluctuation reduction and constant output [22]. The system has been running commercially since September 2009 and has not been followed up until recently.

The Batwind project is using $1MW/1MWh$ Li-ion batteries to increase the value of the power produced by the offshore wind farm in Scotland. The wind turbines are located offshore and connected to a battery system that is located onshore where the export cable reaches the shore [86]. Soon after the announcement of the Batwind project an energy storage solution for an $800MW$ offshore wind farm in Bay State, USA was announced. The sizing of the facility was not reported, but supposedly the storage facility was to gain a price reduction of $158 million per year [87].

2.5. Summary & Conclusion

This literature review looked into large scale energy storage and wind turbine design with the purpose of designing an offshore wind + storage system that can tackle the integration issues. With this review it is concluded that:

Large scale storage of electricity is possible in several forms where the most important characteristics of the relevant options are listed in table 2.1. Evaluating the numbers in table 2.1 led to the conclusion that none of the techniques or stand-alone systems are able to support an OWF into achieving a base load production profile and solve the power quality issues. To comply to all services desired from a storage facility, the usage of hybrid energy storage is necessary. Another possibility is to accept that the system is not able to solve every issue faced. Additionally, the majority of the applied system for grid scale storage techniques, CAES and PHS, have geographical restrictions into being integrated offshore or on the shoreline of the Netherlands. The techniques that make offshore energy storage possible can contribute to the increased (electrical) infrastructure in the North Sea. However, the additional offshore complexity does bring along extra costs. Whether the benefits of offshore energy storage weigh up against the disadvantages or not should be evaluated for every specific location.

Wind turbine design has an influence on the electricity production profile of the turbine and the wind farm. In systems with a high grid penetration of wind energy applying system friendly wind turbine design can be beneficial. By increasing rotor diameter and the height of the hub a more stable production profile is achieved, resulting in less integration costs and higher value electricity. In the offshore application of wind turbines, the manufacturers have less transportation restrictions and are able to further apply system friendly turbine design concept to prevent wind power integration issues. As ancillary service the design of the wind turbines could be altered to perform frequency control reserve (FCR) with the kinetic energy stored in the rotors. The integration cost could be further decreased if the extra equipment for FCR becomes obsolete.

Currently applied wind farms storage combination systems are, as far as literature goes, limited to one realized system that uses NaS batteries to better suit the electricity production of a wind farm to the electricity demand. Every geographical location has its own tailor-made solution for the storage of wind energy, and therefore the proposed system for this research has not been realized on substantial scale. The combination of system friendly wind turbine design in the North Sea together with a storage system assigned to the Dutch electricity market has not been research in literature nor applied in a project.

Storage techniques selection for an offshore wind + storage system in 2025 is based on the literature review that is conducted in this chapter. In section 2.1 eleven storage techniques were identified as suitable techniques for such a system. Several techniques, however, do not meet the requirements of an offshore wind + storage system, or lack (reliable) data in order to determine the economic parameters. Therefore, in this section a pre selection, based on the findings in the literature review, is made of the most promising techniques which are further evaluated in this report. These techniques are:

- CAES
- Li-ion battery
- NaS
- Flow battery
- Hydrogen
- LAES

These techniques are assessed in chapter 4 where the techno-economic optimal configuration, to integrate offshore wind energy into the Dutch electricity system in 2025, is determined. In table 2.1 the characteristics of these techniques are provided in a range. For the assessment however, the mean characteristics for these techniques, found by Schmidt et al. in a meta study [88], are used. The motivation to not include the storage techniques described in this chapter, but not in the list above, is listed per technique on the next page.

Pumped hydro storage is excluded from the assessment due to the lack of elevated water basins and missing data on artificial water basins. The wind farm is to be designed of the Dutch coast where the storage facility would be positioned offshore or onshore. Due to the geographical absence of elevated water basins PHS will drop out the analysis. Ideas for an artificial lake with elevation have been proposed in the Netherlands and the North Sea [89]. These ideas and plans often lack back up from real plans and clear indications for costs.

Gravity storage is left out of the considerations due to a shortage of reliable cost data on the specifications of the technique. The technique is promising with regards to the integration in offshore wind + storage. However, the technique is still in an early development phase, therefore little data is available on the CAPEX and lifetime cost. The available data is originating from one source, thus not possible to verify with other sources and not deemed reliable.

Synthetic natural gas is simplified to be the same as hydrogen storage in the analysis due to lack of economic data on SNG for 2025 and similarities between the techniques. The synthesis of H_2 is an intermediate step of SNG synthesis. This means both techniques need one of the major cost drivers in the synthesis, the electrolyzer. After synthesis of the gaseous energy carriers the characteristics and properties for storage are quite similar. An advantage is that SNG is more versatile applicable in society, but since only P2P solutions are considered, these kinds of solutions are out of the scope of this research.

Supercapacitor, flywheel storage and superconducting magnetic energy storage are left out of the assessment due to limitation in the energy capacity versus the power capacity. In figure 2.12 and table 2.1 is shown that Supercapacitor and Flywheel storage have a maximum discharge time, at rated power, lower than or around one hour. Including a storage facility with such discharge time would cause large errors in the simulations. This is justified for a later stage in the storage facilities have a discharge rate longer than one hour.

Pumped thermal electrical storage is excluded from the assessment due to the lack of data on price expectations for 2025. Instead only LAES, for which sufficient data is available, is considered as technique that uses thermal storage as method to store energy. This choice is justified by the fact that PTES is currently similar in cost competitiveness with LAES [90]. If more LAES would turn out to become the best option PTES should be reconsidered in a more detailed design phase.

3

Methodology

In this chapter the methodology to answer the research questions, as mentioned in section 1.3, is described. The methodology describes the background information and the strategy to assess an offshore wind + storage system. In figure 3.1 the structure is represented in a process diagram with the major steps that are taken to come to the results of this research. In this chapter the background of steps in figure 3.1 are individually and in the same order discussed.

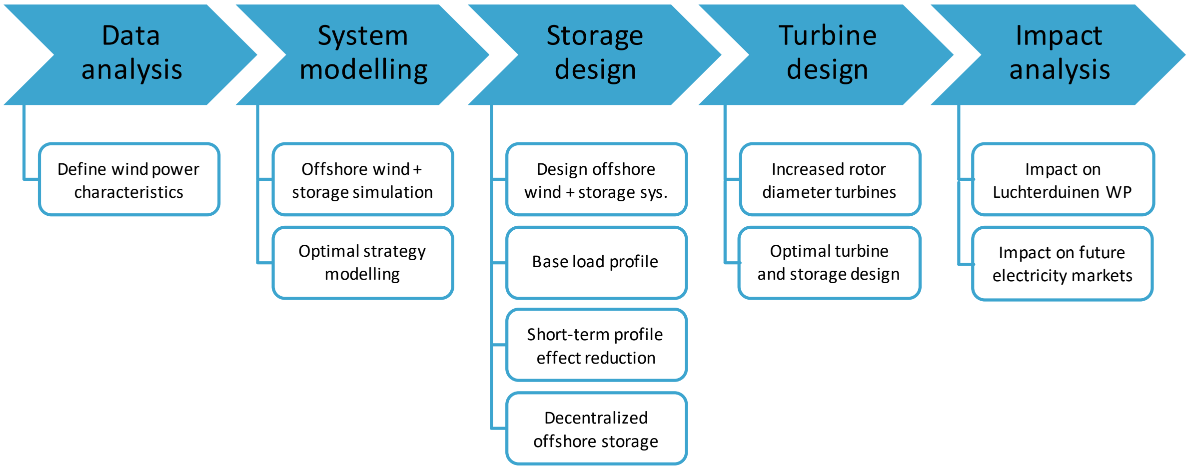


Figure 3.1: Structure for research into the optimal design of an offshore wind + storage system and its impact in the future electricity system.

3.1. Data

The research is based on available data for Luchterduinen Wind Park, described in section 1.4, and market expectations [91] for the demand and price of electricity. Several data sets are available for multiple years, with a time frame of one hour. This section justifies the choice for hourly data and provides background of the different data sets available.

Hourly time steps arise from the fact that all the data for the electricity production and demand is available on this scale. However, the electricity production of a wind turbine is not constant over a whole hour therefore, this data is averaged. This is justified by the fact that the majority of the power produced by an OWF is traded on the day ahead market. The day ahead market is based on hourly bids 24 hours ahead and determines the EPEX price. The production that eventually deviates from the hourly bid should be traded on the imbalance market during the day. The imbalance market conditions and demand are not possible to predict or estimate for a future electricity system, therefore this is not considered. As a result, the storage facility in the model is based on hourly time steps as well.

Measured data is available for the power production of Luchterduinen Wind Park [92]. The electricity production of the wind park is measured over a multiple year period. Using the measured production and the MERRA-2 hind cast study [93] for the known time period it was possible to extrapolate the measured power production for a longer period. This way the data set for the power production includes downtime of turbines due to maintenance and failures. The power production data is used for the data analysis of the power production of offshore wind energy in section 4.1. In this analysis the extrapolated data for a 37-year period is used. The results for the offshore wind + storage system in section 4.2 are based on the production data for the four-year period and serves as the basis for future expectations of the offshore energy production. The four-year period is chosen to limit the computational time of the model. This period includes good and bad wind years while it covers the leap year cycle, making it an accurate representation of the power production of an OWF.

Simulated wind turbine data is used to assess the impact of a varying rotor diameter of the offshore wind turbines. In this case the hourly power production of Luchterduinen Wind Park is modelled for multiple rotor diameters. Since there is no measured data available for alternative rotor sizes, the data is simulated. The power production is modelled for the same period as the measured data, however, are the results not to be compared. The model results should solely be compared with other results for model data, therefore it is qualitatively compared with the base case of the 112 m diameter rotor.

Future day ahead market simulations are used to assess the performance of the offshore wind + storage system in the future electricity market. The data is generated by models, provided by Eneco, using historical experience and future expectations. The data is modelled for a period starting from 2025 to 2050 and consists of the electricity demand and price, which are linked to the expected production of renewable electricity. Since the future expectations are subjected to many variables, three scenarios are used that vary the amount of installed wind energy in the Netherlands and its neighboring countries. The scenarios elaborated in appendix C describe possible configurations of the electricity market up to 2050.

Since the offshore wind + storage system operates in the future energy market, the usage of historical data would provide an incorrect output. Therefore expectations [94] of the energy market are used as input in the model. The offshore wind + storage system is designed to be built in 2025 with a permit and design life of 25 years. If historical market data would be used the problems, described in 1.2, that arise with increased wind energy grid penetration would not be relevant. The result would be a design of the offshore wind + storage system that is not optimized for the market it is operating in.

3.2. System modelling

To quantify the impact of an offshore wind + storage system two models are constructed to simulate and optimize the operation of such a system. The operational model simulates the power output and the state of charge of the storage facility next to the wind farm. The operation of the storage facility depends on the given limits to the system and the desired output. This desired output can be set constant over the simulation or the strategy model can be used to make the desired output hourly dependent on the expected EPEX price. In this section, the operational and strategy model are described, and two examples are shown.

3.2.1. Operational model

The operational model, schematically shown in figure 3.2, is a time-based model. For every time step the model tries to match the reference power by compensating the power production input with the storage facility. In this operation of matching the reference power, the model is constraint by the physical limitations of the storage facility and infrastructure. If it is not possible for the system to achieve the reference power it provides the closest value, possible within the constraints, as power output. The physical limitations are constant during the simulation and are entered in the model at the beginning of the simulation.

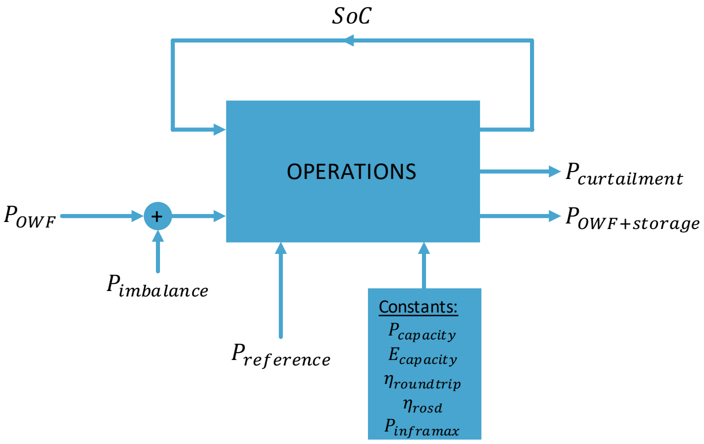


Figure 3.2: Schematic representation of the operational model. This model is executed for every hourly time step that is provided by the power production data. The physical characteristics and limitations of the system, described in section 3.2.1, are constant in time. The constraints in which the limitations of the system are inserted are defined in equation 3.1. The values that vary for every time step are too described in section 3.2.1.

The constraints of the model, as presented in figure 3.2, are defined in equation 3.1.

$$\begin{gathered} 0 < SoC < E_{capacity} \\ P_{OWF} + P_{storage} < P_{inframax} \end{gathered} \tag{3.1}$$

The physical limitations in the model, as presented in figure 3.2 are described as follows:

$\mathbf{P_{capacity}}$ is the power capacity of the storage facility $[MW]$. In the model the charging and discharging power of the storage facility is bounded between zero and the power capacity value.

$\mathbf{E_{capacity}}$ is the energy capacity of the storage facility $[MWh]$ or referred to as storage depth $[hours\ at\ P_{capacity}]$. In reality the energy capacity of the storage facility would deteriorate over time and through the use. However, in this simulation the energy capacity is not deteriorating since only a four-year period is modelled. In the calculation for the cost, described in section 3.3, this deterioration is included.
The $E_{capacity}$ describes the available capacity of the storage facility to function its full complete cycle life. If for example a battery system can only be subjected to 80% DoD to be able to reach its complete cycle life, the $E_{capacity}$ represents this 80% workable domain. In the cost calculation the economical parameters are corrected for this limitation in the system. In the example case, the LCOS of the system is determined to be $E_{capacity} * \frac{1}{0.8}$.

$\boldsymbol{\eta_{rosd}}$ is the rate of self-discharge of the storage facility $[\frac{\%}{day}]$.

$\boldsymbol{\eta_{roundtrip}}$ is the round trip efficiency of the storage facility $[-]$.

$\mathbf{P_{inframax}}$ is the rated power of the offshore infrastructure $[MW]$. This value determines the maximum combined power the OWF and the storage facility can deliver to the grid.

The non-constant operational values in the model, as presented in figure 3.2, are defined as:

P_{OWF} is the power production for the day ahead forecast of the offshore wind farm $[MW]$. This is a data set based on the measured or simulated power production of Luchterduinen Wind Park.

$P_{storage}$ is the power delivered or absorbed by the storage facility $[MW]$.

$P_{imbalance}$ is the imbalance that is added or subtracted to the day ahead forecast to have the realized power as input of the model $[MW]$. Parts of the imbalance of the used data is unknown. To equally simulate the realized power, measured imbalance for several non-corresponding years is sorted in a normal distribution. From this normal distribution the standard deviation is scaled to the rated power of the power production analyzed data set. This value is multiplied by 2.5 and a random number between -1 and 1. This value is added to the power production and the realized power is simulated. The realized power however is bounded by zero and the rated power, as this would be the case in reality too. The value to multiply the standard deviation with was chosen at 2.5 as this was matching the measured imbalance the best.

$P_{reference}$ is the desired power output value for the system $[MW]$. In the base load model this will be a constant value over time. If desired a non-constant reference value can be used.

$P_{curtailment}$ is the required curtailment to not exceed the set infrastructure limit $[MW]$. This would generally occur if the storage system is saturated and the power production of the OWF is above the infrastructure limit.

$P_{OWF+storage}$ is the power output of the offshore wind + storage system, which is fed to the grid $[MW]$.

SoC is the state of charge of the storage facility $[-]$. It is continuously updated and fed back to the system to check the availability in the next time step. If power is discharged from the storage facility the state of charge will be updated according to equation 3.3. If the storage facility is charged, the state of charge will be updated according to equation 3.2. In these equations i represents the time step in the simulation and t_{step} represents the length of the time step used.
In equation 3.1 the workable domain of the SoC is defined. Like the energy capacity the limits describe the domain in which the storage technique can reach its complete cycle life. If for example a battery system can only be subjected to 80% DoD, this 80% region is defined by the limits of 0 and $E_{capacity}$. In the cost calculation the economical parameters are corrected for this limitation in the system.

$$SoC(i) = SoC(i-1) * (1 - \eta_{rosd} * t_{step}) + P_{storage} * t_{step} * \sqrt{\eta_{roundtrip}} \tag{3.2}$$

$$SoC(i) = SoC(i-1) * (1 - \eta_{rosd} * t_{step}) + \frac{P_{storage} * t_{step}}{\sqrt{\eta_{roundtrip}}} \tag{3.3}$$

3.2.2. Strategy model

The electricity demand and the EPEX price fluctuate over time. A storage facility responds to these fluctuations and turns it into profit, this referred to as energy arbitrage. Using the power production and EPEX price forecast it is possible to optimize the strategy and maximize the revenue per produced unit of electricity. To maximize the profit of this energy arbitrage the strategy model is introduced. The model uses the state of charge and the 72 hour ahead predictions for the wind and EPEX prices, which are inserted into a linear solver to determine the best 24 hours ahead strategy for the storage facility.

When 72 hours ahead input data is used, only the strategy for the 24 hours ahead is determined. This walking horizon principle is applied to prevent the storage facility to be always fully discharged at the end of the 24 hours. As the EPEX price is predominantly positive throughout the year, it is profitable to fully discharge the storage facility towards the end of the data set. By setting the boundary at a position further into the future it makes sure the 24-hour strategy also takes into account the coming days. In figure 3.3 a schematic representation of the model is shown. $P_{strategy}$ is the power strategy of the storage facility combined with the OWF. The power production strategy together with the power production of the OWF can serve as bid on the day ahead market as provided to the TSO on a daily basis. $P_{strategy}$ will serve as $P_{reference}$ in the operational model, described in section 3.2.1, for the next 24 hours.

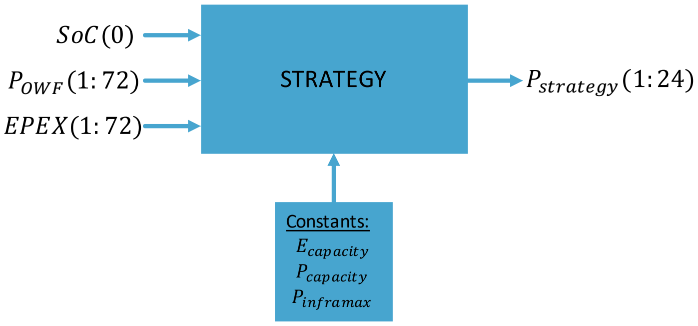


Figure 3.3: Schematic representation of the optimizer to determine the strategy for the storage facility. The state of charge at current time step is used together with the 72 hours ahead predictions for the wind and EPEX prices. Together with the constraints, described in equation 3.5, the most profitable strategy is derived for the next 24 hours. The strategy is set every 24 hours to serve together with the OWF power production as bid for the day ahead market, and the reference power for the operational model shown in 3.2.

In reality predictions for the day ahead market power production and EPEX price are considered to be quite accurate for three days ahead. In this analysis the actual data is used to predict where the overlap can be considered sufficiently accurate. To solve this maximization problem the linear solver *linprog*, part of the optimization toolbox in Matlab[95], is used. In appendix D.3 is further clarified how the constraints are included in the solver and which functions are used. The general optimization problem is presented in equation 3.4 with general constraints in equation 3.5.

$$maximize[\sum_{n=1}^{72} EPEX_i * P_{strategy\ i}] \tag{3.4}$$

The limits are defined by:

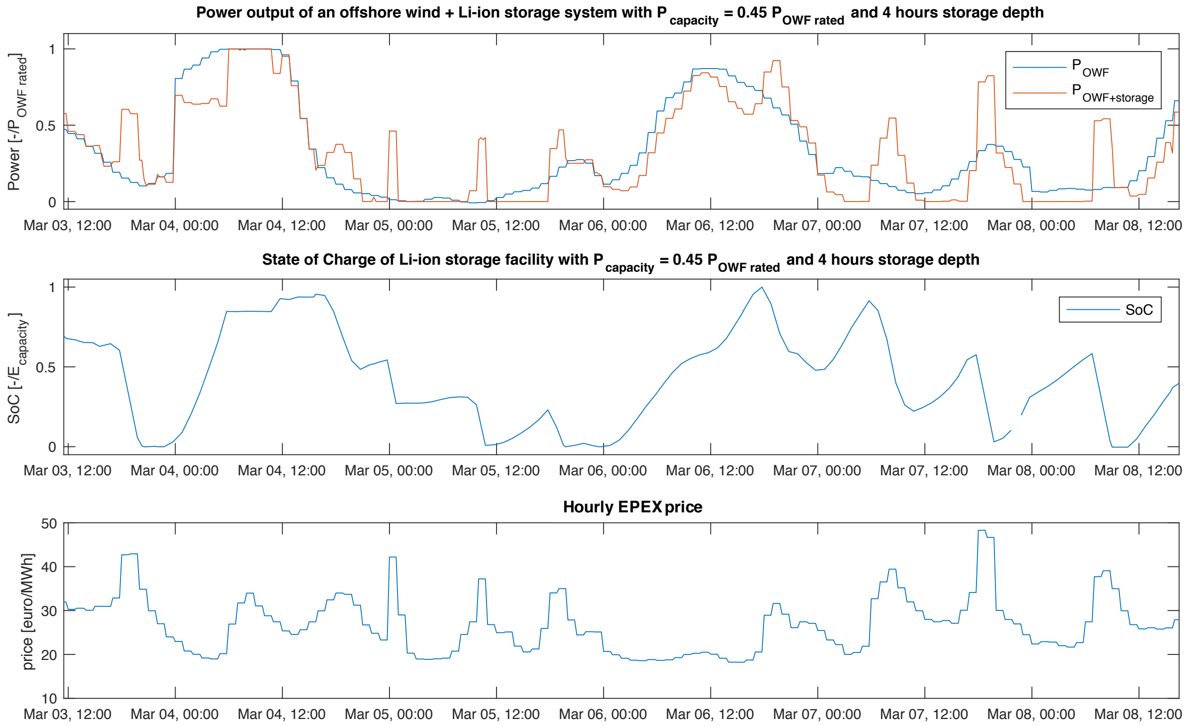
$$\begin{gathered} 0 \leq P_{OWF} + P_{strategy} \leq P_{inframax} \\ 0 \leq SoC + t_{step} * P_{strategy} \leq E_{capacity} \\ -P_{capacity} \leq P_{strategy} \leq P_{capacity} \end{gathered} \tag{3.5}$$

To better account for the physical limitations of the storage system and the different techniques it would be more accurate to use a non-linear solver. In such a solver non-linear functions and constraints could be included to better include the conversion losses and the limitations of the system. However, the available data sets are of such significant size that it would take too much computational power to solve the problem in a non-linear solver.

3.2.3. Model in practice

In this research the model described in section 3.2 is used in two configurations, depending on the goal. The first configuration is the EPEX follow model and the second configuration is the base load model. In this section the two configurations are described and an example of the two models is demonstrated.

The EPEX follow model is identified by the non-constant value for $P_{reference}$ over time. In this case the strategy model, described in section 3.2.2, determines the reference power per hour for a day ahead. An example of the EPEX follow model is shown in figure 3.4. Contrary to the base load model is the result of the EPEX follow model less constant than the power output of the wind farm. $P_{OWF+storage}$ is fluctuating around P_{OWF} in approximately the same profile as the EPEX price. This operation is aimed at maximizing the profit of the offshore wind + storage system.

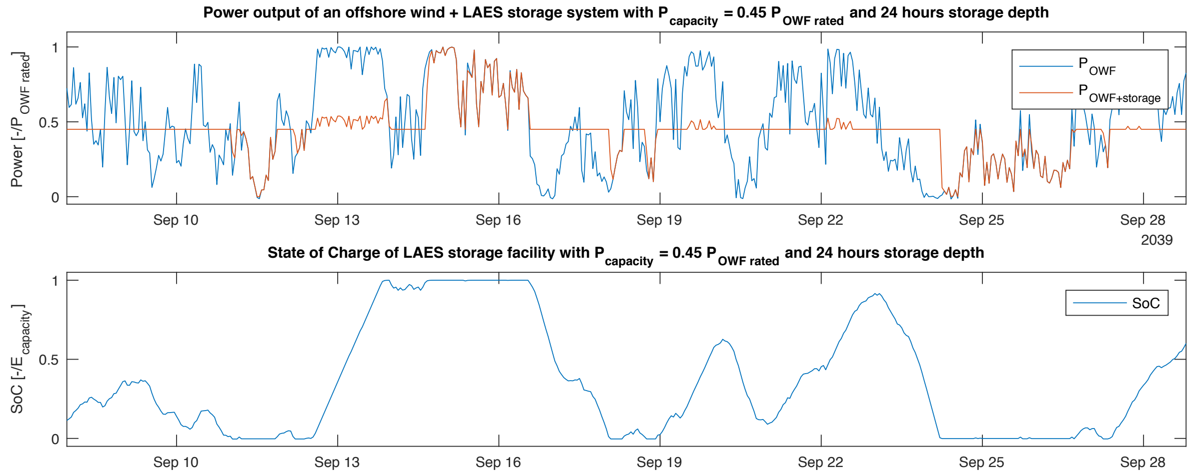

Power output of an offshore wind + Li-ion storage system with $P_{capacity}$ = 0.45 $P_{OWF\ rated}$ and 4 hours storage depth

State of Charge of Li-ion storage facility with $P_{capacity}$ = 0.45 $P_{OWF\ rated}$ and 4 hours storage depth

Hourly EPEX price

Figure 3.4: Example of a simulation from the EPEX follow model where a Li-ion storage facility is used with $P_{capacity} = 0.45 P_{OWF\ rated}$ and $E_{capacity} = 4P_{capacity}$. The storage facility aims to maximize the profit by charging when the EPEX price is low and discharging when the price is high. The strategy is determined daily for 24 hours ahead with the strategy model described in section 3.2.2. In this interval the offshore wind + storage system was able to increase the revenue with 2.5%.

The base load model is identified by the constant value for $P_{reference}$ over time. In this case the strategy model is not used, and the reference power is determined in advance. A sample of the simulation results of this base load model is presented in figure 3.5. This model aims for a constant value of $P_{OWF+storage}$ but does not always achieve this due to the physical limitations or constraints in the system.


Power output of an offshore wind + LAES storage system with $P_{capacity} = 0.45\ P_{OWF\ rated}$ and 24 hours storage depth

State of Charge of LAES storage facility with $P_{capacity} = 0.45\ P_{OWF\ rated}$ and 24 hours storage depth

Figure 3.5: Example of the simulation from the base load model where a LAES storage facility is used with $P_{capacity} = 0.45 P_{OWF\ rated}$ and $E_{capacity} = 24 P_{capacity}$. The storage facility aims to reduce the profile effects by charging when the power production is high and discharging when it is low. The figure demonstrates that the storage depth is not sufficient to completely eliminate the profile effects.

3.3. Storage cost

Several simulations are executed within this research. The performance and the results arising from these simulations are processed in order to be able to extract the relevant information. As the simulations will have several different input parameters and outcomes it is necessary to introduce several variables that are used to quantitatively compare the results. In this section first the levelized cost of storage with the source and motivation of which the data originates are discussed, subsequently the cost of storage and the AEP reduction are introduced. This is done in order to be able to compare the results of the different configurations analyzed with the model.

Levelized Cost of Storage (LCOS) is used to quantitatively compare the different storage techniques, as every technique has its own characteristics in performance and costs. Which is defined in equation 3.6. The LCOS determines the cost per unit energy discharged over the whole lifetime of the storage facility, where in this case the cost of electricity is included.

The LCOS is an industry standard and is important to determine the initial cost of the storage facility. However, it is depending on the utilization and the strategy of the storage facility and cannot be used without the context.

$$LCOS = \frac{Investment + \sum_{n=1}^{N} \frac{OPEX}{(r+1)^n} + \sum_{n=1}^{N} \frac{C_{charging}}{(r+1)^n}}{\sum_{n=1}^{N} \frac{E_{discharged}}{(r+1)^n}} = [\frac{euro}{MWh}] \tag{3.6}$$

In appendix D the equations for the different terms in the LCOS calculation are provided. Generally, the end of life cost should be included in such an evaluation but due to lack of information it is left out of the evaluation in this case. The summation of $E_{discharged}$, given in equation D.2, appears to be discounted over the period of time over which the costs are discounted too. However, in this case only the time and cycle degradation are discounted.

This cycle degradation is included in the lifetime costs of the storage facility but not in the model. Due to limitations in computational power for the calculations in cycle degradation it was not possible to implement this in the model analysis.

LCOS in 2025 is identified as one of the design parameters to select the most cost efficient storage technique. As in section 1.4 2025 is identified as moment of investment. The cost and characteristics for the storage techniques analyzed need to be estimated for this moment in time. In the analysis model predictions are used that originate from technology and cost model predictions [88]. This paper models the LCOS of different storage techniques under multiple circumstances. The model data is independent of the power capacity of the storage facility. The LCOS in this data only depends on the storage depth and the number of annual cycles of the facility. By determining the number of cycles, resulting from the base load or EPEX follow model, and the storage depth it is possible to look up the resulting LCOS for 2025. The model predictions are not specifically made for the Dutch electricity market but for an average electricity price of 44 $\frac{euro}{MWH}$. However, in the cases analyzed the main driver for the LCOS is not the electricity price but the CAPEX of the facility.

In this meta study data thermal storage is not included in the predictions for the LCOS. However, in chapter 2 it was identified that thermal storage is a group of storage techniques to have high potential. To include a technique that uses thermal storage, LAES is added to the model data. Known cost data for LAES in 2025 data could be inserted in equation 3.6 making it possible to compare to the other techniques. For some variables in equation 3.6 operational data was missing for LAES. In these cases, the properties for CAES were used for LAES. This is justified by the fact that both techniques have operational cost components such as compressors and turbines. In table D.1 all the input values for the different techniques used in the analysis are listed.

Cost of Storage is a parameter to compare the wind + storage configurations. The cost of storage (COS) is introduced to compare the configurations on the LCOS and the context in which the storage facility is operating. For the COS the LCOS is scaled towards the total electricity production of the offshore wind + storage system. The COS together with the levelized cost of energy of the OWF (LCOE$_{OWF}$) comprise the total levelized cost of the offshore wind + storage system LCOE$_{OWF+storage}$. The COS is defined in equation 3.7, $E_{\text{storage discharged}}$ represents the electricity discharged by the storage system, AEP$_{OWF+storage}$ represents the AEP of the offshore wind + storage system and $t_{lifetime}$ represents the lifetime over which the storage is discharged.

$$COS = LCOS * \frac{\sum_{n=1}^{N} E_{\text{storage discharged}}}{t_{lifetime} * AEP_{OWF+storage}} = [\frac{euro}{MWh}] \tag{3.7}$$

Annual Energy Production Reduction is introduced to account for conversion losses in charging and discharging of the storage facility energy. The loss in energy output, of the offshore wind + storage system, with respect to the electricity produced by the OWF is referred to as AEP reduction, defined in equation 3.8. AEP_{OWF} represents the AEP of only the offshore wind farm and $AEP_{reduction}$ represents the reduction in AEP of the offshore wind + storage system relative to the OWF.

$$AEP_{reduction} = \frac{(AEP_{OWF} - AEP_{OWF+storage}) * EPEX_{mean}}{AEP_{OWF+storage}} = [\frac{euro}{MWh}] \tag{3.8}$$

3.4. Offshore electrical infrastructure

Offshore storage of the electricity generated by the OWF can contribute to savings on the electrical infrastructure. To determine the cost savings on the infrastructure it is important to identify of what components it is comprised of. The cost of the infrastructure consists of several major components of which the costs can be estimated by the corresponding equations, based on market research [96]. This section contains the methodology on how the cost and performance of the electrical infrastructure is determined.

The goal is to compare the simulation on the: Curtailment, AEP reduction, COS and the levelized cost of energy of infrastructure ($LCOE_{infra}$). In this case the curtailment is already included in the cost for the AEP reduction but will be calculated to determine its the impact in the operation. Curtailment occurs when electricity is produced above the rated power of the infrastructure and the storage facility is not able to store the energy due to saturation of the facility. The power of the wind turbines has to be reduced, resulting in a reduction in AEP. The total AEP reduction is defined in equation 3.8 and the COS is defined in equation 3.7. The $LCOE_{infra}$ is used to express the total cost to the services provided in transporting electricity, which is defined in equation 3.9. In this equation the $OPEX$ is assumed to be two percent of the total investment.

$$LCOE_{infra} = \frac{Investment + \sum_{n=1}^{N} \frac{OPEX}{(r+1)^n}}{\sum_{n=1}^{N} E_{transported}} = [\frac{euro}{MWh}] \tag{3.9}$$

3.4.1. Components of the offshore infrastructure

The investment in the electrical infrastructure is determined by four major components: the export cable, the substation, the back-up generator and the transformer. The total investment is given in equation 3.10 and the components are further elaborated below.

$$Investment = C_{cable} + C_{ss} + C_{gen} + C_{trafo} \tag{3.10}$$

The offshore substation is the central point to which the infield cables, coming from the wind turbines, are connected. On this support structure the transformers and other auxiliary equipment are located. The cost for the substation (C_{ss}) is estimated using equation 3.11 [96].

$$C_{ss} = 2.8286 + 0.099 P_{OWF\ rated} \quad [Meuro] \tag{3.11}$$

The transformers located on the substation transform the power to the desired voltage for the transportation to shore, through the export cable. The cost for the transformers (C_{trafo}) is estimated using equation 3.12 [96].

$$C_{trafo} = 0.0477 P_{OWF\ rated}^{0.7513} \quad [Meuro] \tag{3.12}$$

The backup diesel generators are necessary to run essential substation equipment and are positioned on the substation. The cost for the generators (C_{gen}) is estimated using equation 3.13 [96]. In the presence of a storage facility the need for backup generators is assumed unnecessary.

$$C_{gen} = 0.0237 + 0.0023 OWF\ rated \quad [Meuro] \tag{3.13}$$

The export cables are the high voltage cables that transport the electricity from the substation to shore. Standardization has been one of the drivers for cost reductions in the offshore wind industry, this is the same for export cables. The cost for cables per unit length are determined by the available design of the manufacturer. This limits a complete optimization since custom manufactured cables are not available or too expensive. The way to decrease the costs for the cable is to downsize the cable with manufacturer prescribed dimensions. The cost for the manufacturing and installation of the export cable (C_{cable}) is estimated using equation 3.14 [96]. $C_{cable\ manu}$ is the manufacturing cost for the cable, $C_{cable\ instal}$ is the installation cost of the cable, l_{cable} the length of the cable and $l_{offshore}$ is the distance for the cable to shore.

The infield cables, which connect the turbines to the substation, are not considered in this analysis due to the lack of data. Including these cables would, like the export cable, result in a reduction in investment and a reduced LCOE. However, compared to the export cable these costs are considered small.

$$C_{cable} = C_{cable\ manu} * l_{offshore} + C_{cable\ instal} * l_{cable} \quad [euro] \tag{3.14}$$

In table 3.1 three different types of cables are listed with their characteristics. In this analysis $220kV$ HV-AC connection is considered as this is the standard for the to be built OWFs in the North Sea. The rated power of the export cable determines the maximum power capacity of the other infrastructure components. For the data analyzed, and also assumed for the designed OWF, the $l_{cable} = 30km$ and the $l_{offshore} = 20km$.

Table 3.1: Export cable characteristics [96]

		HVac		
$U_{OWF\ rated}$	$[kV]$	220	220	220
$P_{OWF\ rated}$	$[MW]$	250	295	330
$C_{cable\ manu}$	$[\frac{keuro}{km}]$	772	1009	1301
$C_{cable\ instal}$	$[\frac{keuro}{km}]$	720	720	720

The rated power of the export cables in table 3.1 do not match the rated power of the OWF of which the data originates. No exact cost data is available for cost of export cables with the same rated power as the OWF however, it is assumed that for new OWFs an exact match will be the case. Therefore, the power production data for the OWF is scaled to the rated power of base case of a cable with $P_{rated} = 330MW$. To analyze the impact of peak shaving with storage the P_{rated} of the OWF is kept at the base case and the P_{rated} of the cable and the other components are reduced.

3.5. Turbine design + storage

Influencing the power production profile of a wind turbine is possible by in or decreasing the rotor diameter of the turbine, while keeping the other turbine components the same. To analyze the performance of the wind turbines, the power production profiles are analyzed against each other. Data sets with the power production profile for multiple years are available for the different rotor diameters. Due to limitations in the model, is this data not comparable with the extrapolated measured data that is used in the analysis of the other sections. However, it will be possible to qualitatively determine the influence of the rotor diameter on the offshore wind + storage system, of which the methodology is presented in this section.

The cost for turbine design is compared in different configurations. To do so the CAPEX of the different turbines is determined using the Innwind cost modelling tool [97] and compared with the other configurations in the levelized cost of energy of the wind turbine ($LCOE_{turbine}$). The cost for the turbine ($C_{turbine}$) is in this case dependent on the increased size of the rotor and the reinforcements necessary to deal with the increased weight and load. The $LCOE_{turbine}$ is derived in equation 3.15 and considered because with changing the rotor size the AEP of the wind turbine also affected.

$$LCOE_{turbine} = \frac{C_{turbine} + \sum_{n=1}^{N} \frac{OPEX}{(r+1)^n}}{AEP * n_{lifetime}} \tag{3.15}$$

The power production data used for the rotor diameter variation originates from different models than the data used for the other offshore wind + storage systems. The data is used to qualitative analyze the influence of the rotor diameter on the cost effectiveness of the offshore wind + storage system. If the real impact of the system is required, performance data should be acquired that includes the increased height of the nacelle, the altered layout of the turbines in wind farm and the shutdown of turbines due to maintenance or failure. Therefore, in this report the data is only used qualitatively to the base case with $d_{rotor} = 112m$. All the results will be represented as a value relatively to the base case result.

4

Results

This chapter will describe the impact of the addition of a storage facility to offshore wind power production in several configurations. This is provided in sections that contain:

- An analysis of the power production data of Luchterduinen Wind Park to identify the critical issues in integrating offshore wind power into the electricity system.
- A design and impact analysis of a base load offshore wind + storage system, designed to eliminate the profile effects of offshore wind power.
- A design analysis of the most optimal configuration of an offshore wind + storage system, designed to reduce short-term profile effects of offshore wind power.
- An analysis in the role and impact of offshore storage towards cost savings on the infrastructure.
- The role of rotor diameter design of the offshore wind turbines towards short-term profile effect reduction.
- The impact of the most techno-economic design of an offshore wind + storage system, where the design is based on the example case of Luchterduinen Wind Park in 2025.
- Identification of the additional utilization of a storage facility in an offshore wind + storage system.

4.1. Integration of Wind Power

In this section the power production of offshore wind energy is analyzed and will provide the results to answer the sub question: What are the challenges for offshore wind energy in the future energy system in the Netherlands?

The increasing penetration of wind power into the electricity mix is increasing the efforts necessary to integrate this into the grid. The integration complications arise from the intermittency of wind energy and the location where the electricity is produced. The cost that arise from the measures necessary to integrate this wind energy is referred to as integration cost [7]. The integration cost of wind energy become more significant for the increasing market penetration of wind energy and are expressed in $[\frac{euro}{MWh}]$. By subtracting the integration cost from the system base price, the market value of wind power is left.

Integration costs of wind power are composed of three separate costs that can be quantified; 1. profile cost, 2. imbalance cost and 3. grid/location cost. Hirth et al. have modelled these costs to an increasing market penetration of (on and offshore) wind energy in general, of which the results are shown in figure 4.1. It is observed that for an increasing market penetration the integration costs grow to become of significance. This is mainly caused by the increasing profile cost and the location/grid related cost for wind power. The balancing costs stay constant for an increasing grid penetration and become relatively less significant.

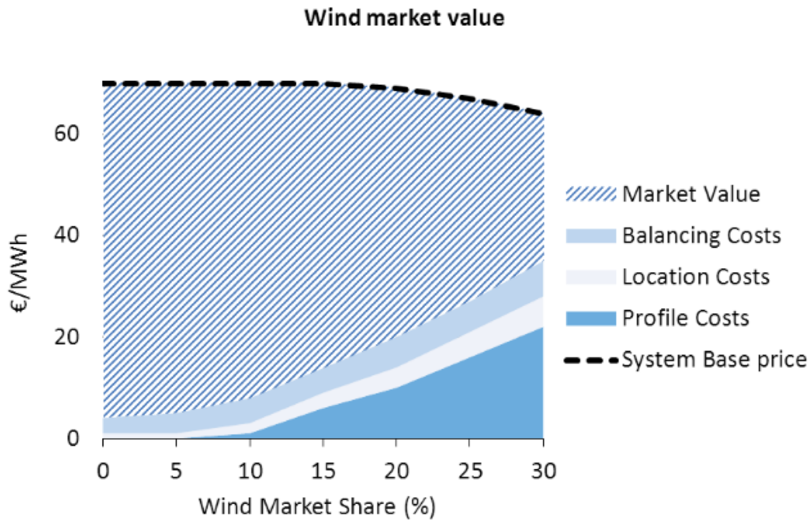


Figure 4.1: Market value plot as a function of the market penetration of wind energy [7].

4.1.1. Imbalance

If the imbalance development in figure 4.1 is analyzed for an increasing grid penetration of wind power, it is observed that the costs are quite stable compared to the profile and location/grid cost. Nowadays the imbalance is resolved by trading on the imbalance and intraday markets. By buying or selling energy on short notice and in small time frames it is possible to comply with the bid made 24 hours in advance. The prices are generally reasonable and besides the extreme prices, that occur little times during the year, do these market systems satisfy. Based on figure 4.1 will these costs not increase significantly for high market penetration, and it is assumed the imbalance cost will not drastically increase in price. The systems in place to solve imbalance are working properly against a reasonable allowance and will do so for high market penetrations of wind energy.

Besides the working systems in place does historical data for imbalance costs show that the majority of the costs arise from the few extreme peaks in the year. At these moments a lot of imbalance occurs, and the price increases exponentially. If the imbalance should be resolved for these moments the power capacity of the storage facility should be significantly higher than the optimal power capacity for the storage facility would be. The imbalance costs that would be saved would not weigh against the extra investment necessary for the storage facility. High costs for storage and small reward in costs savings will make it hard for storage to compete with the imbalance market. Therefore, reduction in imbalance using storage should not be the main focus but could contribute to the final feasibility of wind + storage.

4.1.2. Location and grid related costs

With the allocation of the areas for wind farms far offshore it was evident that the location and grid related costs become more significant. The electricity produced by wind farms on the North Sea, is produced on a location where it is not directly consumed. The electricity has to be transported to the consumer in the most efficient way. The question here arises how offshore wind + storage could contribute to a more cost effectively use of the infrastructure. If the offshore wind + storage facility can perform load shifting and decrease the power capacity of the infrastructure, the capacity factor can be increased. By increasing the capacity factor of the infrastructure, it is possible to reduce the LCOE for this component. When the supply of the electricity is steered more towards the demand it is possible to reduce the congestion issues that the TSO is facing at times of high wind and low local demand.

4.1.3. Profile effects

From figure 4.1 it is concluded that the profile costs are the major contributor to the increasing integration cost that is observed for an increasing wind market penetration. The profile costs resulting from the profile effects, described in appendix A.2, find its nature in the intermittency of wind energy. The profile effects of wind are divided into two groups; short-term profile effects and seasonal profile effects.

Short-term profile effects

Profile effects are translated to profile cost in the decrease in market value and backup power necessary in an electricity system that is relying on wind power. In periods of high wind, most of the wind turbines on the market are producing electricity and the price drops below average. In times of little wind, the majority of the wind turbines are not producing any electricity. In this case the demand cannot be met by wind power and back-up power is necessary. From a societal point of view the latter is more interesting since it has impact on the energy security and the backup power that is necessary for these periods of little wind. Currently this backup power is in the form of carbon emitting plants. The times of high wind are of lesser importance in the point of view of the TSO due to the fact that the wind turbines could be curtailed. Curtailing is a measure that is relatively easy, but undesirable as renewable electricity capacity is purposely not utilized. Contrary to seasonal profile effect are the short-term profile effects not subjected to reoccurring cycles over seasons, but more randomly occurring throughout the year.

To get a better understanding of the intensity and the frequency of the low wind periods a four-year period of Luchterduinen Wind Park is analyzed. In the case of electricity production, it is more interesting in how many periods the electricity production is below a certain level rather than the velocity of the wind. In figure 4.2 the average occurrence of low power production period, with respect to a fraction of the rated power, are given. In this case a lack of power production due to too much wind is included as well since it has the same effect on the power production as too little wind. For this data set [92], the average power production is $0.52 * P_{rated}$.

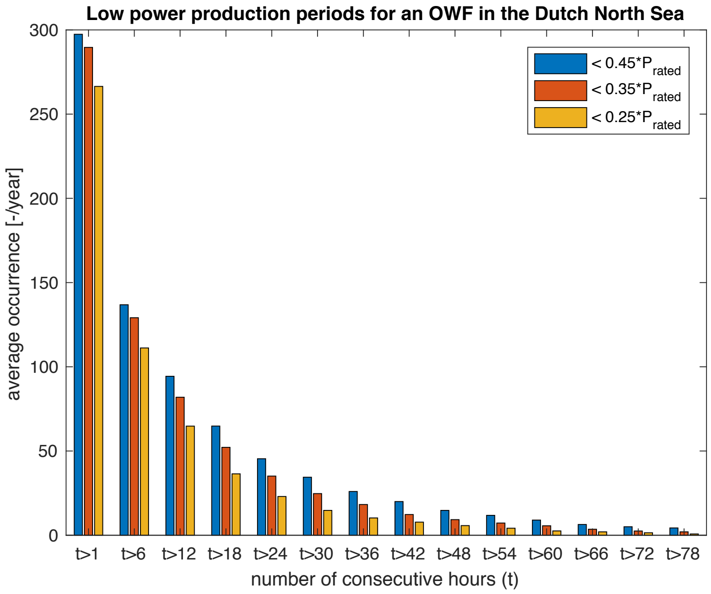


Figure 4.2: Number of low power production periods for an OWF in the North Sea as a function of the length of the period [92]. This figure represents the short-term profile effects of offshore wind energy. The number of occurrences shown in the bar graph determine the maximum amount of cycles for the system, if a storage facility would be used to counter these effects. In the case the storage depth is equal to the duration of the period shown in the figure.

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[1] The storage depth is a function of the energy capacity of the storage facility defined by: *storage depth* = $\frac{E_{capacity}}{P_{capacity}}$.

Figure 4.2 is a representation of intensity of the short-term profile effect of offshore wind energy. The number of occurrences for a certain length of period represents the maximum amount of cycles a storage facility with that storage depth[1] is able to make per year. In the case that the storage facility would solely be used for short-term profile effect reduction. An important observation that is made in this figure is the fact that periods longer than 72 hours are almost never occurring. This results in the fact that for a reduction in short-term profile effects it is not necessary to design the facility at larger storage depth.

Seasonal profile effects

Wind power is subjected to seasonal fluctuations of which the peak in electricity production is in winter and the low in summer. For offshore wind power to fit the electricity demand it would be expected that a deviation would occur in this seasonal cycle. However, if the monthly average offshore wind power production is observed against the demand it is observed that they are both fluctuating in somewhat the same pattern, as shown in figure 4.3. The curves shown are comprised of monthly averages, the electricity production as well as the demand can differ for the specific year with, for example, a particular cold winter.

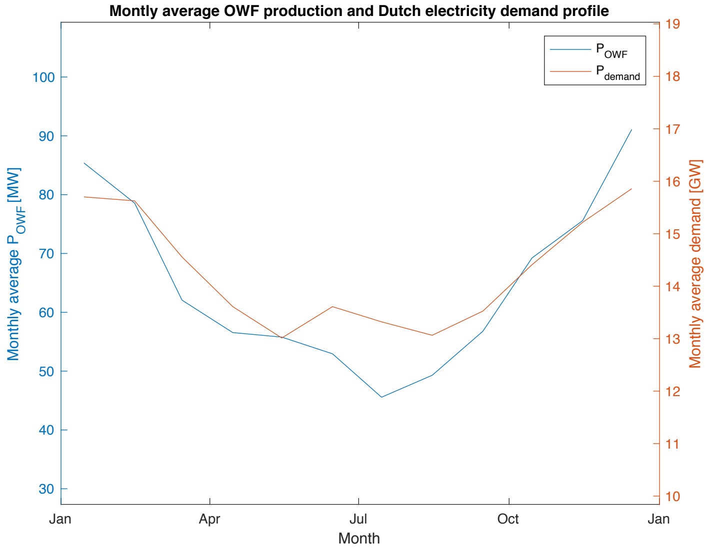

Figure 4.3: Monthly average profile of OWF power production [92] and the Dutch electricity demand [91], corrected for future electricity demand expectations. In this figure it is observed that the averaged offshore wind production profile experiences the same seasonal fluctuation as the demand curve.

4.2. Offshore wind + storage in 2025

After identifying the characteristics for offshore wind energy in the data the optimal energy storage solution is determined. The goal for offshore wind + storage is to push out the carbon emitting power plants that are providing electricity to the grid at all times. An important supplier to the electricity mix is the coal fired plants which provides a base load supply of electricity and represents the lower merit order plants. Secondly there are the peaking power plants, mainly natural gas combined cycle (NGCC), that provide electricity in times of high demand or low supply of renewables. In this section the role and impact of the storage techniques available to replace these carbon emitting plants is analyzed. Firstly, it is analyzed what would be necessary for an OWF to completely eliminate profile effects and create a base load profile with the use of a storage facility. Secondly, it is analyzed what the optimal configuration is for reduction of short-term profile effects. Lastly it is analyzed how energy storage can aid in cost savings on the offshore infrastructure.

4.2.1. Profile effect elimination by creating a base load electricity production profile in an offshore wind + hydrogen storage system

In this section the optimal dimensions of a storage facility in order to achieve a year-round base load profile from the power production of an OWF is determined. In figure 4.3 it is observed that to achieve this year-round base load profile, seasonal storage of electricity is required. As the (monthly averaged) power production of an OWF is not constant over a year. The base load profile, as a fraction of the rated power of the wind farm, ensures a constant power output over the year. In figure 4.4 an example of the ideal operation of an offshore wind + storage base load system is shown. By storing electricity in winter and releasing the stored energy in summer a base load profile can be achieved. In this figure no conversion losses are included thus the base load is achieved at the average power production of $0.52 * P_{rated}$.

The base load profile in an offshore wind + storage system can be seen as a replacement of the coal fired plants which currently provide the base load electricity to the grid. The goal of obtaining a base load profile is to eliminate the profile effects of the power production of offshore wind energy. Therefore, will this section provide the answer to the sub question: What form and how much energy storage is necessary to solve these challenges faced with offshore wind?

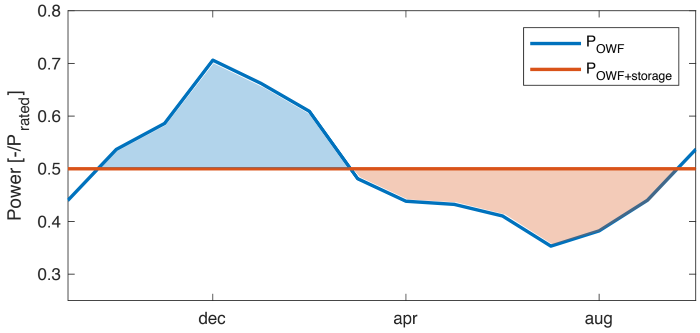

Figure 4.4: Monthly averaged production profile of Luchterduinen Wind Park and an example of a desired base load profile with an offshore wind + storage system. By storing the electricity generated in the blue shaded area and releasing it in the orange shaded area a year-round base load profile is obtained.

Figure 4.4 shows the operation of an idealized base load system which does not represent reality. To analyze a system that better represents reality several assumptions are made to come to the optimal configuration of the system. The assumptions are:

- According to Schmidt et al. is hydrogen storage economically and technically the most feasible technique for seasonal storage of P2P appliances in 2025 [88]. Therefore, in the analysis in this section is hydrogen storage assumed the optimal technique, and no other technique is considered.
- Hydrogen is synthesized with an alkaline electrolyser and converted back to electricity using a PEM fuel cell. The dimensions of the storage facility make this the optimal configuration in components for seasonal hydrogen P2P appliances in 2025. This setup results in a round trip efficiency: $\eta_{roundtrip} = 0.41$ [88].
- The energy capacity of the storage facility is sufficient for the system to provide the desired base load power capacity ($P_{\text{base load}}$) throughout the year. $P_{\text{base load}}$ is varied as a fraction of the rated power of the OWF, with the reference value (*ref value*).
- The electricity price is assumed constant in this analysis for 2025 expectations [98] at: $EPEX_{mean} = 48\frac{euro}{MWh}$.
- To limit the number of variables in the analysis the power capacity of the storage facility is fixed at: $P_{\text{storage}} = 0.68 P_{\text{rated OWF}}$. The value for 0.68 is chosen because this power capacity is necessary to enable the lowest $P_{\text{base load}}$ analyzed.

By storing and releasing energy the storage facility is subjected to conversion losses. Due to the losses in conversion it will not be possible for the system to have a base load at the average power production of the wind farm. This fraction however is not known yet, therefore the analysis is made for a non-constant base load power capacity by varying the fraction of the rated power of the OWF. In figure 4.5 the number of hours below the base load power capacity is shown as a function of the storage depth of the facility.

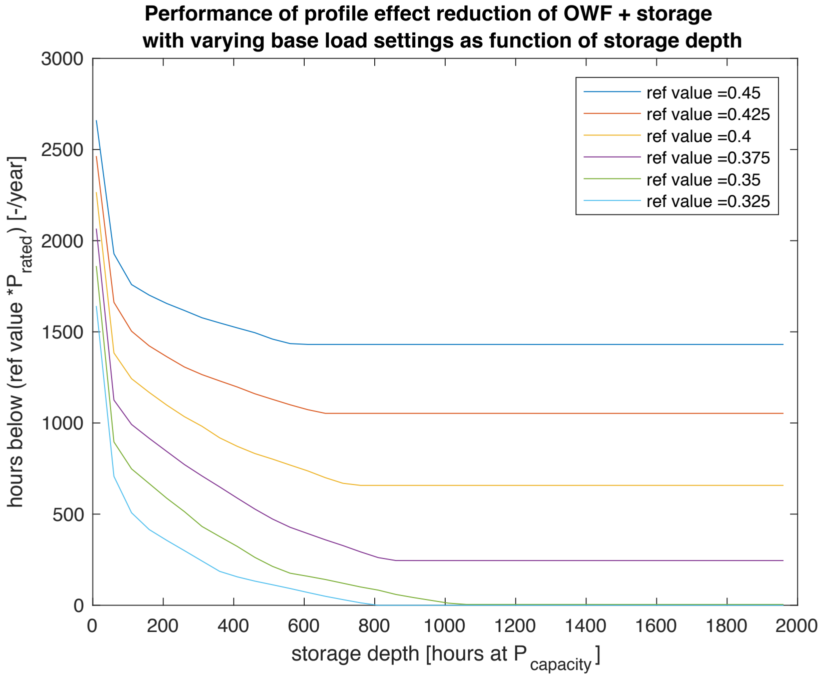

Figure 4.5: Base load hydrogen storage as a function of the storage depth of the storage facility, with $P_{capacity} = 0.68 * P_{\text{OWF rated}}$. The information in this figure is used to determine the minimal values for the storage depth and $P_{\textit{base load}}$ to achieve a year-round base load profile with an offshore wind + storage system. It is observed that for a ref value higher than 0.35 a full base load profile is not obtained, even though the $P_{\text{OWF mean}} = 0.52 P_{\text{OWF rated}}$. This is caused energy losses in conversion. The minimal values at which this is achieved is at 800 hours storage depth at $P_{\text{base load}} = 0.325 P_{\text{rated OWF}}$

In figure 4.5 it is observed that all the lines are converging to a constant value of hours below the base load value. However, for the lines with a fraction of rated power above 0.35 are not converging to 0. This entails that no year-round base load profile is achieved. The reason for the storage facility not reaching a full base load profile is the conversion losses in synthesizing hydrogen and the fuel cell. In figure 4.5 it is observed that a base load profile above the reference value of 0.35 is not possible, even though the $P_{\text{OWF mean}} = 0.52 P_{\text{OWF rated}}$. From this figure it is concluded that a minimal storage depth of 800 hours is necessary to achieve a year-round base load at $P_{\text{base load}} = 0.325 P_{\text{rated OWF}}$.

The conversion losses in the system impact, besides the base load capacity, the total amount of electricity that is discharged by the system. This is referred to as the reduction in AEP of the offshore wind + storage system ($AEP_{reduction}$). The $AEP_{reduction}$ directly influences the revenue of the system and is therefore an important parameter. To assess the $AEP_{reduction}$ caused by the conversion losses in the storage facility, this value is determined relative to base case. The base case represents the AEP of the OWF without a storage. In figure 4.6 the AEP is shown for multiple base load power capacities as a function of the storage depth.

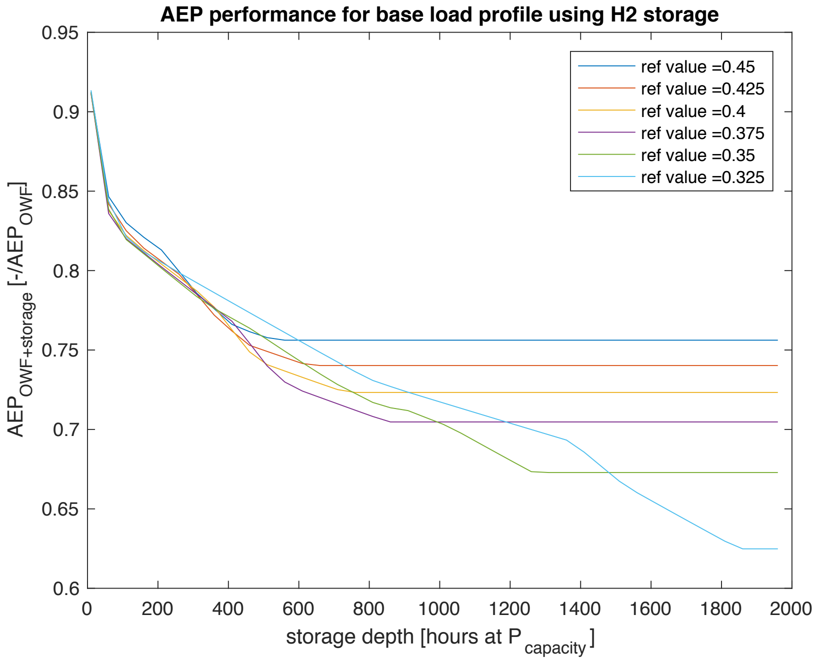

Figure 4.6: The AEP for multiple base load power capacities as a function of the storage depth. The reduction in AEP becomes larger for an increasing storage depth. This is caused by the system being able to store more energy over the year, resulting in more conversion losses. At a storage depth of 800 hours it is observed that the $AEP_{reduction}$ for a *ref value* of 0.325 is less than for 0.35, resulting in a more economical favourable system for a *ref value* of 0.325.

In figure 4.6 it is observed that the AEP decreases for the growing size of the storage facility. This is caused by the system being able to store more energy throughout the year, resulting in more conversion losses. As the higher reference values all seem to converge at a certain storage depth, do the lowest two values experience a new decrease in AEP. This is caused by the four-year period, containing different wind years, for which the storage facility is designed. The number of hours below the base load power capacity will only converge to zero if in the most difficult year a year-round base load profile is achieved. The result is that during the other three years the system provides the same set base load but needs less of the stored energy in summer than is actually stored in winter. This energy accumulates in the facility and causes the second decrease in AEP before steady state is achieved.

From figure 4.5 and 4.6 it is concluded that the economical favourable option for the base load system is at $P_{base\ load} = 0.325 P_{OWF\ rated}$ and a storage depth of 800 hours. The impact of this system is shown in table 4.1. The $AEP_{reduction}$ and the COS were determined by entering the given parameters into the base load model. The model resulted in an average of 2.1 cycles per year, which was then used to determine the LCOS. Using equation 3.7 the cost of storage was obtained that is shown.

Table 4.1: Most economical dimensions of the storage facility in an offshore wind + storage system to obtain a year-round base load profile.

Property	Characteristics	Dimensions	
$P_{capacity}$	$0.68 P_{\text{OWF rated}}$	85	MW
$E_{capacity}$	$800 P_{capacity}$	68	GWh
$P_{\text{base load}}$	$0.325 P_{\text{OWF rated}}$	40.6	MW
$AEP_{reduction}$		19.84	$\frac{euro}{MWh}$
COS		603	$\frac{euro}{MWh}$

In figure 4.7 the load curve of base load system is shown with respect to the load curve of the wind farm. The load curve in the figure illustrates that there are moments when the system exceeds the $P_{base\ load}$. This occurs when the storage facility is saturated and the OWF is generating more electricity than the $P_{base\ load}$, in this case there is an excess in electricity. If possible, this electricity can be sold on the grid or otherwise be curtailed.

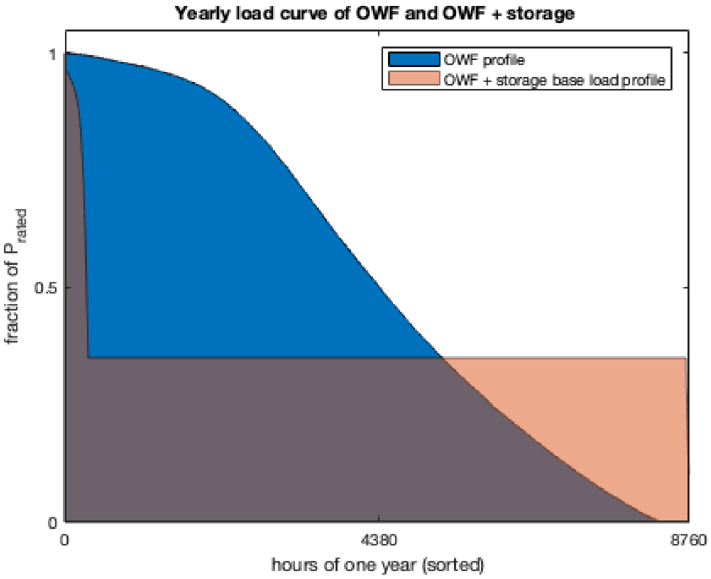

Figure 4.7: Load curve for an OWF and for a base load offshore wind + storage system, of which the dimensions are given in table 4.1. In a load curve the hourly power production of the system is sorted in descending order with respect to the power generated. In this figure the base load profile achieved is shown as well as the load curve of the OWF. It is shown that a full base load is achieved, but that the base load was exceeded for several hours in the year.

In section 4.1 it is identified that the advantage of creating a base load profile out of offshore wind energy is expressed in cost per unit energy. The costs are made up of elimination of profile costs, balancing cost and potentially reducing the location cost. From figure 4.1 it is derived that the major cost reduction is made in the profile effect reduction which comes to $15 - 35\frac{euro}{MWh}$ [7]. Using table 4.1 these avoided costs can be compared to the $AEP_{reduction}$ that is achieved for the base load system. For these results it is observed that a large share of the cost savings is cancelled by the reduction in AEP, thus the revenue of the system. This $AEP_{reduction}$ originates from the conversion losses in hydrogen synthesis and converting it back to electricity.

Besides the reduction in revenue is the investment in storage facility high when expressed per unit of energy produced by the system. The COS is more than ten times the EPEX price and is additional to the cost for the OWF itself. The costs for the storage facility are high due to the fact that seasonal storage requires a large size system that is used for a small amount of cycles per year. The small number of cycles results in high cost per energy capacity of the storage facility.

4.2.2. Short-term profile effect reduction by levelling out the peaks and lows in electricity production with an offshore wind + storage system

In this section the design of a storage facility for the reduction of short-term profile effects of offshore wind energy is analyzed. From appendix C it is known that the wind power capacity installed in the Netherlands is strongly correlated in power production. Reducing short-term profile effect results in shifting power produced during peak periods to periods of low power production. This operation is referred to as load shifting and an example of this operation is shown in figure 4.8. The short-term profile effects are reduced to prevent peaks and lows in power production. However, from an economical point of view this operation makes sense too. The residual load steers the EPEX price through the merit order, like explained in appendix B. By moving the load from a low-price region to a high price region it is possible to generate more profit per unit of energy.

The optimal configuration for short-term profile effect reduction is determined for the different storage techniques as a function of the power capacity and the storage depth of the facility. The storage technique is selected on the LCOS and the performance of the system. This in order to answer the sub question: What is the techno-economic optimal configuration of an offshore wind + storage system in 2025?

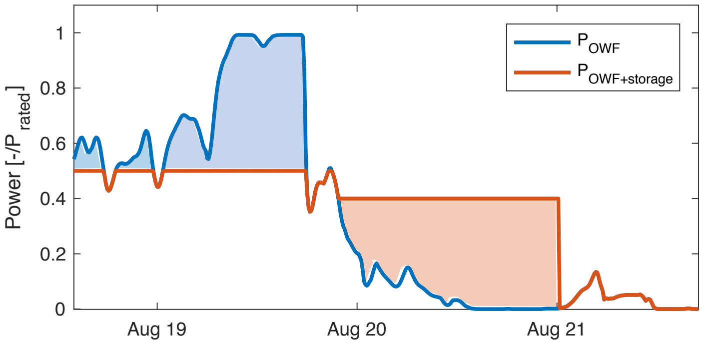

Figure 4.8: Example of load shifting to reduce short-term profile effects for offshore wind energy. By storing the electricity generated in the blue shaded area and releasing it in the orange shaded area the peaks and lows in electricity production are flattened.

The characteristics of short-term profile effects are identified for the wind power production for Luchterduinen in section 4.1.3. Low power production periods of multiple days are rarely occurring and the cost for the storage facility is highly depending on the number of cycles in a year. Therefore, it is expected that designing the storage facility for this longer period of time will lead to high cost per unit energy stored. This is due to the limited amount of cycles the storage facility is making. Which is caused by the fact that an offshore wind + storage does not require large discharging times that often, and the limited amount of (dis)charging time in the lifetime of the facility.

Next to the growing costs is the relative impact of the storage facility reduced with an increasing storage depth. In figure 4.9 the number of hours below $0.3P_{\text{OWF rated}}$, a measure for the short-term profile effect reduction, is shown as a function of the storage depth for the different storage techniques. In this figure a reduction in the rate of decrease is observed for an increasing storage depth. Around a storage depth of 50 hours the rate of decrease in short-term profile effects is reduced to close to zero. Due to this levelling out of the decrease in performance is the next part of the analysis only executed for a maximum storage depth of 50 hours.

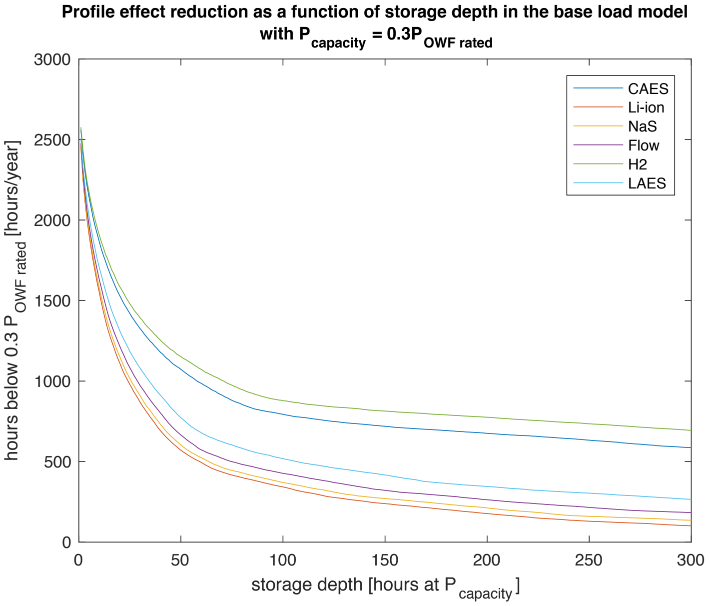

Figure 4.9: Hours in a year where the offshore wind + storage system is not able to reach $P_{reference}$ power where: $P_{capacity} = P_{reference} = 0.3P_{OWFrated}$. The reduction in hours below $P_{reference}$ is a measure for the reduction in short-term profile effects. For storage depth above 50 hours the rate of decrease in short-term profile effects is reduced to close to zero for all the storage techniques analyzed.

Storage technique analysis

To come to the best technology for profile effect reduction the different techniques are compared. In this section the key parameter to compare the different techniques with each other is the LCOS. The LCOS is derived from the investment necessary and the performance in the model. For a storage facility the number of cycles in a year or lifetime is of high significance to the LCOS. The number of cycles is determined by the power capacity, the storage depth of the storage facility and the storage technique used. If the storage depth, and thus indirectly the performance in profile effect reduction, is varied it is possible to determine the technology with the most cost-efficient operation. In figure 4.10 the LCOS is shown for the different storage techniques as a function of the storage depth. The power capacity of the storage facility is constant at $P_{capacity} = 0.3P_{OWF\ rated}$. The LCOS was obtained from the results from varying the storage depth in the base load model for the different techniques. In this figure the charging and discharging strategy is the same for the different techniques and for the varying storage depth. This, to equally compare the different configurations in the system. To be able to compare the results throughout the analysis, the strategy is the same for the continuation of the analysis. When the power capacity of the storage facility is referred to this determines the $P_{capacity}$, but also the $P_{reference}$ in setting in the base load model. Contrary to the analysis in section 4.2.1 the $P_{capacity} = P_{reference}$.

In figure 4.10 the LCOS of the storage facility is shown. In this case it is fully based on reduction of profile effects. The number of cycles for the storage facility results from the base load model. It is observed that the lowest LCOS in general is achieved with CAES at a storage depth of approximately 20 hours. However, it is not clear what the optimal power capacity is for the wind + storage system, and how the techniques might change if this power capacity of the storage facility is varied.

The small fluctuations in the results in figure 4.10 are caused by the model results not being completely smooth. The input of the model works through in the whole solution of the time series. If the input value changes with a small step size it could occur that another route is chosen which could be less beneficial in the end. In small step size the results can fluctuate a bit which causes the small fluctuations in the figure, but this is not influencing the result for larger step sizes.

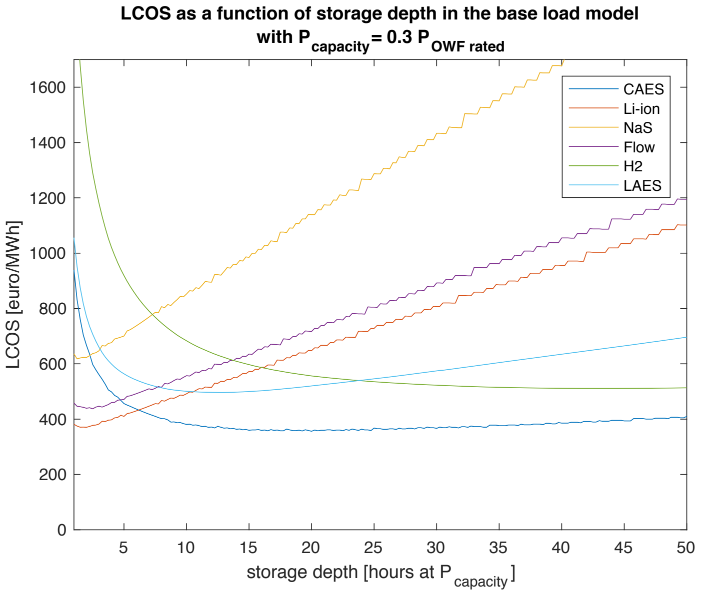

Figure 4.10: LCOS for the different techniques [88] as a function of the storage depth and number of cycles where: $P_{capacity} = 0.3P_{OWF\ rated}$. The LCOS is in this figure completely based on the results of short-term profile effect reduction. For a small storage depth Li-ion has the lowest LCOS, where for larger storage depths CAES is the cheapest option. The absolute minimum of the figure lies at a storage depth of approximately 20 hours.

To illustrate the variation in power capacity the LCOS is derived as a function of storage depth and power capacity of the storage facility, which is shown in figure 4.11. In this figure the combined lowest LCOS of the different storage techniques is shown over the domain that is analyzed. Figure 4.12 shows which technologies make up the lowest LCOS over the domain that is shown in 4.11. In figure 4.12 also shows how significantly cheaper the cheapest technology is with respect to the second cheapest technology. The intensity of the color represents how the technique shown is performing compared to the second cheapest storage technique. This could be of importance when the other characteristics of the different storage technologies are considered.

The LCOS in figure 4.11 is based on a number of cycles of the storage facility that is achieved with the base load model in an ideal situation. It is observed that there is a sweet spot in the domain analyzed at a $P_{capacity} = 0.23P_{\mathrm{OWF\ rated}}$ and a storage depth of 19 hours. The cheapest LCOS is, over the complete domain of the figure, high if compared to the costs of electricity generation and the average EPEX price.

In figure 4.12 it is found that the technique that is responsible for the sweet spot in the LCOS is CAES technology. At the position of the sweet spot CAES is significantly cheaper than the second cheapest technology. For the larger part of the domain is CAES significantly cheaper than the other techniques analyzed, only for small storage depths is Li-ion cheaper. If the figure would be expanded, then hydrogen storage will become the cheapest option at a larger storage depth.

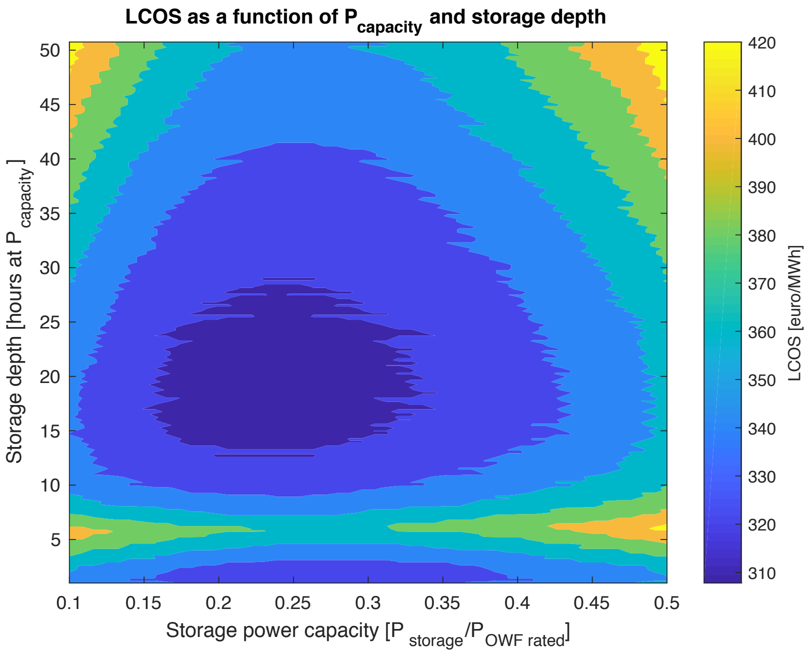

Figure 4.11: LCOS for an offshore wind + storage system as a function of the power capacity and the storage depth. In this figure the combined lowest LCOS of the different storage techniques analyzed is shown. Figure 4.12 shows which technologies make up the LCOS shown in this figure. From this figure it is concluded: 1. There is a sweet spot for approximately $P_{capacity} = 0.23P_{\text{OWF rated}}$ and a storage depth of 19 hours. 2. The LCOS is high for the whole domain analyzed, including the sweets pot.

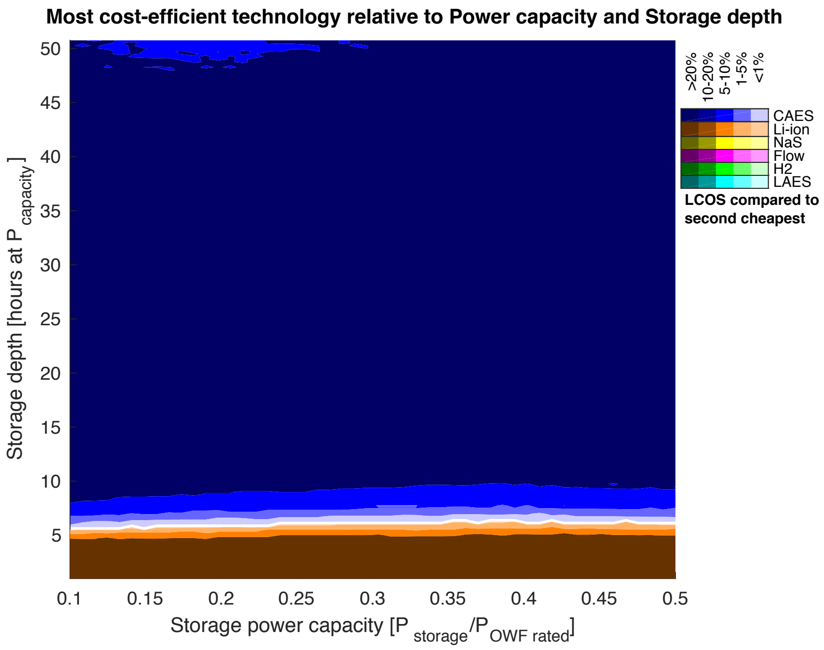

Figure 4.12: The most cost efficient technique with respect to the second cheapest as a function of the power capacity and the storage depth. In this figure the techniques corresponding to the LCOS shown in figure 4.11 are shown. The intensity of the color represents how the technique shown is performing compared to the second cheapest technology. It is concluded: 1. For small storage depths Li-ion is significantly cheaper than the second best, and 2. for larger storage depths CAES is significantly cheaper than the other techniques.

Cost effectiveness for CO_2 abatement for wind + storage

Offshore wind + storage aims to transform the renewable and carbon free electricity from the wind power into dispatchable power generation [1]. In times of low wind, the storage facility reduces the need for conventional, carbon emitting, dispatchable power plants into the electricity mix. The reduced need for coal and gas fired plants is expressed in the cost effectiveness per ton avoided CO_2. Using equation 4.1 the cost effectiveness (C_{eff}) of the different storage techniques are determined. The price for electricity and the emission factor (ef_{CO_2} $[\frac{ton\, CO_2}{MWh}]$) for carbon emissions originate from the National Energie Verkenning [98], according to the ”referentiepark-methode”. The cost effectiveness can determine how offshore wind + storage compares to other green dispatchable power technologies that qualify for the SDE++ subsidy scheme [2].

$$C_{eff} = \frac{LCOS - EPEX}{ef_{CO_2}} = [\frac{euro}{ton\, CO_2}] \tag{4.1}$$

The cost effectiveness is like the LCOS analyzed for the different configuration of the storage facility. In figure 4.13 the best cost effectiveness obtained is shown. This cost effectiveness is calculated and represented as a function of the power capacity and the storage depth of the system, derived from equation 4.1. In figure 4.14 the technology with the best cost effectiveness is shown as a function of the power capacity and the storage depth. In this figure the different techniques are represented by color and coincide with the values shown in figure 4.13. The intensity of the color represents how the best technique is performing compared to the second cheapest storage technique.

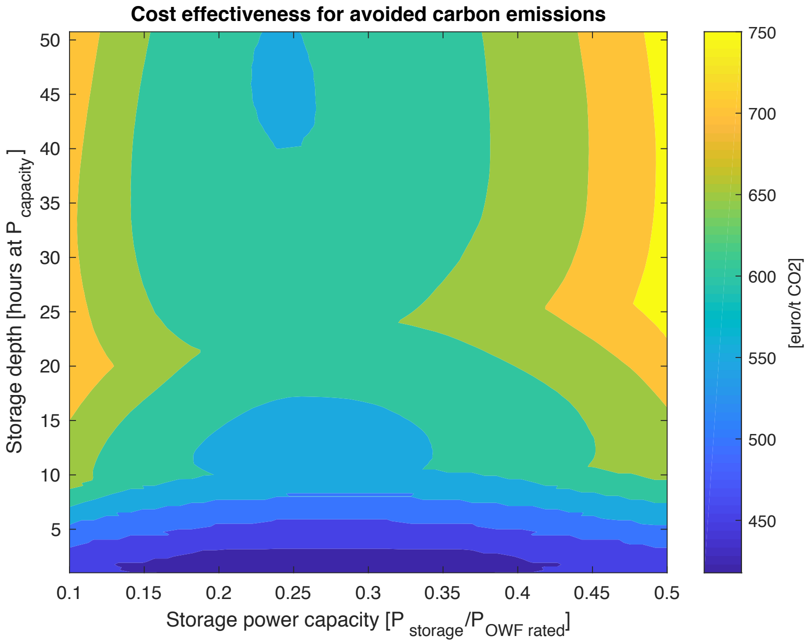

Figure 4.13: Cost effectiveness for avoiding carbon emissions for an offshore wind + storage system as a function of the power capacity and the storage depth. In this figure the combined lowest cost effectiveness of the different storage techniques analyzed is shown. Figure 4.14 shows which technologies make up the LCOS shown in this figure, and it is concluded: 1. The cheapest configurations for the power capacity lies within $0.23P_{OWF\ rated} < P_{capacity} < 0.27P_{OWF\ rated}$, depending on the storage depth and the technique that is most cost-efficient at that storage depth. 2. The cost effectiveness for avoiding carbon emissions for the storage facility is much higher compared to conventional methods.

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[1] Electricity that available on demand and on request of the grid operators be dispatched to the needs of the market

[2] The SDE++ subsidy plan is a follow up version of the SDE+ where the focus is on avoided CO_2 emissions instead of produced unit of power [99]

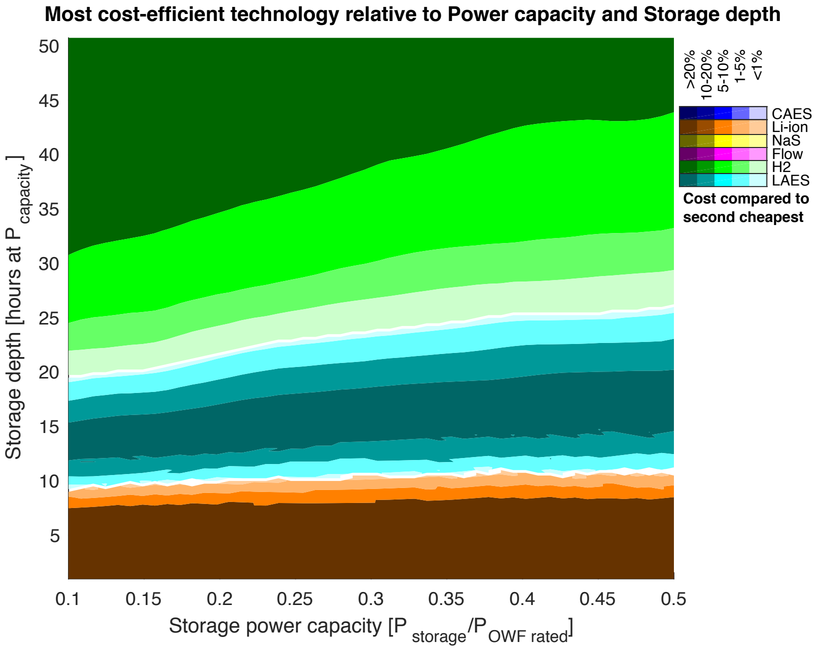

Figure 4.14: The most cost efficient technique with respect to the second cheapest as a function of the power capacity and the storage depth. In this figure the techniques corresponding to the cost effectiveness shown in figure 4.13 are shown. The intensity of the color represents how the technique shown is performing compared to the second cheapest technology. It is concluded: 1. For small storage depths Li-ion is significantly cheaper than the second best. 2. For the medium sized storage depth LAES is marginally cheaper than the second best. 3. For large storage depth hydrogen storage is the cheapest technology.

In figure 4.13 it is observed that the cheapest configuration for the power capacity lies within $0.23P_{OWF\ rated} < P_{capacity} < 0.27P_{OWF\ rated}$. Depending on the storage depth and the technique that is most cost efficient at that storage depth. This result is consistent with the results for the LCOS in figure 4.11. Instead of the sweet spot at 19 hours storage depth is the cost effectiveness gradually increasing for increasing storage depth, and no optimum is found.

The average cost effectiveness for avoided carbon emissions that is found for the optimal power capacity of the storage facility is high. Compared to conventional methods renewable dispatchable generation, such as biomass plants or synthetic natural gas, the offshore wind + storage system is more expensive. However, is this dependent on the context in which the systems are operating and can therefore not directly be compared with the system analyzed. As addition is it observed that at the extremes in power capacity analyzed the cost effectiveness experiences a steep rise with respect to the optimal power capacity.

Upon observing figure 4.14 it is clear why the sweet spot around 19 hours storage depth has disappeared. CAES, which has a sweet spot of 19 hours storage depth, is no longer present as most cost efficient technology. This is to blame to the carbon emissions of the natural gas combustion in the discharging phase of CAES. If these extra carbon emissions are added to the cost effectiveness it is not only the LCOS which determines the cheapest option in avoiding carbon emissions. CAES is for the lower storage depths replaced by Li-ion, the moderate storage depth region is filled by LAES and for the larger storage depths hydrogen storage is the cheaper choice.

4.2.3. Offshore infrastructure + storage

Offshore storage of energy is possible but more costly than onshore storage. In this section an analysis is performed to determine if offshore storage makes sense. To determine if the benefits of offshore storage are worth considering, firstly the possible benefits should be analyzed. The goal of offshore storage would be to achieve cost savings by decreasing the size of the electrical infrastructure to shore. If the rated power, and thus the size, of this infrastructure could be decreased, the total investment is be reduced. The electrical infrastructure, consisting of the components described in section 3.4, is decreased in size by peak shaving of the power output of the wind turbine. During the peaks in electricity production of the OWF the energy is stored in a storage facility, if this facility is saturated the peak shaving is performed by curtailing the power. The goal of this section is to contribute to the answer to the sub question: What is the techno-economic optimal configuration of an offshore wind + storage system in 2025?

In an OWF little suitable space is available for a storage facility. The only space, of significant size, available is in the monopile of the wind turbine. Therefore, in this analysis it is chosen to not construct new facility but use the space in the monopile, which results in decentralized storage. For this decentralized storage Li-ion battery storage was, in section 2.1.6, determined to be the best technique. For the peak shaving it is therefore assumed that every wind turbine has a Li-ion storage facility installed that has a storage depth of 4 hours and $P_{capacity} = P_{OWF\ rated} - P_{infra\ rated}$. A storage depth of 4 hours is chosen as this is an industry standard for larger storage depth Li-ion battery systems. In table 4.2 the results for a reduction in the rated power of the electrical infrastructure are shown.

No cost data on the infrastructure is available that matches the rated power Luchterduinen Wind Park. Therefore, the power production data is scaled to the power of the infrastructure, of which the cost data is known. To come to the results in table 4.2 the power production data was scaled to a rated power of $330MW$ for every analysis. Subsequently the rated power of the infrastructure is decreased, while keeping the $P_{\text{OWF rated}} = 330MW$. In this operation the storage facility tries to store the electricity when the rated power of infrastructure is exceeded. If the storage facility is saturated the excess power will be curtailed.

Table 4.2: Cost and performance of the different configurations for offshore storage [96] with an offshore 4-hour Li-ion storage facility installed at the wind turbines to perform peak shaving.

$P_{infra\ rated}$	MW	250	295	330			250	295	330
$Investment$	euro	68.7M	80.8M	93.4M	$LCOE_{infra}$	$\frac{euro}{MWh}$	2.45	2.69	3.05
$OPEX$	$\frac{-}{year}$	2%	2%	2%	Curtailment	%	8.84	1.9	0
Lifetime	year	25	25	25	AEP$_{reduction}$	$\frac{euro}{MWh}$	4.12	1.02	0
Discount rate	-	8%	8%	8%	COS [1]	$\frac{euro}{MWh}$	16.6	6.90	0

Table 4.2 shows the possible cost savings versus the performance and cost of the storage facility. It is observed that cost savings are achieved for the $LCOE_{infra}$, however these cost savings seem to be limited versus the extra investment necessary in equipment and the reduction in AEP. The reduction in AEP is caused by the significant curtailment necessary besides the storage of electricity to achieve the peak shaving required. This curtailment is to blame to the limited storage depth of the storage facility. The wind farm is often producing at rated power for longer periods of time due to the wind speed operation window for rated power. The first reduction in infrastructure size is suffering less from an AEP reduction due to curtailment as the peak power production of the wind farm is reduced. The reduction is caused by turbines having reduced power production result from; reduced wind power due to wakes from other turbines, failures or maintenance. Choosing a larger storage depth system would result in less curtailment in the system, this however is limited by the available space in the turbine and the limitations in the optimal operation of the Li-ion batteries.

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[1] In table 4.2 the COS is for an ideal situation usage of the storage facility resulting in an ideal LCOS. Potential revenue streams for the storage facility are not taken into account

Under the current regulations in the Netherlands are the location and grid related costs the responsibility of the TSO. The TSO is responsible for the connection from high voltage substation (HVSS) to shore and the distribution of the electricity inland. The costs for the offshore components are possible to define, but the connections inland are harder to define. Nevertheless, Jepma et al. [100] state that the cost for the offshore electrical infrastructure necessary can be considered equal to the extra investment needed in the electrical infrastructure onshore. Therefore, the cost savings made offshore are doubled if the inland connections are considered as well. However, in the Netherlands is there little incentive to focus on the infrastructure as a component to save cost. This is due to the arrangement between the government and the OWF developers. The TSO, which has a monopoly on the high voltage grid, builds and pays for the connection up to the substation of the wind farm. The result is that the costs for the connection offshore are not directly passed on to the offshore producer of electricity. The costs are included in the transport rates of electricity that apply to every electricity producer. For the offshore electricity producer to invest in its equipment to save cost on the infrastructure, that is not build by the producer but by the TSO, would not make sense under the current regulations.

The LCOE for the electrical infrastructure derived in table 4.2 is lower than the values known for the existing wind farms. However, if the results are extrapolated to the known costs the same conclusion holds. Offshore storage of electricity to reduce the size of the electrical infrastructure is possible but it is probably not worth the effort as the cost savings are small. Next to the fact that the cost savings are limited is the incentive to save cost in this regard not a number one priority. From this analysis the conclusion is to install a storage facility on land with the proper connection to make sure no curtailment is necessary.

4.3. Turbine rotor variation

The production profile of the wind turbine is determined by the design of the different components of the wind turbine and the winds it is subjected to. To apply system friendly wind turbine design, introduced in section 2.2.2, in this regard an important design parameter is the rotor diameter size. Using a larger rotor diameter will result in the ability to produce power at lower winds speed and in an increased AEP. To determine the influence of the rotor diameter on the performance, the rotor diameter is varied, and the production profile is analyzed. Using parameters from table 4.3 and power production profile, the impact of increasing the rotor diameter is determined. The cost of the turbine ($C_{turbine}$), the levelized cost of energy of the turbine ($LCOE_{turbine}$ and power density for the rotor swept surface ($P_{density}$) are shown in this table together with the AEP relative to the base case with the 112 m diameter rotor. In this analysis only the rotor diameter is varied, the design and the generator size will stay equal to the base case.

The goal of increasing the rotor diameter of the turbine is to reduce the profile effects in the power production profile of offshore wind energy. Additionally, it is analyzed if the offshore wind + storage system can benefit from an increased rotor size turbine with respect to the performance of short term profile effect reduction. With this analysis a contribution is made to the answer to the sub question: What is the techno-economic optimal configuration of an offshore wind + storage system in 2025?

In figure 4.15 the load curves of the base case, a $d_{rotor} = 95.2m$ and $d_{rotor} = 128.8m$ are shown to illustrate the impact of the rotor diameter on the power production profile. In the figure it is observed that the number of low power production hours is decreased. This is due to the increase in AEP and the fact that the load curve is shifted to the right. Therefore, does increasing the rotor diameter have a positive effect on profile effects, which is observed in figure 4.16. In this figure are the number of low power production periods shown for the wind turbine without storage.

The data for the turbine rotor variation is sourced from a Eneco inhouse model simulations [94]. As the simulation results are different than the measured data for Luchterduinen Wind

Park are the results in this section not be compared with the results in the previous sections. The data in this section is used to derive the relative impact of increasing the rotor diameter. In section 4.2.2 the Luchterduinen data was analyzed for turbines with $d_{rotor} = 112m$. As it is not the goal to increase the problem of low power production periods, the rotor variation analysis is only performed for an increasing rotor diameter.

Table 4.3: Characteristics for a 3.0MW offshore wind turbine with varying rotor diameter

Rotor diameter	m	112	117.6	123.2	128.8
$C_{turbine}$	$euro$	3.25M	3.42M	3.61M	3.80M
$LCOE_{turbine}$	$\frac{euro}{MWh}$	28.30	29.09	30.01	31.08
AEP	$\frac{-}{AEP_{112}}$	1	1.024	1.046	1.065
$P_{density}$	$\frac{W}{m^2}$	305	276	252	203.3

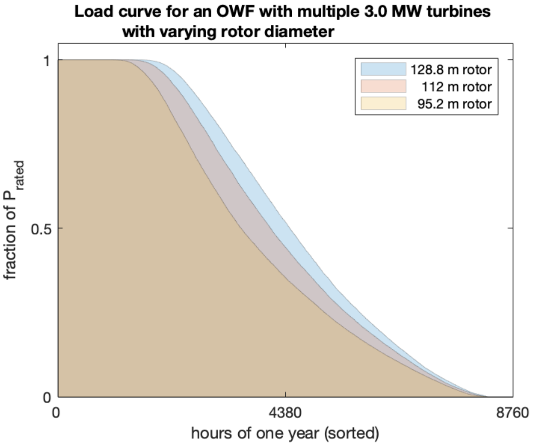


Figure 4.15: The load curve of Luchterduinen WP with varying rotor diameter. In a load curve the hourly power production of the system is sorted in descending order with respect to the power.

In figure 4.16 low power production periods, a measure for the short-term profile effects, are shown for the number of occurrences and the length of the period. For this figure $P_{reference} = 0.27P_{OWF\ rated}$ is chosen to execute the analysis. This is an arbitrary value that lies within the optimal range of power capacity of the storage facility determined in figure 4.13. In the short-term profile effects in figure 4.16 it is observed that increasing the rotor diameter of the turbine results in less long periods of low power production, but more total and short time periods. The impact of the longer periods is more significant, and therefore increasing the rotor diameter of the turbine is considered to have a positive effect on short-term profile effect reduction.

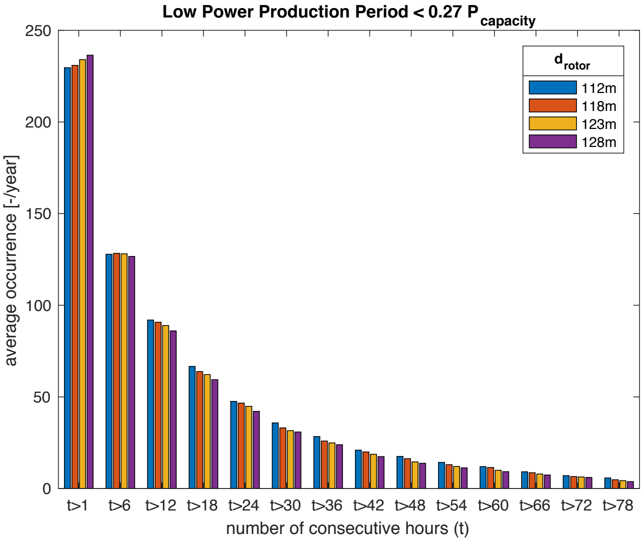


Figure 4.16: Number of low power production periods for an OWFs with varying rotor diameter wind turbines in the North Sea [94]. This figure represents the short-term profile effect of offshore wind energy. From this figure it is concluded that increasing the rotor diameter will result in less longer, and high impact, periods of low power production.

4.3.1. Base load profile with increased rotor diameter and storage

The turbines with a larger rotor diameter have an increased performance in profile effect reduction, as is observed in figure 4.16. To see if this can contribute to a reduction in the dimensions, and thus costs for the storage facility, the combination is analyzed in this section. The analysis for a year-round offshore wind + storage base load system, conducted in section 4.2.1, is repeated for the different rotor diameter configurations of the wind turbine. In table 4.4 the results are shown relative to the base case of the 112 m diameter rotor, as the results can only be qualitatively compared. In this table do $AEP_{red.\ 112m\ rot}$, $E_{cap.\ 112m\ rot}$ and $COS_{112m\ rot}$ represent the results for the 112 m rotor diameter base case.

Table 4.4: Reduction in cost to obtain a year-round base load profile by increasing the rotor diameter relative to the 112 m diameter rotor base case.

d_{rotor}	m	112	117.6	123.2	128.8
$AEP_{reduction}$	$\frac{-}{AEP_{red.\ 112m\ rot}}$	1	0.908	0.859	0.844
$E_{capacity}$	$\frac{-}{E_{cap.\ 112m\ rot}}$	1	0.91	0.84	0.77
COS	$\frac{-}{COS_{112m\ rot}}$	1	0.950	0.932	0.885

In table 4.4 it is observed that increasing the rotor diameter has a positive effect on the dimensions of the storage facility. With that the COS of the storage facility needed to obtain a year-round base load profile is reduced. The results, however, are hard to compare because the increased rotor size does not only have a different production profile, but also an increased AEP. This changes the whole dynamic of the offshore wind + storage system and its performance difficult to quantify for the different configurations. The results for the base load system in this section, however, are shown to illustrate how the storage facility is affected when the production profile is altered.

4.3.2. Rotor diameter impact on cost effectiveness for avoided CO_2 emissions

In the previous section it is shown that for base load storage increasing the rotor diameter could be advantageous in; the COS and the performance of the storage facility. In this section it is analyzed if the smaller storage depth systems designed for short-term profile effect reduction, can benefit from an alternative rotor design. This is done by determining the cost effectiveness for avoiding carbon emissions for the different rotor diameters and including the additional cost for increasing the rotor. If the results in the variation of the rotor diameter are compared it is determined which configuration has the best cost effectiveness.

In figure 4.17 the comparison is shown for four configurations of the rotor diameter. In this figure the $COC_{eff\ rotor\ var}$ is represented as a function of the hours below the reference power in a year. Like in figure 4.16, is an arbitrary value chosen at $P_{capacity} = 0.27 P_{OWF\ rated}$. The cost effectiveness for avoiding carbon emissions combined with the turbine cost ($COC_{eff\ rotor\ var}$), is defined in equation 4.2. In this variable the LCOE for the turbine with respect to the base case is added in the cost effectiveness for avoiding carbon emissions. This is done to assess the impact of the whole system as a function of the added cost with respect to the base case. In equation 4.2 the electricity discharged is represented by $E_{storage\ discharged}$ and the levelized cost of energy of the base case turbine by $LCOE_{d_{rotor}=112m}$.

$$COC_{eff\ rotor\ var} = C_{eff} * \frac{\sum_{n=1}^{N} E_{storage\ discharged}}{t_{lifetime} * AEP_{OWF+storage}} + (LCOE_{turbine} - LCOE_{d_{rotor}=112m}) = [\frac{euro}{MWh}] \quad (4.2)$$

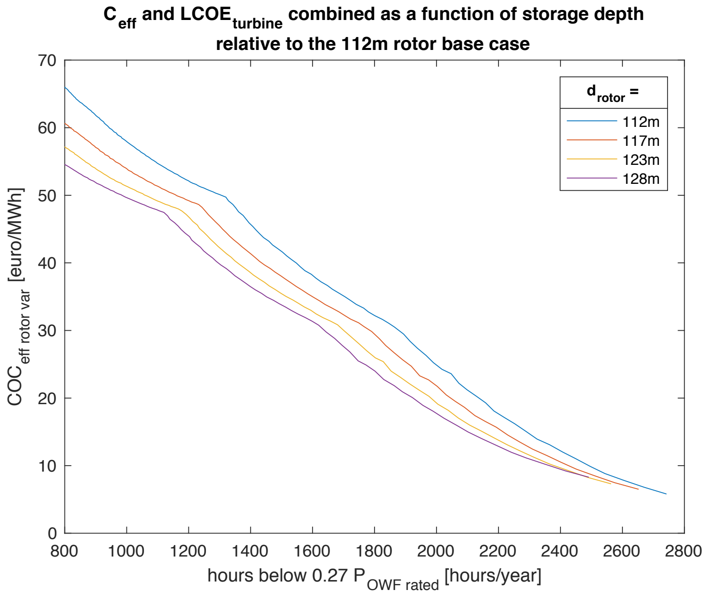


Figure 4.17: The cost effectiveness and LCOE for the turbine combined for varying rotor diameter as a function of low power production hours in a year, with $P_{capacity} = P_{reference} = 0.27P_{OWF\ rated}$. For an increasing impact on short-term profile effect reduction, represented by the decreased hours below the reference power, the cost savings with the larger rotor diameter turbines are present and become more significant.

In figure 4.17 it is observed that increasing the rotor diameter has a positive effect on the combined cost of short-term profile effect reduction, represented by the decreased hours below the reference power. The decrease in combined cost for the same result becomes more significant when a larger impact on the short-term profile effect is achieved. For a short-term profile effect reduction of 43%, from 2790 to 1600 hours below $0.27P_{OWF\ rated}$, a cost reduction of 26% is realized by increasing the rotor diameter with 15%.

The results presented in this section are not completely accurate with reality. In real operation the turbine hub should be increased in height if the rotor is increased. This is due to government regulations where the minimum height of the rotor is $25m$ above the waterline. In this section the height of the hub is not increased together with increasing the rotor diameter, as no simulation results were available for an increased hub height. If the nacelle of the turbine is heightened it will increase the need for steel in the monopile and the foundations of the turbine. Additionally, to maintain the fatigue life of the monopile structure a higher stiffness is required, this will too result in more steel in the whole structure. Together, this results in a higher CAPEX and an increase in the LCOE of the turbine. The fact that in reality the LCOE of the turbines will be higher, do the results have a slightly less positive outcome for the larger rotor diameter turbines analyzed in this section.

4.4. Impact of storage on Luchterduinen Wind Park in 2025

In this section the impact of the storage facility in an offshore wind + storage system is analyzed for the, in section 1.4 introduced, $129MW$ OWF Luchterduinen Wind Park. The analysis is made on an existing OWF to illustrate what would change for an offshore wind + storage system with respect to an OWF. The results from this section are generated in order to answer the sub question: Can an offshore wind + storage system cost effectively eliminate the risks of self-cannibalization for North Sea wind farms in 2025?

In the analysis in section 4.2.2 it is concluded that the optimal power capacity for the storage facility varies per storage technique. The most cost-efficient storage technique again varies per particular storage depth. The optimal power capacity varies within: $0.23P_{OWF\ rated} < P_{capacity} < 0.27P_{OWF\ rated}$. However, for the cost effectiveness in avoiding carbon emissions no optimal storage depth was found in the analyzed domain, as the cost effectiveness was gradually increasing with increasing storage depth. To determine the optimal storage depth of the system, the costs for avoiding carbon emissions are shown as a function of the impact in this regard in figure 4.18. To compare the results of the different storage depths configurations, the cost of cost effectiveness for avoiding carbon emissions is introduced (cost of C_{eff}) and defined in equation 4.3. Like the COS versus the LCOS is the cost of C_{eff} a scaled version of the C_{eff} that includes the context in which the system is operating. In figure 4.14 it was determined that, for the domain analyzed, Li-ion, Hydrogen and LAES are technologies that have the best cost effectiveness. Therefore, are the other techniques, analyzed in this chapter, left out in figure 4.18. In this figure an arbitrary power capacity is chosen, at $0.27P_{OWF\ rated}$. In the case of Luchterduinen Wind Park this results in a $P_{capacity} = 35MW$.

$$\text{cost of } C_{eff} = \frac{LCOS - EPEX}{ef_{CO_2}} * \frac{\sum_{n=1}^{N} E_{\text{storage discharged}}}{t_{lifetime} * AEP_{OWF+storage}} = [\frac{euro}{ton\ CO_2}] \tag{4.3}$$

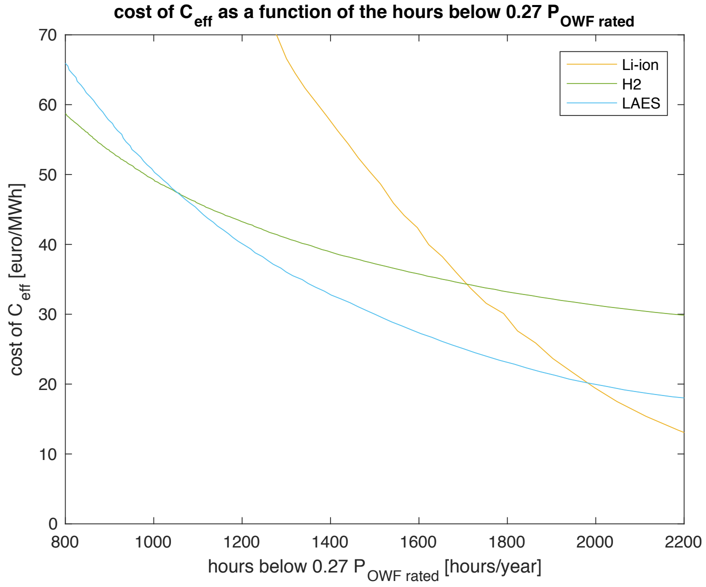


Figure 4.18: The cost of cost effectiveness as a function of low power production hours per year at $P_{capacity} = 0.27P_{OWF\ rated}$, shown for the most cost effective storage techniques determined from figure 4.14. No optimum is found in the system cost versus the impact on profile effect reduction, thus no optimal storage depth is found for this system.

In figure 4.18 it is observed that no optimum is found for the impact on short-term profile effect versus the costs for the most cost effective storage technique. This results in the fact that there is no optimal solution for an offshore wind + storage system, and the configuration should be determined for the case dependent and desired impact. Since it is desired to show the impact of the storage facility an arbitrary storage depth size is chosen that makes sense if the results from figure 4.2 are taken into account. This figure shows that for a system to make an impact a storage depth of at least 20 hours is required. Therefore, the storage depth is chosen arbitrary at 24 hours, for a LAES facility. The characteristics and the model results for such a system are shown in table 4.5. The performance on profile effect reduction of this system with the base load model simulation are shown in figure 4.19. In table 4.5 the AEP and market value of the offshore wind + storage system ($AEP_{OWF+storage}$ & $MV_{OWF+storage}$) are shown relative to the AEP and market value of the OWF (AEP_{OWF} & MV_{OWF}).

In table 4.5 the results for an offshore wind + storage system that is simulated with the base load model are shown. As the goal is to eliminate self-cannibalization of offshore wind, the most interesting property is the market value with respect to the OWF. This value is only marginally increased, and it is concluded that with the base load model the self-cannibalization is not eliminated. The cost of storage is relatively high, but since the system is operating below its theoretical and operational limit, in number of cycles, this could be improved.

Table 4.5: Characteristics and the results for an offshore wind + LAES with the storage facility at a $P_{capacity} = 0.27P_{\text{OWF rated}}$ and an arbitrary chosen storage depth of 24 hours. The charging and discharging strategy for the storage facility is determined by the base load model.

Property	**Characteristics**	**Dimensions**	
$P_{capacity}$	$0.27P_{\text{OWF rated}}$	35.2	MW
$E_{capacity}$	$24P_{\text{capacity}}$	845	MWh
$n_{\text{an cyc}}$		56.1	
COS		35.5	$\frac{euro}{MWh}$
C_{eff}		732	$\frac{euro}{MWh}$
$AEP_{OWF+storage}$	$0.961AEP_{OWF}$		
$MV_{OWF+storage}$	$1.004MV_{OWF}$		

To analyze the system to its operational limit and to maximize the market value the offshore wind + storage system is simulated with strategy model included. The strategy model is reactive on the expected EPEX price and its success is dependent on the spread in this price. Therefore, will the system be simulated in three scenarios of market expectations from 2025 to 2050. In these scenarios, described in appendix C, the amount of wind capacity installed is varied. The results of these simulations are shown in table 4.6. As the goal of the storage system was to reduce the short-term profile effects of wind energy, the performance in this regard is shown in figure 4.19. In this figure the operation of the three different scenarios with regard to profile effect reduction is quite similar, and therefore shown as one result.

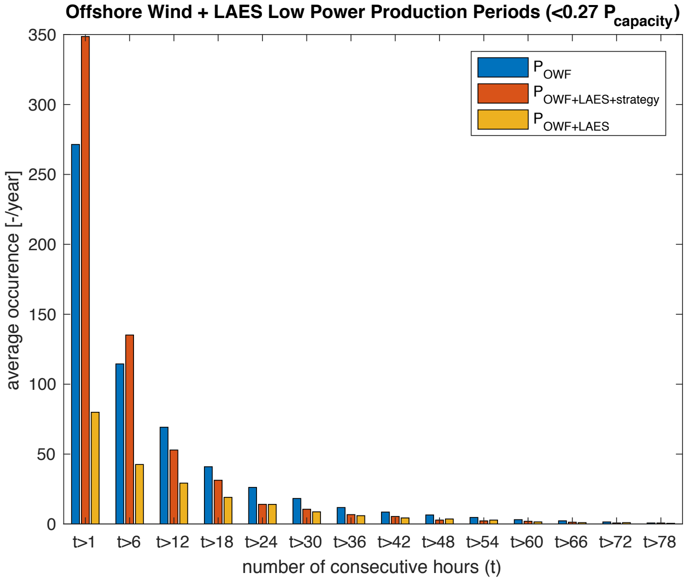


Figure 4.19: The impact of a 24 hours LAES facility on the profile effect reduction, where the performance of the static model and the strategy-based model is shown. A significant reduction in short term profile effect reduction is achieved with the storage facility included if the base load model is applied. For the strategy model applied only a reduction is achieved for the short-term profile effects that exceed 12-hour periods.

Table 4.6: Market value for an offshore wind + storage system with LAES and Li-ion battery storage, where both configurations have a $P_{capacity} = 0.27 P_{OWF\,rated}$. The results have been simulated using the strategy model for the operation of the storage facility. It is aimed at maximizing the revenue and the market value of the system.

		LAES 24-hour storage			Li-ion 4-hour storage		
		Low	**Medium**	**High**	**Low**	**Medium**	**High**
$MV_{OWF+storage}$	$\frac{-}{MV_{OWF}}$	1.03	1.05	1.09	1.017	1.023	1.034
$n_{an\ cyc}$		91.3	91.5	91.2	370	344	320
$LCOS$	$\frac{euro}{MWh}$	359	359	360	196	205	213

In table 4.6 it is observed that it is possible to improve the market value of an offshore wind farm by adding a storage facility and using the strategy model. However, the energy arbitrage operation that is induced by the strategy model affects the performance of the reduction in short-term profile effects. For the strategy model applied only a reduction is achieved for the short-term profile effects that exceed 12-hour periods. It is debatable if the increase in short low power production periods are a bad development. The model is responding to the EPEX price, which in its place is responsive to the residual demand. This residual demand represents the gap between the demand and the renewable supply of electricity. If for example, there is a large supply of wind and solar energy the strategy model could decide to charge the storage facility even though that would entail creating a low power period.

Interesting to see is that the market value is only slightly increased if only load shifting of energy is considered. This, while costly storage is necessary to perform this operation. The small impact is partly assigned to the limited power capacity of the storage facility, but also to the conversion losses in LAES that are basically lost energy. The underlying problem of the energy arbitrage operation is the fact that the electricity price is not fluctuating enough for load shifting and energy arbitrage to have a major impact. In some days in the future market expectations the daily spread is zero due to the fact that the electricity price is zero for a whole day.

4.4.1. Impact of rotor diameter increase

In section 2.2.2 system friendly wind turbine design is introduced. To see how the results of Luchterduinen would compare to the proposed methods in literature, for system friendly wind turbine design, the same analysis is performed on solely the increased rotor diameter wind turbines. In this section it is analyzed how the altered configuration of the wind turbine design affects the performance in the electricity market. In table 4.7 the results are shown for the configurations where the rotor diameter was increased in the design of the wind turbine.

Table 4.7: Influence of the rotor diameter of the turbine on the profitability of the OWF in three scenarios.

		117 m rotor			123 m rotor			128 m rotor		
$LCOE_{increase}$	$\frac{euro}{MWh}$	0.79			1.71			2.78		
Scenario		**Low**	**Med.**	**High**	**Low**	**Med.**	**High**	**Low**	**Med.**	**High**
MV_{OWF}	$\frac{-}{MV_{112}}$	1.002	1.007	1.013	1.004	1.013	1.024	1.007	1.019	1.035
$AEP_{increase}$	$\frac{euro}{MWh}$	0.10	0.29	0.65	0.20	0.55	1.19	0.35	0.80	1.74

In table 4.7 it is observed that the impact of solely increasing the rotor diameter is not a significant improvement for the low scenario. In the high scenario this impact is a bit more, but still not that significant with respect to the extra cost that is required for the installation of the larger rotors.

4.5. Additional utilization of storage

In the previous sections an analysis is made for the use of storage for load shifting to reduce short-term profile effects in the power production of wind energy. However, in this case the storage facility is solely used for this operation it is not utilized to its full potential. A possibility to improve the utilization of the storage facility is by extending the services it is providing to the electricity grid. These services can provide extra revenue streams or can reduce the power quality equipment necessary in wind turbines [101]. The potential of the storage which is not fully utilized is referred to as the unused space of the storage. This unused space can refer to the power capacity that is not fully utilized, or the energy capacity that is not fully utilized to its optimal amount of cycles. For an offshore wind + storage system four (potential) additional functions are identified and briefly explained. These are: Power Purchase Agreements (PPA), Energy arbitrage and intraday trading, Capacity market compensation and Power quality control.

The goal of this section is to identify additional advantages and utilization options of a storage facility in an offshore wind + storage system. Additional services provide supplementary revenue which could contribute to the economic feasibility of the system.

4.5.1. Power purchase agreements

By reducing the profile effects of wind power, it is possible for the power producer to create a more useful electricity production profile. A steadier production profile can make the renewable produced electricity more attractive to be sold in a Power Purchase Agreement. Having a secure consumer at a set price can be an advantage in an uncertain market as the energy market. Additionally, does this provide more security in the financing of a new project. Together this is an advantage in the bidding process for new OWFs. There is always a risk that the wind farm will not be built due to a changing market, and the government wants to prevent this.

The government is working on the energy transition, but according to many companies nowadays not fast enough. These companies stopped waiting for the government to act and started to take matters into their own hands by pledging to reach a 100% renewable electricity goal [102]. In the current system this is not possible on an hourly basis but only by buying generation of origin (GOO) certificates for the electricity that is consumed. Companies that are pledging for a 100% renewable electricity do want the hourly matching with green electricity and are willing to pay a premium price for it. Electricity suppliers have realized this and started developing products that could provide this service to companies. Offshore wind + storage could add to this hourly match on a large scale from a centralized point where electricity is generated and stored.

4.5.2. Intraday trading

Load shifting and energy arbitrage are the main activities for which the storage facility in section 4.2.2 is assessed. Both have shown to disappoint in creating additional market value. Intraday trading could contribute to this market value by trading in smaller time frames that experience larger price fluctuations. Energy arbitrage uses the fluctuations in the 1-hour slots of the day ahead market and Intraday trading makes use of the Intraday market of 5 to 15 min slots. Due to the limited daily spread in electricity price and fast reaction time necessary not all storage techniques are suited for this operation. From a data analysis it is concluded that the technique most suited for Intraday trading is Li-ion battery storage. Future data for Intraday trading is not available and is harder to predict and to model for future scenarios. If historic data is analyzed it is concluded that the average real time daily price spread is higher than the average day ahead daily price spread [102]. If it is assumed that this will be the case for the future price spread too, then will Intraday have a higher potential profit than energy arbitrage.

4.5.3. Capacity market compensation

The larger share of intermittent renewables is pushing the traditional dispatchable power plants out of the market due to the low marginal cost, as is described in appendix B. With the rising share of renewables in the market there is a chance that at some point in time the intermittent sources of electricity are not able to comply with the demand. In some countries around the Netherlands there is a mechanism in place to secure the electricity supply at such moments, preventing blackouts. In these cases, dispatchable power suppliers are, within a certain market mechanism, compensated for being able to supply power in times of a shortage. Power producers are compensated a set amount per power capacity unit to have this capacity available at all times. As it is not possible for a power producer to have 100% availability at all times there are de-rating factors applied to the different techniques available. Wind + storage can serve as such a dispatchable power produced. If the storage depth is chosen above 5 hours the de-rating factor becomes negligible [103]. As an advantage over thermal plants that make up for a large part of the capacity markets is an offshore wind + storage system free from carbon emissions.

4.5.4. Power quality

Like conventional power plants in the mix are wind turbines expected to deliver ancillary services to the grid that ensure the power quality. In this section the services where energy storage could aid in the power quality or contribute to the reduction equipment in the wind turbine are assessed.

Frequency Control Reserve

The frequency in the electricity grid is fluctuating around $50Hz$. If this frequency deviates too much it should be counterbalanced otherwise it will pose a problem for the consuming electrical devices connected to the grid. When the frequency falls below $49.8Hz$ or increases beyond $50.2Hz$ the frequency control reserve (FCR) should act by adding or absorbing power from the grid. The FCR facility should be able to react within 30 seconds and be able to do so for 15 min [104]. Up to date this FCR service is mainly provided by coal fired plants and gas turbines, but these kinds of facilities are undesired for the future and being phased out. Currently the compensation for a FCR facility is sufficient for commercial companies to build storage systems that can replace the conventional plants with this service without the need for fossil fuels [105]. These systems are assigned only for FCR operation because the space is traded on an international platform that sells the capacity in slots of a week [106]. In the near future this FCR market will shift to 4-hour slots where the capacity can be bid in a spot market. If this will be the case it will be possible for the storage facility in a wind + storage system to partake in this bid, as it is possible to predict and guarantee the availability of the storage facility versus the potential other revenue streams. With the new 4-hour slots it is expected that the compensation for FCR capacity will go down as much more facilities are able to enter this market.

Reactive Power Compensation

Reactive power compensation is required to maintain the stability in the electricity grid. To do so the TSO requires for electricity producers to be able to perform this reactive power compensation when this is required. Wind turbine manufacturers have adjusted the design such that these are able to provide such services. However, is this only possible when the turbine is producing power and not when the rotors have stopped due to little or too much wind. Next to the inability to compensate reactive power when the rotors have stopped. Do the turbines experience a decrease in reactive power capacity when the generators are increased in power without increasing the other components of the turbine, as described in section 2.2. Under current regulations is the reactive power compensation performance of the (upgraded) turbines sufficient to comply. However, in the new proposed European Netcode for electricity producers it is required for all producers to be able to compensate reactive power at all times [82], and in higher quantity. The regulations are not definitive, but if enforced, it will be necessary for the producers of offshore wind energy to install additional installations to comply with these regulations. In an offshore wind + storage system the storage facility could assist the wind farm in providing this reactive power compensation at all times. The fact that no additional installations are necessary could save several tens of millions of euros in case of a 700 MW wind farm [102, 107].

Active Power Control

Active power control, also referred to as ramp rate control or power gradient reduction, is in some markets regulated for wind power producers. Here the ramp rate is regulated within a range where the wind turbine is operated. If this range is exceeded a penalty is imposed. In normal operation the ramp rate can be controlled in the control of the blade pitching, but this requires sacrificing potential power generated [102]. Energy storage could contribute to limiting this ramp rate to the maximum range by charging or discharging electricity.

Voltage Ride Through

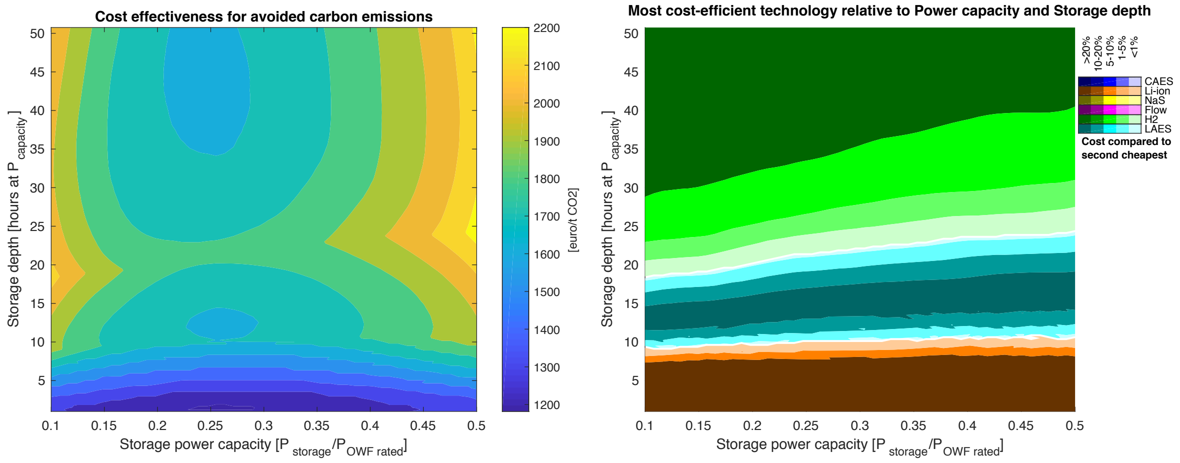
TSOs that operate in markets where the penetration of intermittent renewables is high are requiring for wind power producers to provide additional support to the grid. Voltage ride through requires the wind power producers to generate reactive power at times of a network fault, to more quickly restore and support the grid voltage. Restoring the grid voltage ensures the balance in the power system after disturbances in the grid, which could lead to blackouts [102]. A storage facility could prevent the need for reactive compensation devices or curtailments in the power output, which will lead to higher investment and a reduction in AEP. An additional advantage of the storage facility is that the DC link capacitor can be protected against overvoltage.

4.6. Sensitivity analysis

In this section the sensitivity of the model and the results derived from the model is analyzed. The model uses the performance of the storage facility together with price predictions for 2025 to come to the cost effectiveness in figure 4.13 and 4.14, in section 4.2.2. To check the robustness of these results several alternative scenarios are fed to the model. Of the scenarios analyzed are the most important results shown and discussed in this section. The other results are shown in appendix E and discussed in this section. The four scenarios that are discussed in this section are:

- In and decreased utilization of storage facility
- Alternative moment of investment, 2020 and 2030
- Raw lithium shortage
- LAES experiences no price reduction

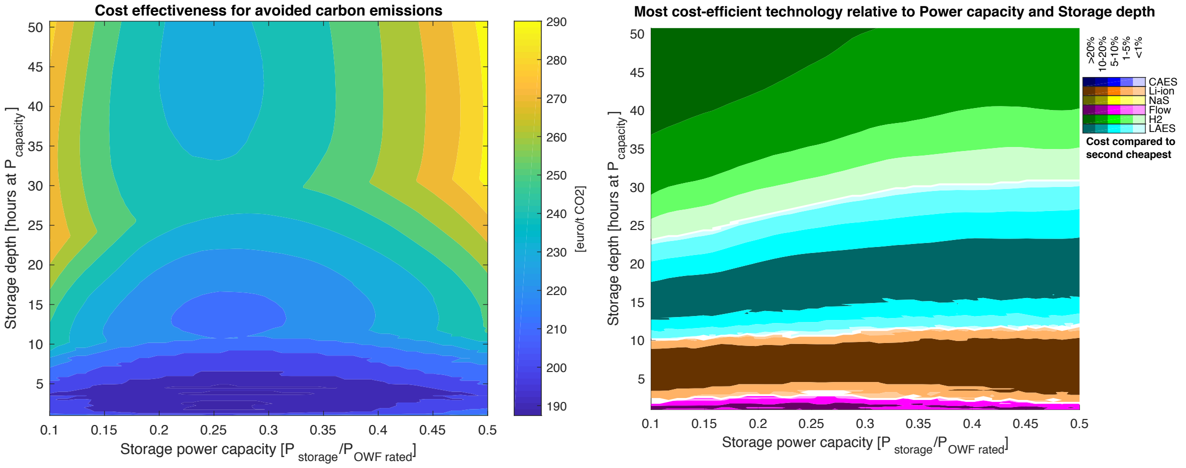
In and decreased utilization of storage facility results are shown in figure 4.20 and 4.21. In these figures it is observed that varying the number of cycles has a large impact on the cost effectiveness over the whole domain that is analyzed. The overall cost effectiveness is approximately linear dependent on the number of cycles of the system. The decrease in number of cycles does not influence the order of the cheapest storage techniques. The increase in number of cycles does alter the order of techniques. For low storage depth the flow battery becomes cheaper than the Li-ion battery. The appearance of the flow battery is due to the smaller cycle life of Li-ion batteries with respect to flow batteries. In the low power capacity medium to large storage depth, LAES has gained ground in the domain as most cost effective technique at the cost of hydrogen. This is caused by the increased operation of the facility. In this case the round trip efficiency becomes a more important parameter in the final cost determination, in which LAES is more advantageous over hydrogen.



(a) Cost effectiveness for the storage facility as a function of the power capacity and the storage depth

(b) The most cost efficient technique wrt the second best as a function of the power capacity and the storage depth

Figure 4.20: Model run for the case where the number of cycles in the system is decreased with a factor 3. Compared to the results in figure 4.13 and 4.14 little is changed in the shape of the figures and the distribution of the most cost-efficient storage techniques. The cost effectiveness for avoiding carbon emissions, however, is increased significantly.



(a) Cost effectiveness for the storage facility as a function of the power capacity and the storage depth

(b) The most cost-efficient technique wrt the second best as a function of the power capacity and the storage depth

Figure 4.21: Model run for the case where the number of cycles in the system is increased with a factor 3. Compared to the results in figure E.1 is the order of the most cost effective storage technique changed. For small storage depth flow battery storage becomes cheaper than Li-ion battery storage, and LAES is has gained ground in the domain as cheapest technology for large storage depth at the expense of hydrogen. As a result, is the cost effectiveness distribution changed and decreased significantly in cost.

2020 and 2030 investment results are shown in appendix figure E.2 and E.3. In these figures it is observed that if the moment of construction of the storage facility is varied that the overall cost effectiveness is experiencing a steep decrease from 2020 toward 2030. The improvement of the technology together with the reduction in construction price accelerates decrease. Interesting to see is the faster decrease in cost of Li-ion batteries with respect to other technologies. In 2030 it is expected Li-ion batteries are dominating the analyzed domain as most cost-efficient technology.

Raw lithium shortage results are shown in appendix figure E.4. Li-ion battery storage is a popular method all over the world. It is expected that the prices will drop significantly over the coming years, further increasing the popularity. Some studies, however, are stating that at some point the extraction of natural raw material, necessary for the production of the Li-ion batteries, cannot keep up with the demand [108]. This would result in a steep increase in the material cost for the Li-ion batteries. In appendix figure E.4 a scenario is shown where raw materials for Li-ion batteries are scarce and thus very expensive. In this figure the position of Li-ion batteries is almost completely filled by flow batteries, and a tiny bit with an increased area for LAES. The increase in cost effectiveness is moderate for the flow battery compared to the Li-ion battery.

LAES experiences no price reduction in the coming years results in figures shown in appendix figure E.5. If LAES experiences no price reduction towards 2025 it will no longer be the most cost-efficient technique in an offshore wind + storage system. The domain in which it was the cheapest technology is now largely replaced by Li-ion batteries and for a smaller part hydrogen storage.

Concluding, the sensitivity analysis in this section the model used in this report:

- Has a high dependency on the number of cycles for the cost effectiveness.
- Has an available back up technique for Li-ion batteries available against a moderate increase in price.
- Has high dependency on the expected cost reduction for Li-ion storage over time, which has a large impact on the overall costs and distribution of the most cost effective techniques.
- Has a constant optimal range for power capacity over all the scenarios analyzed. Therefore, the optimal power capacity for the storage facility determined is a robust conclusion.

4.7. Summary & Conclusion

In this chapter the results of a data analysis together with an impact and design analysis of an offshore wind + storage system are presented. The key findings are summarized in:

- Short-term profile effect is the major challenge for offshore wind energy to be solved with energy storage.
- Base load profile from an offshore wind + hydrogen storage system is the most cost-efficient for a $P_{baseload} = 0.325 P_{OWF\ rated}$ and a storage depth of 800 hours.
- Achieving a base load profile with an offshore wind + storage system is highly expensive and is suffering in high losses in the AEP.
- The optimal power capacity for a storage facility in an offshore wind + storage system is within the range of $0.23 P_{OWF\ rated} < P_{capacity} < 0.27 P_{OWF\ rated}$, depending on the storage depth and most cost-efficient storage technique.
- Li-ion is the most cost-efficient storage technique for an offshore wind + storage system with a storage depth up to 8 hours, with an optimal power capacity of $P_{capacity} = 0.23 P_{OWF\ rated}$.
- LAES is the most cost-efficient storage technique for an offshore wind + storage system with a storage depth 8 - 24 hours, with an optimal power capacity of $P_{capacity} = 0.27 P_{OWF\ rated}$.
- Hydrogen is the most cost-efficient storage technique for an offshore wind + storage system with a storage depth larger than 24 hours, with an optimal power capacity of $P_{capacity} = 0.25 P_{OWF\ rated}$.
- Offshore energy storage can save costs on the electrical infrastructure by peak shaving. However, the extra investment for storage is not cost-efficient against the losses in conversion and due to curtailment.
- Increasing the rotor diameter has a positive effect on profile effect reduction and the cost of storage. Increasing the rotor diameter with 15% results in a 26% cost reduction, if the system is designed for a 43% reduction in short-term profile effects. In the case when the cost effectiveness is combined with the increased cost of the wind turbine.
- Profile effect reduction with storage does not increase the market value significantly. Optimizing the revenue of the offshore wind + storage does increase the market value but does not eliminate self-cannibalization.
- The profitability of the storage facility can be increased by utilizing the storage facility to the optimal operation and assigning it for the power quality on the grid.
- A sensitivity analysis was performed, and the result were robust for the choice of technique and optimal configurations found. The system is most impacted by in or decreased utilization of the storage facility.

5

Discussion

This chapter contains the discussion of the results from chapter 4. Firstly, the consequences of the results are discussed, secondly the storage technique results and lastly the method and assumptions of this research. In chapter 4 a design and impact analysis is performed on an offshore wind + storage system. In chapter 2 such a system is defined as; an offshore wind farm in combination with a storage facility, located offshore or onshore, that together as one system feed electricity through the high voltage connection to the grid.

5.1. Consequences of the results

In chapter 4 it became clear that the additional cost for the storage facility to reduce profile effects are high. However, in this discussion it is concluded that storage to counter short-term profile effects is unavoidable in a future electricity system. The future energy system in this case is defined by the fact that it is dominated by Dutch wind and solar power. In this system the conventional fossil fueled electricity generation has reached its lifetime or is pushed out of the market by the dominating low marginal renewables.

To conclude this, it was first determined that storing electricity produced by OWFs for seasonal purposes is not the most economical option. In the future electricity system this seasonal storage is most likely avoidable for offshore wind energy due to two arguments. Firstly, the monthly averages of the OWF production profile and the demand profile are of similar shape and therefore, no seasonal storage is required. It could be that the fluctuation is not precisely the same or the demand profile changes in the future, but most likely this will not make seasonal storage a favourable option. Secondly, seasonal storage of offshore wind energy is, for the current outlooks, still subjected to high cost of storage and many losses in energy conversion. Seasonal storage to provide electricity in the off season will have to compete with system integration of power sources and the overplanting of wind energy. Other sources of renewable energy, like solar power, could be integrated in the wind energy system. Solar power has as advantage that the seasonal peak production is in summer and can thus supplement the seasonal low of wind energy. Overplanting of wind energy is a method to counter the seasonal profile effect because the electricity production in the low season is not zero but less than in winter. If more capacity is installed this low season capacity is increased too. An advantage of overplanting of wind energy is the contribution to the AEP of the system over the whole year, opposite to the seasonal storage facility which loses a lot of energy in the conversion. The overcapacity can, in times of overproduction, be curtailed or used in the non-electricity based energy industry.

Short-term profile effects are identified by randomly occurring low power production periods that are a result of the intermittency of energy. From the strong correlation between all the wind turbines connected to the (international) power grid, it is known that these low power production periods all occur at approximately the same time. In fact, from historical weather data it is known that the wind and solar energy production can even drop below 1% of the peak power installed. In case of such an occurrence the electricity system needs sufficient dispatchable generation. However, because the system is dominated by low marginal electricity generation, the conventional dispatchable generation plants have disappeared. Biomass plants and demand response are able to cover a part of this back up power, but the first is limited to the resources available and second limited by the response system [98]. New renewable dispatchable generation of significant size is necessary to cover the extremes in short-term profile effects of renewable electricity generation. The overplanting of wind turbines provides no solution to the lack of power due to the short-term profile effects. The correlated power production makes that the plentifully turbines together won't be producing any power either. Policy makers should realize the fact that intermittent sources of energy do have their disadvantages and cannot replace the conventional electricity production without taking any measures. For the case of offshore wind energy, the reduction of short-term profile effects is crucial. Offshore wind + storage systems offer a solution that is reducing this issue and tackling a range of other issues that arise with integrating large shares of wind energy in the electricity system. If offshore wind + storage systems will be gradually implemented over time it will make a proper replacement for the conventional thermal generation plants, that are disappearing from the market.

5.1.1. The real cost of electricity

The additional measures of storage necessary for wind energy, together with the direct cost of wind energy, count up to real cost of wind energy. To put this in perspective there are indirect costs in nearly all methods of electricity production. The indirect costs are, unlike the direct costs only consisting of OPEX and CAPEX, generally difficult to determine. This is because the result and disadvantages of the electricity production are not always directly measurable. However, the indirect costs, or internalized external costs, for thermal electricity generation have been determined in hindsight [109] for the period of 2008 to 2012 in the EU. The results of these internalized external costs are shown in in table 5.1.

Table 5.1: Internalized external costs of conventional dispatchable electricity production for a four-year period in the European Union [109].

Internalized external costs of electricity production	
Energy source	**Costs** $[\frac{euro}{MWh_e}]$
Hard coal	101
Natural gas	40
Biomass	19

The internalized external costs of electricity production are on top of the costs that the power producer is paid, and in retrospect to the direct cost paid for by the government and society. This is because the external costs are comprised of: climate change, particular matter formation, human toxicity, depletion of energy sources and a couple of minor cost drivers. If the external costs of these drivers are evaluated for offshore wind, they turn out close to zero. Now if the cost for storage are included in the real cost of wind energy and compared to the real cost of thermal power electricity generation the optimum is shifted in favor of the offshore wind energy.

Even though the comparison is different if the real costs are analyzed, it is not the core of the problem. The energy transition has started, and it is not a numbers game against carbon emitting power plants, but it is looking for a method of the most cost-efficient way to integrate the intermittent sources of electricity in to the grid. Taking this into account offshore wind + storage that counters short-term profile effects of wind energy is crucial in the energy transition.

5.2. Results for storage

The LCOS, and the other economical values derived from it, is highly dependable on the number of cycles the particular storage facility is making. The number of cycles is limited by the storage depth of the facility and what is required from the system. This entails that the strategy of the storage facility is important for the profitability the offshore wind + storage system, but also in how the costs for the storage are determined.

A second important parameter in the feasibility and the costs of the storage facility is the round trip efficiency of the used technique. The efficiency determines the impact that the system is able to make on profile effect reduction, but also on the profitability of the whole system. If the results for the year-round base load profile of a wind farm are analyzed, it can be concluded that seasonal P2P storage is technically and economically not a favourable option. This is caused by the high cost of storage, and the fact the economic gains, reduction in integration costs, are almost nullified due conversion losses thus a reduction in AEP. If hydrogen storage is applied for short-term profile effect reduction this is of lesser importance, however there is a decreased impact experienced when it is compared to the impact of LAES. LAES has a higher efficiency and is able to more effectively reduce short-term profile effects. In the analyzed domain this is eventually cancelled out by the fact that hydrogen storage becomes much cheaper when the storage depth in increased. It can, however, be concluded that applying a large storage depth P2P storage facility in combination with an OWF is not economical favourable.

The fact that hydrogen storage is not economical favourable in the system analyzed does not suggest that the synthesis of hydrogen with offshore wind electricity is a bad idea in general. Hydrogen is a key component in the energy transition for many appliances in the industry and mobility, but not for large P2P storage depth on the electricity grid. If offshore wind energy is used for hydrogen production, it is better to fully devote the system to hydrogen production. This way the utilization of the electrolysers and the other storage components is maximized, and no fuel cell is necessary in the system. Other means could be to integrate the storage facility with other systems to increase the utilization or performance. For example, LAES could be integrated in areas with much low temperature waste heat available, which could increase the round trip efficiency of the facility to 70%. The Port of Rotterdam area, where the export cables of several OWFs will be reaching shore and lots of waste heat is available, is such an area suited for this operation.

In this report CAES is not recommended as a technique to apply in an offshore wind + storage system. The fact that the system emits CO_2 in the discharging phase makes this technique not future proof. However, it can be seen that this storage technique is much more economically attractive than the other techniques at larger storage depth. This is especially the case in the Netherlands where many caverns are available for CAES. If there is a clean and cheap way to deliver heat to the turbine in the discharging phase, CAES would become an attractive technique to use in an offshore wind + storage system. Possibly CAES could be integrated with hydrogen production, where the hydrogen could be combusted in the turbine instead of natural gas.

The design of the OWF has a large influence on short term profile effect reduction in an offshore wind + storage system. This is due to the fact that the production profile is influenced by the design of the turbine. In this regard the design of such a system should always be assessed in a whole. Altering the design could result in a larger positive impact on (short-term) profile effect reduction with a smaller storage facility. If subsidy scheme for the integration of wind energy are introduced, the concessions made in the design towards short-term profile effect reduction should be included. Also, because a larger rotor diameter can contribute to a more effective use of the storage facility in an offshore wind + storage facility.

5.3. Methodology and assumptions

The methodology described in chapter 3 is discussed together with the underlying assumptions. The results for the power production of the wind turbines is based on hourly historical data. In no way can this be assumed to have guarantees that this data can be extrapolated towards the future. However, this same historical data teaches us that the data used is a good representation of winds over longer periods of time. Influences of for example climate change are not account for in such an analysis and could become of influence on the weather in the future. Contrary to the wind data, the historical data for the demand and price of electricity is not a good representation of the future. Therefore, are for these parameters price expectations for three scenarios used. The data is generated by models that account for future developments of the electricity markets, but again are expectations and do not represent the future perfectly. In this data it is not accounted for that adding a storage facility of significant size to a wind farm will influence the price of electricity. The results given for the market value will be slightly decreased due to the storage facility altering the position of the wind farm in the merit order. In the absence of the complete merit order data the available EPEX price data was used.

The system proposed is based on the production profile of an offshore wind farm with second-generation offshore wind turbines. The power can be scaled to today's third generation offshore wind farms, but this will not hold as the turbines have grown massively in size and characteristics. The production profile of the third-generation wind turbines is changed significantly with respect to the second-generation turbines. However, the choice to extrapolate the measured data is founded on the fact that it represents the real operation of a wind farm. Turbines break down, or have to be stopped due to maintenance, which impacts the power output of the wind farm.

The results in chapter 4 are largely obtained with simulations in the base load model. The base load model uses one reference value for the whole year, which does not account for the seasonal fluctuations of OWF power production. During the summer months the average energy production is less than in winter. What occurs in the summer period of the operation of storage facility is that two low power production periods are close to each other. Between these periods there is not enough power production above the reference value to fill the storage facility again. Changing the reference value in summer and winter could potentially balance this better and increase the performance of the storage facility. On the other hand, the research is based on one wind farm in the North Sea, and this is a good representation of the offshore wind energy production versus the electricity demand. If a system with all Dutch renewable generation would be considered it, is more accurate to identify where the generation units complement each other and where the critical moments in time are. The offshore wind + storage system and its controller can be designed to maximize the impact on the system and minimize the system wide costs.

If the system friendly wind turbine design results are analyzed a discrepancy arises between this report and literature. The market value increase that is derived for the variation in the rotor diameter without storage in the system is significantly lower than the values that are derived by Hirth et al. [77]. The benefit of the system friendly wind turbine design in the offshore wind + storage system is less than beforehand assumed. The causes for this deviation cannot be precisely determined but are assumed to originate from the following causes:

- The hub height was not increased with the increase of the rotor diameter, where it could be possible that the winds at higher altitude result in a more system friendly production profile.
- The paper assesses land-based turbines instead of offshore turbines in this report. The offshore turbines generally have larger rotor diameter relative to the hub height than the land-based ones. It might be that the offshore wind turbines are already more system friendly than the land-based turbine that was improved by Hirth et al.. Improving the turbines to be even more system friendly might be more difficult than the first improvement.
- The paper assesses several markets in Europe but not the Dutch electricity market. It might be that the fluctuation and spread in electricity price is less influenced by a large penetration of wind energy and or is less sensitive to system friendly wind power.
- The spacing of the offshore turbines is not altered with the increasing of the rotor diameter. Turbines that are downwind from other turbines suffer in power production from the wakes that are created. The effects of the wakes are the greatest for the wind regimes in which the market value is increased the most.

6

Conclusion & Recommendations

6.1. Conclusion

The objective of this thesis was to identify the challenges of offshore wind farms in the Dutch electricity system in 2025, and to research how energy storage can aid in these challenges. For this research a literature review was conducted, after which measured and simulated data of offshore wind electricity production was analyzed. Subsequently the data is used in a Matlab model, constructed to simulate a storage facility, to assess the role of energy storage in the future electricity system. This has led to the conclusions:

The challenges for offshore wind energy in the future Dutch electricity system have been identified in multiple elements. Of these elements profile effects, and in particular short-term profile effects, of wind energy have been determined to have the most negative impact. The short-term profile effects negatively affect: 1. the security of supply in the electricity system, 2. the stability of the load on the high voltage grid and 3. the market value of the produced electricity. The high correlation in power production between the connected (future) onshore and offshore wind farms are intensifying the short-term profile effects and its impact. The long-term profile effects and imbalance, experienced with offshore wind energy, are of lesser importance for the large scale implementation of offshore wind energy.

The characteristics of a storage facility to completely eliminate profile effects have been determined by designing a base load offshore wind + hydrogen storage system. Hydrogen power to power storage was determined as the most cost-efficient technique. In the system the base load is designed at 0.325 times the rated power of the wind farm. The most cost-efficient design for the hydrogen storage system is determined for 800-hour storage depth at a power capacity of 0.68 times the rated power of the offshore wind farm. For Luchterduinen Wind Park this system resulted in the desired base load, but at the cost of a large share of the annual energy production (41% reduction), and a high cost of storage (603 $[\frac{euro}{MWh}]$).

The seasonal fluctuation of wind power and the seasonal fluctuation in electricity demand experience the same profile. This, together with the high cost for seasonal storage make a base load production profile in an offshore wind + storage system not a preferred method to counter profile effects. Other measures that prevent the need for seasonal storage, such as overplanting of wind energy and better system integration with solar power, are more likely to be competitive.

The techno economic optimal configuration of an offshore wind + storage system is designed to counter short-term profile effects. In this design the storage facility has a power capacity between 0.23 and 0.27 times the rated power of the wind farm, depending on the storage depth. The optimum for the storage depth of this system is not determined, because there is no optimum in the cost effectiveness of the storage versus the impact. It should be case specific assessed what the optimal dimensions are to the desired impact. It is however determined that the most cost-efficient storage technique is; Li-ion for small storage depth, LAES for 8-24 hours storage depth and hydrogen for 24+ hours storage depth.

Offshore storage to decrease the costs for electrical infrastructure is determined to be non-feasible. Decentralized Li-ion battery storage systems positioned in the monopile was identified as the most cost beneficial configuration. Using 4 hours Li-ion batteries it was concluded that the cost savings in infrastructure are less than the actual losses in energy production. Due to peak shaving and curtailment, to not exceed the rated power of the infrastructure, the overall losses for offshore storage are higher than the benefits.

Increasing the rotor diameter, while keeping the generator the same size, has a positive result on the cost effectiveness of an offshore wind + storage system. Applying this system friendly wind turbine design becomes more cost-efficient in an offshore wind + system when a high impact on short-term profile effect is desired. Increasing the rotor diameter with 15% results in a 26% cost reduction, if the system is designed for a 43% reduction in short-term profile effects. This is the case when the cost effectiveness is combined with the increased cost of the wind turbine. The cost savings are achieved due to the altered production profile of the turbine with increased rotor size.

Cost effective elimination of self-cannibalization for North Sea wind power in 2025 is not possible in an offshore wind + storage system. This conclusion is based on the result of an offshore wind + 24-hour depth LAES system and a 4 hour depth Li-ion battery system at the optimal power capacity. For solely profile effect reduction there is no significant increase in market value of the offshore wind + storage system with respect to the offshore wind system. If the operation of the storage system is designed to optimize the revenue of the system, it is able to increase the market value in all price scenarios. This increase however is limited and not sufficient to eliminate the self-cannibalization of the offshore wind.

Summarily, the addition of a storage facility in an offshore wind + storage system is not economical feasible. However, energy storage is essential in a future Dutch renewable energy system that is dominated by wind and solar power. The short-term profile effects of wind energy are correlated too much and have a too high of an impact on the system if no storage is applied. The additional cost for a storage facility necessary to integrate offshore wind energy into the electricity system comprises the real cost of wind energy. These real costs of wind energy are higher than the previously assumed direct costs, which are only correct for small wind market penetration. The result is that the actual large scale deployment of wind energy in the electricity system will cost more effort and money than is assumed beforehand. However, if the real cost of conventional fossil fuel generation (including cost for environmental and societal impact) are compared to the offshore wind + storage cost, the real costs of conventional electricity generation are higher.

6.2. Recommendations

Based on the results and the conclusions of this report several recommendations will be given. These recommendations are given in a twofold: First the policy recommendations and secondly the recommendations for further research.

Policy recommendations:

- Realize the strengths and weaknesses of intermittent renewables in the energy transition. The energy transition is taking off and now it is important to make sure this is properly implemented. By stimulating the development and testing of renewable energy systems, combined with storage facilities, it is possible to make sure the energy system is ready by the time it is dominated by wind and solar power.
- Assign a part the SDE+(+) to the development and installation of renewable, dispatchable generation to stimulate storage facilities as renewable dispatchable generation, alongside the installation of intermittent renewables.
- Include design concessions of the wind turbine design into the subsidy scheme. Altering the design of the wind turbines can result in a more cost-efficient configuration for the dispatchable generation.
- Create better ground rules for (future) markets and returns for all the markets and applications the storage facility can be useful for. The storage facility will soon become economical feasible and contribute to the critical flaws in a wind and solar dominated electricity market.

Focus further research on:

- Including storage for renewables, besides offshore wind energy, that have a large expected penetration in the electricity grid, such as solar PV.
- A full system analysis where all the (future) renewable capacity is modelled against the electricity demand to identify the synergy solutions of techniques and critique points or locations. In this analysis the challenges faced on the electricity grid could be identified as well.
- Further research the potential (new power quality) markets and revenue streams for an offshore wind + storage system. These (new) markets can be included in the controller of the storage facility. To further improve the controller, it is possible by applying a more dynamic and seasonal dependent controller, the impact and cost efficiency of the storage facility can be improved.
- Centralized storage where the utility of the facility is combined with other functions in society, like the Delta 21 project [89]. In this project coastal protection is combined with an artificial lake which can be used for PHS.
- The renewable application of CAES. CAES is a cost-efficient storage technique with a huge potential in the Netherlands. Replacing natural gas combustion with a renewable heat source would make it an attractive option for offshore wind + storage.
- Determining the market value of offshore wind + storage with a merit order approach instead of a static EPEX price. The operation of a storage facility has an influence on the EPEX price and in this research, it is assumed not to influence the price. If the power output of the offshore wind + storage is included in the modelled merit order data, the market value of the system can be determined more precisely.
- The third-generation offshore wind turbines. The analysis in this report was performed with the second-generation offshore wind turbines. If new data is available such an analysis should be performed with the latest power production profiles. Including the system friendly offshore wind turbine design for the new generation turbines could serve as an extension on the land-based system friendly wind turbines of Hirth [77].

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A

Fluctuating wind power

Wind energy is an intermittent source of energy, resulting in an intermittent supply of electricity from wind turbines. In this section the profile effects of wind energy together with the imbalance are evaluated in model data for an existing offshore wind farm on a reference location in the Dutch North Sea. The wind data used in the model originates from the publicly available MERRA2 hind cast study data from NASA.

A.1. Long term profile effects in seasonal and annual fluctuations

The velocity and the direction of the wind is constantly changing in time and per location. However, if the wind is analyzed in a more generalized and averaged way trends and patterns start occurring. When the direction of the wind is analyzed over a whole year a trend pops up which is called the dominant wind direction. If the wind speed is averaged and analyzed it can be observed that fluctuations over year start occurring, as shown in figure A.1. If the wind data is analyzed more closely using monthly averages new reoccurring patterns fluctuations start showing, seasonal fluctuations. Generally, the offshore locations in the Netherlands experience stronger winds in winter than in summer, which is shown in figure A.2.

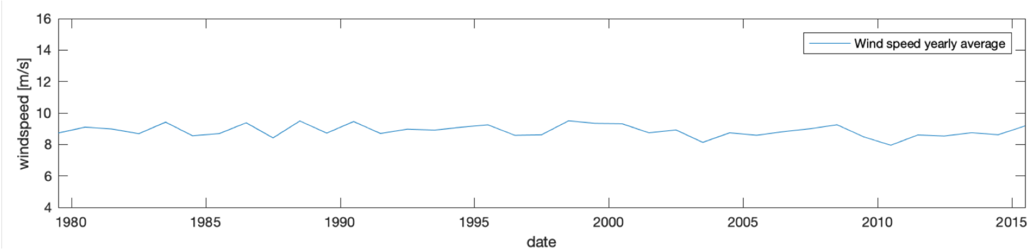

Figure A.1: Annual fluctuations of wind velocity on the North Sea. The average wind speed over a whole year is fluctuating per year.

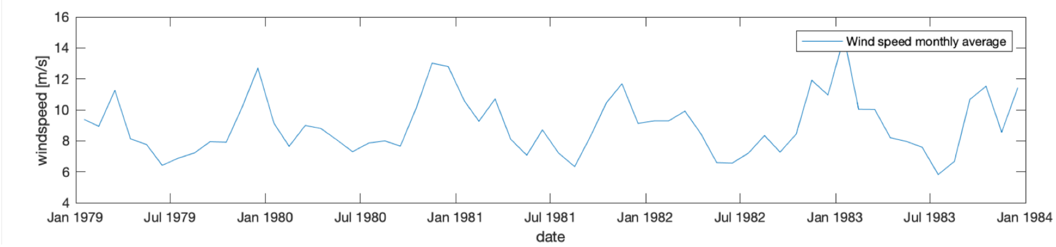

Figure A.2: Seasonal fluctuations of wind velocity on the North Sea. The average velocity is significantly higher in winter and lower in summer.

A.2. Short-term profile effects

If the data shown in section A.1 is analyzed in more detail to daily and hourly basis, more variability in the wind speed is observed. However, in this case the fluctuations are more random and less re-occurring than the seasonal fluctuations. These fluctuations on daily and hourly basis are specified as short term profile effects of the wind. These effects are not subjected to precise periods during the week or season. Onshore wind is somewhat subjected to the daily cycles of the sun heating up the ground, and this ground cooling at night, creating a flow of air. Offshore wind however is influenced less by this effect because of the water being a larger and better mixed buffer. As a result, no daily reoccurring fluctuations in offshore wind energy are observed.

A.3. Imbalance

In the Dutch electricity system, the TSO requires to submit the day ahead program, which is stating how much power is going to be produced in the next 24 hours. The operator of the offshore wind farm has to make a projection of the produced power based on the weather predictions. As it is hard to predict the weather precisely the power predictions will be subjected to errors. The deviation in the predicted and realized power is specified as imbalance. An example of the deviation between the day ahead forecast and the realized power production of an OWF is shown in figure A.3. If imbalance occurs the operator of the wind farm has to buy or sell electricity on the imbalance market. The revenue on this imbalance market is on average less profitable than the day ahead market, therefore is trading on the imbalance market not desired [110].

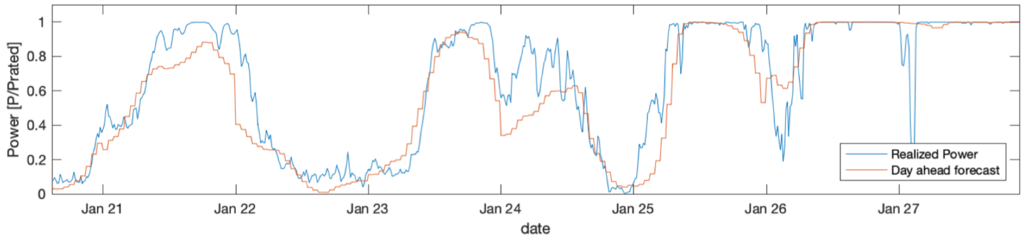

Figure A.3: Example of imbalance between the day ahead forecast and the realized power of an OWF. The realized power is deviating from the day ahead forecast the most for non-constant wind speeds. The least deviation occurs when the wind velocity exceeds the rated wind speed.

B

Electricity day ahead market

To understand the issues that arises with the integration of offshore wind energy into the electricity market some basic understanding of the Dutch electricity market is needed. In the Netherlands the high voltage grid is controlled and balanced by a TSO. This is a state-owned company and is in charge of distributing the electricity from where it is produced to where the power is demanded. This supply of electricity has to be, at all times, balanced with the demand since this is required for electrical systems. Knowing that not all producers have a direct consumer of the electricity, some of the electricity is traded on the spot market; the European Power Exchange (EPEX) market in the Netherlands. This market is formerly known as the Amsterdam Power Exchange (APX) market. To balance the demand and supply every day at 12 o'clock the daily programs/bids per hour for the high voltage grid are submitted. These bids are ordered in ascending order with respect to the price per capacity, constructing the merit order [1] for every hour. A simplified version of such a merit order is shown in figure B.1. The TSO will add the power production capacity until it meets the demand in electricity for the particular hour. The highest offer needed to meet the demand determines the price for this hour, for every producer of electricity. The price is represented by the horizontal red line in figure B.1.

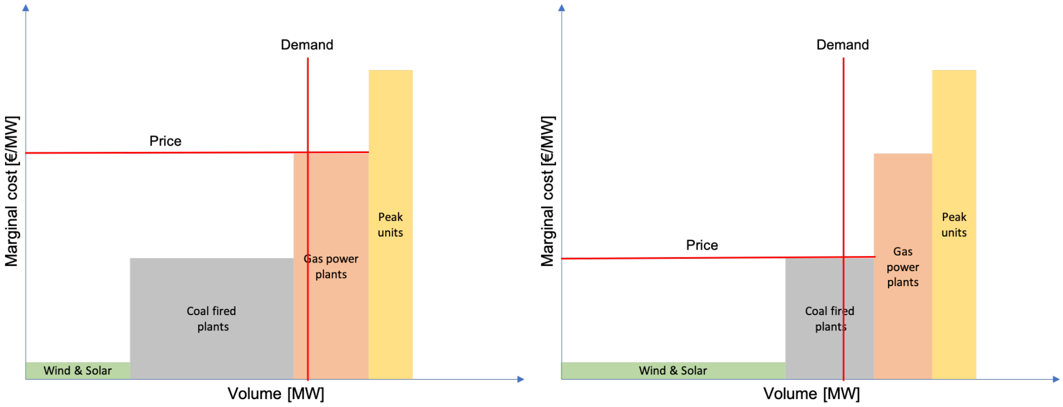

Figure B.1: Simplified representation of the merit order on a certain hour in two situations

Electricity producers that make use of wind and solar power have low marginal costs with respect to fuel-based power producers, which is also visible in the left side of figure B.1 as it is positioned closest to the y axis of the diagram. When the capacity of wind and solar increases, the volume of low marginal cost electricity will increase and eventually push the fossil fuel-based facilities further towards the right in the merit order. As a result, the price is steered down, as visualized on the right side of figure B.1. This will eventually result in the

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[1] The Merit Order of a process indicates the order in which it will be dispatched [111]

fact that the fossil fuel-based plants are pushed out of the market, due to too little running hours per year to break even. Now as wind and solar are intermittent there will be times where there is no full capacity available from these sources. By this time the cheaper must run plants have been pushed out of the market and only the high marginal cost plants are left, steering the price up. This is referred to in literature as the self-cannibalization effect of intermittent renewable energy sources [77]. As these fluctuations in power production from intermittent sources go fast and are not always predictable does the addition of a large share of these sources result in an unpredictable and volatile pricing of the day ahead market.

C

Wind power in europe

In this section the three scenarios that are sketched by Wind Europe, the representative of the wind industry in Brussels, will be evaluated. The scenarios are the: Low, Medium and High scenario, that refer to the amount of capacity that is expected to be realized until 2030 [5]. The figures of the three scenarios are shown in table C.1. Together with the offshore wind energy roadmap 2030 [6], that is published by the Dutch Minister of Economic Affairs and Climate Policy Eric Wiebes, it is the guideline for this report in term of future outlook.

Table C.1: Growth outlook for installed wind capacity in the EU in 2030 [5]

	Installations [GW]			**Generation [TWh]**			**EU wind grid penetration**		
	onshore	offshore	total	onshore	offshore	total	onshore	offshore	total
High scenario	299	99	397	706	422	1129	23.5%	13.9%	37.6%
Medium scenario	253	70	323	599	290	888	19.9%	9.9%	29.9%
Low scenario	207	49	256	453	195	648	15.1%	6.5%	21.6%

C.1. North Sea offshore wind

The large expected growth of installed wind capacity is not evenly distributed throughout the EU since not all countries have attractive locations or do not have the focus to install more wind capacity. A location that is attractive due to the shallow waters and high winds is the North Sea basin. The neighbouring countries of this sea are all planning to install large amounts of offshore wind capacity in this area to in the future provide clean energy for their citizens. This results in a relative growth of offshore wind in the North Sea that is much larger than the EU average (shown in table C.1). The steeper growth in wind power capacity, with respect to the EU average, entails that the expected penetration of wind energy in the grid for the North Sea adjacent countries is much higher than that of the EU average. The expected grid penetration for these countries is shown in table C.2.

Table C.2: Expected grid penetration for North Sea adjacent countries in the central scenario for 2030 [5]

Country	Grid penetration
Denmark	61-80 %
Netherlands	41-50 %
United Kingdom	41-50 %
Germany	31-40 %
Belgium	31-40 %
Norway	-

C.2. Dutch North Sea wind power

The ambition of the government to keep using the North Sea as a source of energy, but now in the form of renewable wind power, is being realized by setting clear ground rules for the industry in a three-stage project. The first two stages of this project are nearing completion. The first stage to build OWFs as knowledge gathering, and the second stage to use the learning curve to achieve a major cost reduction to realize multiple large scale OWFs as planned in the wind power roadmap 2023 [6]. The cost reduction in the second phase was so successful that the latest OWF tender bid has been submitted without the need of subsidy from the SDE+ fund [112]. The third stage, wind power roadmap 2030, is just about started with an additional 9 GW capacity that is to be tendered and built from 2018 to 2030. The tender bids will be expected to not have the need for subsidies from the government. In figure C.1 the different (to be) realized OWFs are shown on the map of the Dutch North Sea.

C.2.1. Correlation between wind farms

In figure C.1 the Dutch North Sea is shown with: the existing OWFs, the planned OWFs up to 2030, the neighbouring countries OWFs and the interconnecting cables. The expected power output of these OWFs is modelled together with twelve onshore locations to analyze the relation between the different locations in the Netherlands. The results are shown in the correlation matrix in figure C.2. From these results the following is concluded:

- Offshore wind in the Dutch North Sea is strongly correlated
- Onshore wind in the Netherlands is strongly correlated
- Onshore and offshore wind in the Netherlands are strongly correlated
- The majority of the Dutch offshore wind capacity in 2030, $9.2/11GW$, will be 92% correlated in power production.
- It is likely that the power production of the OWFs in the surrounding North Sea countries will be strongly correlated as well.

The data originates on models that use the following assumptions:

- Correlation based on hourly basis yield of the different wind farms according to Pearson method.
- Offshore yield based on wake model of true (for existing wind farms) or expected (for future wind farms) layout of the wind farms.
- Onshore yield based on representative land-based wind farm on the reference locations.
- Wind climate data from the: Dutch North Sea Wind Atlas for a period from 1979 - 2017

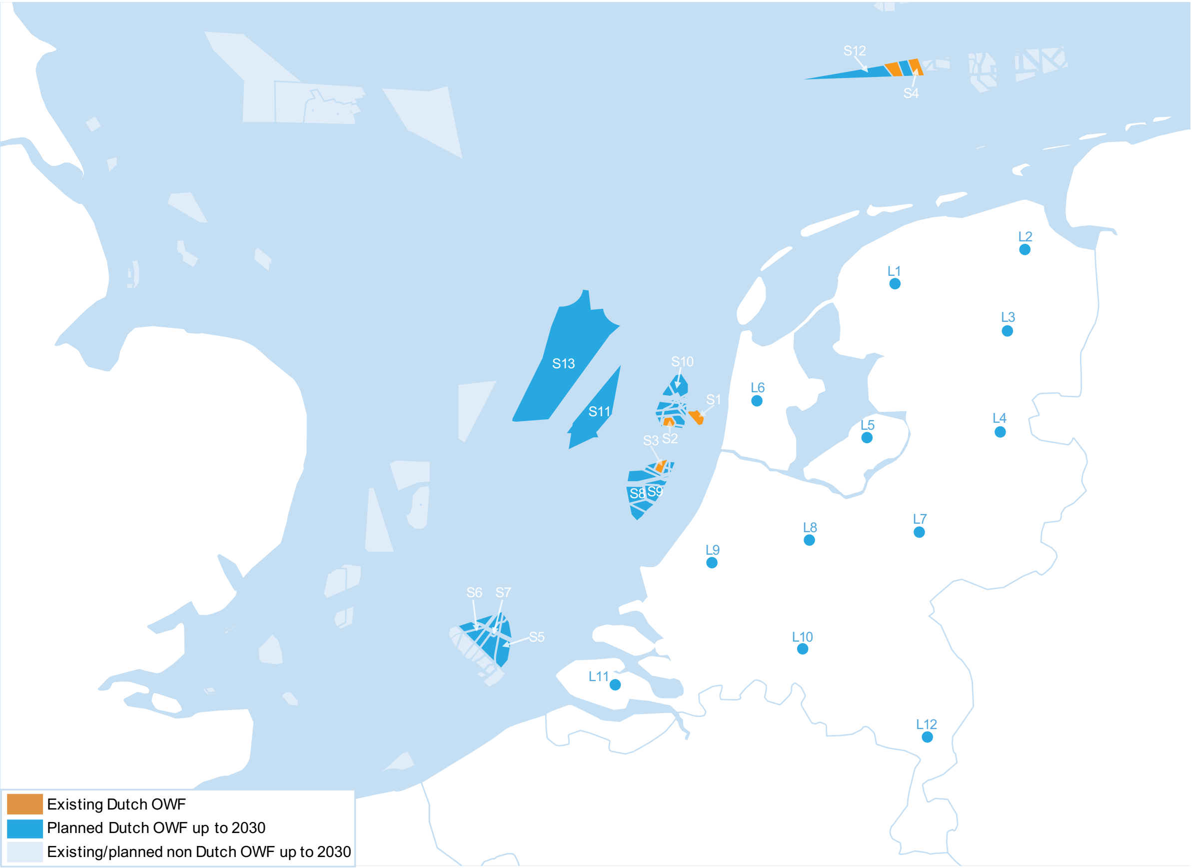
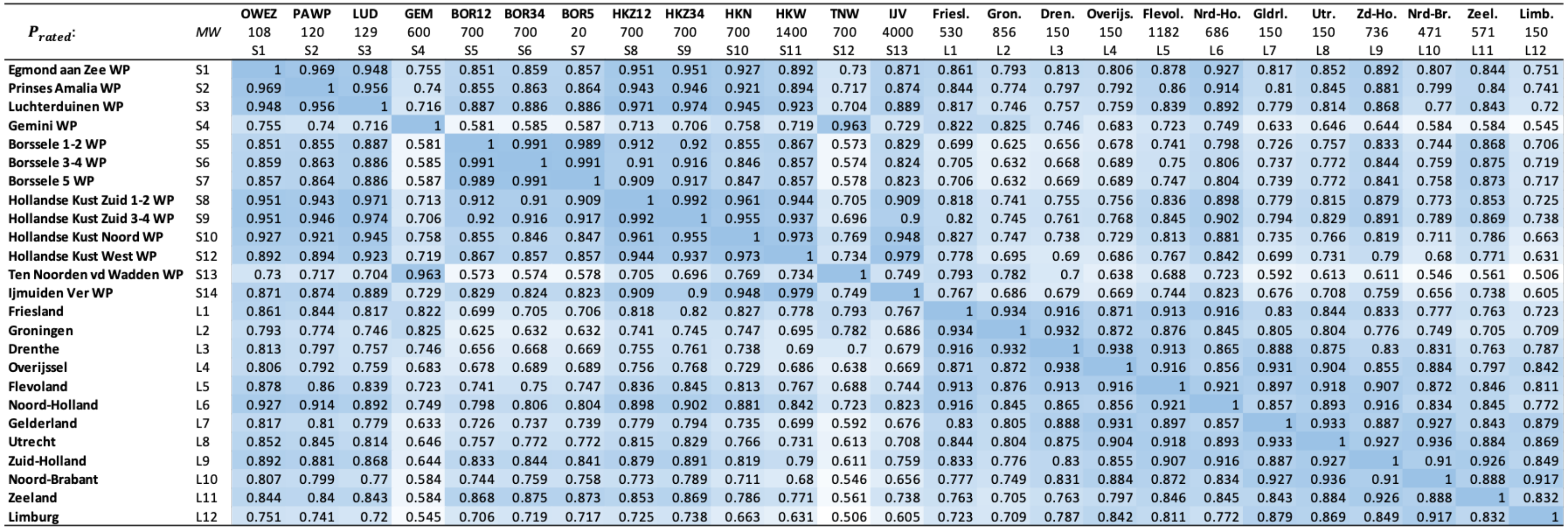


Figure C.1: Overview of the existing and planned offshore wind farms in the North Sea



		OWEZ	PAWP	LUD	GEM	BOR12	BOR34	BOR5	HKZ12	HKZ34	HKN	HKW	TNW	IJV	Friesl.	Gron.	Dren.	Overijs.	Flevol.	Nrd-Ho.	Gldrl.	Utr.	Zd-Ho.	Nrd-Br.	Zeel.	Limb.
P_{rated}:	*MW*	108	120	129	600	700	700	20	700	700	700	1400	700	4000	530	856	150	150	1182	686	150	150	736	471	571	150
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12
Egmond aan Zee WP	S1	1	0.969	0.948	0.755	0.851	0.859	0.857	0.951	0.951	0.927	0.892	0.73	0.871	0.861	0.793	0.813	0.806	0.878	0.927	0.817	0.852	0.892	0.807	0.844	0.751
Prinses Amalia WP	S2	0.969	1	0.956	0.74	0.855	0.863	0.864	0.943	0.946	0.921	0.894	0.717	0.874	0.844	0.774	0.797	0.792	0.86	0.914	0.81	0.845	0.881	0.799	0.84	0.741
Luchterduinen WP	S3	0.948	0.956	1	0.716	0.887	0.886	0.886	0.971	0.974	0.945	0.923	0.704	0.889	0.817	0.746	0.757	0.759	0.839	0.892	0.779	0.814	0.868	0.77	0.843	0.72
Gemini WP	S4	0.755	0.74	0.716	1	0.581	0.585	0.587	0.713	0.706	0.758	0.719	0.963	0.729	0.822	0.825	0.746	0.683	0.723	0.749	0.633	0.646	0.644	0.584	0.584	0.545
Borssele 1-2 WP	S5	0.851	0.855	0.887	0.581	1	0.991	0.989	0.912	0.92	0.855	0.867	0.573	0.829	0.699	0.625	0.656	0.678	0.741	0.798	0.726	0.757	0.833	0.744	0.868	0.706
Borssele 3-4 WP	S6	0.859	0.863	0.886	0.585	0.991	1	0.991	0.91	0.916	0.846	0.857	0.574	0.824	0.705	0.632	0.668	0.689	0.75	0.806	0.737	0.772	0.844	0.759	0.875	0.719
Borssele 5 WP	S7	0.857	0.864	0.886	0.587	0.989	0.991	1	0.909	0.917	0.847	0.857	0.578	0.823	0.706	0.632	0.669	0.689	0.747	0.804	0.739	0.772	0.841	0.758	0.873	0.717
Hollandse Kust Zuid 1-2 WP	S8	0.951	0.943	0.971	0.713	0.912	0.91	0.909	1	0.992	0.961	0.944	0.705	0.909	0.818	0.741	0.755	0.756	0.836	0.898	0.779	0.815	0.879	0.773	0.853	0.725
Hollandse Kust Zuid 3-4 WP	S9	0.951	0.946	0.974	0.706	0.92	0.916	0.917	0.992	1	0.955	0.937	0.696	0.9	0.82	0.745	0.761	0.768	0.845	0.902	0.794	0.829	0.891	0.789	0.869	0.738
Hollandse Kust Noord WP	S10	0.927	0.921	0.945	0.758	0.855	0.846	0.847	0.961	0.955	1	0.973	0.769	0.948	0.827	0.747	0.738	0.729	0.813	0.881	0.735	0.766	0.819	0.711	0.786	0.663
Hollandse Kust West WP	S12	0.892	0.894	0.923	0.719	0.867	0.857	0.857	0.944	0.937	0.973	1	0.734	0.979	0.778	0.695	0.69	0.686	0.767	0.842	0.699	0.731	0.79	0.68	0.771	0.631
Ten Noorden vd Wadden WP	S13	0.73	0.717	0.704	0.963	0.573	0.574	0.578	0.705	0.696	0.769	0.734	1	0.749	0.793	0.782	0.7	0.638	0.688	0.723	0.592	0.613	0.611	0.546	0.561	0.506
Ijmuiden Ver WP	S14	0.871	0.874	0.889	0.729	0.829	0.824	0.823	0.909	0.9	0.948	0.979	0.749	1	0.767	0.686	0.679	0.669	0.744	0.823	0.676	0.708	0.759	0.656	0.738	0.605
Friesland	L1	0.861	0.844	0.817	0.822	0.699	0.705	0.706	0.818	0.82	0.827	0.778	0.793	0.767	1	0.934	0.916	0.871	0.913	0.916	0.83	0.844	0.833	0.777	0.763	0.723
Groningen	L2	0.793	0.774	0.746	0.825	0.625	0.632	0.632	0.741	0.745	0.747	0.695	0.782	0.686	0.934	1	0.932	0.872	0.876	0.845	0.805	0.804	0.776	0.749	0.705	0.709
Drenthe	L3	0.813	0.797	0.757	0.746	0.656	0.668	0.669	0.755	0.761	0.738	0.69	0.7	0.679	0.916	0.932	1	0.938	0.913	0.865	0.888	0.875	0.83	0.831	0.763	0.787
Overijssel	L4	0.806	0.792	0.759	0.683	0.678	0.689	0.689	0.756	0.768	0.729	0.686	0.638	0.669	0.871	0.872	0.938	1	0.916	0.856	0.931	0.904	0.855	0.884	0.797	0.842
Flevoland	L5	0.878	0.86	0.839	0.723	0.741	0.75	0.747	0.836	0.845	0.813	0.767	0.688	0.744	0.913	0.876	0.913	0.916	1	0.921	0.897	0.918	0.907	0.872	0.846	0.811
Noord-Holland	L6	0.927	0.914	0.892	0.749	0.798	0.806	0.804	0.898	0.902	0.881	0.842	0.723	0.823	0.916	0.845	0.865	0.856	0.921	1	0.857	0.893	0.916	0.834	0.845	0.772
Gelderland	L7	0.817	0.81	0.779	0.633	0.726	0.737	0.739	0.779	0.794	0.735	0.699	0.592	0.676	0.83	0.805	0.888	0.931	0.897	0.857	1	0.933	0.887	0.927	0.843	0.879
Utrecht	L8	0.852	0.845	0.814	0.646	0.757	0.772	0.772	0.815	0.829	0.766	0.731	0.613	0.708	0.844	0.804	0.875	0.904	0.918	0.893	0.933	1	0.927	0.936	0.884	0.869
Zuid-Holland	L9	0.892	0.881	0.868	0.644	0.833	0.844	0.841	0.879	0.891	0.819	0.79	0.611	0.759	0.833	0.776	0.83	0.855	0.907	0.916	0.887	0.927	1	0.91	0.926	0.849
Noord-Brabant	L10	0.807	0.799	0.77	0.584	0.744	0.759	0.758	0.773	0.789	0.711	0.68	0.546	0.656	0.777	0.749	0.831	0.884	0.872	0.834	0.927	0.936	0.91	1	0.888	0.917
Zeeland	L11	0.844	0.84	0.843	0.584	0.868	0.875	0.873	0.853	0.869	0.786	0.771	0.561	0.738	0.763	0.705	0.763	0.797	0.846	0.845	0.843	0.884	0.926	0.888	1	0.832
Limburg	L12	0.751	0.741	0.72	0.545	0.706	0.719	0.717	0.725	0.738	0.663	0.631	0.506	0.605	0.723	0.709	0.787	0.842	0.811	0.772	0.879	0.869	0.849	0.917	0.832	1

Figure C.2: Correlation matrix for model results of the offshore wind farms and land locations in the Netherlands. The power of the offshore wind farms is based on known and existing layouts for the turbines up to 2030. The power for the land locations is based on 2020 expectations [113]. The codes for the wind farms and land location correspond to the locations in figure C.1

D

Supporting data & equations

In this appendix the additional equations and data are provided that are relevant for chapter 3 and chapter 4. Due to the readability of the report the formulas and tables were not included in the main text.

D.1. Storage characteristics for cost modelling

The input values to determine the LCOS, of which the equations are given in section D.2, are shown in table 2.1. For CAES, Li-ion, NaS, Flow and H_2 these are the base case values for 2015. Model predictions for future development of the technique and the costs, determine the LCOS for 2025. This model data produced by Schmidt et al. [88] is publicly available and used in this report. The starting characteristics of hydrogen have been altered due to the fact that some sources [62, 114, 115] were not compliant with the sources used by Schmidt et al. [88]. For the 2025 predictions in the hydrogen cost reduction curve proposed by Schmidt et al. are used. The cost reduction curve used for hydrogen was confirmed by Eneco internal sources, and therefore assumed valid to use for the values sourced from other literature.

As addition to the energy storage analysis of Schmidt et al., is LAES added due to its promising characteristics, its safety and independence of environmental aspects. As no cost reduction curve is found for the investment of LAES are the predicted characteristics for 2025 directly used in the equations in section D.2. For the characteristics where no information was available are the characteristics for CAES used. This is justified by the fact that both techniques use some of the same critical components, compressors and turbines. The fact that no cost reduction is expected for the 2025 investment of CAES makes it possible to use these characteristics in the future predictions.

To validate the use of equation D.1 the original values used by Schmidt et al. were inserted into the equations and compared to the original data. The results provided by the equations did not coincide with the data generated by Schmidt et al., but there was a consistent deviation of 16% in LCOS. Therefore, all the results of these equations are nudged down with an amount of 16%. This makes it possible to compare the cost results with the data, provided by [88], that is used for the cost calculations of the other storage techniques. This measure is justified by the fact that the deviation was constant for the different techniques in the analyzed domain.

Table D.1: Input values for CAES, Li-ion, NaS, and Flow used in model data generated by Schmidt et al. [88]. In the model by Schmidt et al. the investment is discounted with a cost reduction curve, except for LAES. For LAES the characteristics shown are 2025 values used in equation D.1

			CAES	**Li-ion**	**NaS**	**Flow**	**Hydrogen**	**LAES**[2]
Round trip efficiency	%	$\eta_{roundtrip}$	44%	86%	81%	73%	41% [62]	62% [36]
Investment cost - Power	$\frac{euro}{kW}$	C_{power}	766	597	578	730	2465 [62]	1320 [90]
Investment cost - Energy	$\frac{euro}{kWh}$	C_{energy}	34	706	649	669	31 [62]	121 [36]
Operation cost - Power	$\frac{euro}{kW\,yr}$	$C_{OPEX\,P}$	4 [1]	9	10	11	25 [62]	4
Operation cost - Energy	$\frac{euro}{MWh}$	$C_{OPEX\,E}$	2	3	3	1	0	2
Replacement cost	$\frac{euro}{kW}$	$C_{repl\,P}$	82	0	0	0	1441	82
Replacement interval	$cycles$	cyc_{repl}	1460	3250	4098	8272	6388	1460
Rate of self-discharge	$\frac{\%}{day}$	η_{rose}	0%	0%	20%	0%	1%	0%
Cycle life	$cycles$	cyc_{life}	16250	3250	4098	8272	20000	16250
Time degradation	$\frac{\%}{year}$	t_{deg}	0.7%	1.3%	1.6%	1.7%	1.3%	0.7%
Cycle degradation	$\frac{\%}{cycle}$	cyc_{deg}	0.0014%	0.0069%	0.0054%	0.0027%	0.001%	0.0014%
Construction time	$years$	$t_{construction}$	2	1	1	1	1	2

D.2. Levelized Cost of Storage

The LCOS is calculated according to the equations shown in this section. To obtain the cost for 2025 the cost and performance are updated along experience curves and future cost ranges [88]. The discount rate $r = 0.08$ and the results from the models are used in this report.

$$LCOS = \frac{Investment + \sum_{n=1}^{N} \frac{OPEX}{(r+1)^n} + \sum_{n=1}^{N} \frac{C_{charging}}{(r+1)^n}}{\sum_{n=1}^{N} \frac{E_{discharged}}{(r+1)^n}} = [\frac{euro}{MWh}] \tag{D.1}$$

$$\sum_{n=1}^{N} \frac{E_{discharged}}{(r+1)^n} =$$
$$n_{an\,cyc} * DoD * E_{capacity} \eta_{roundtrip} (1 - \eta_{rosd}) * \sum_{n=1}^{N} \frac{(1 - cyc_{deg})^{(n-1)*n_{an\,cyc}} * (1 - t_{deg})^{(n-1)}}{(1+r)^{n+t_{constr}}} \tag{D.2}$$

$$Investment = C_{power} * P_{capacity} + C_{energy} * E_{capacity} + \sum_{n=1}^{R} \frac{C_{repl\,P} * P_{capacity}}{(1+r)^{t_{constr}+repl*t_{repl}}} \tag{D.3}$$

---

[1] The OPEX mistakenly does not account for the cost of burning natural gas, this is not of a significant influence on the LCOS to have a major influence on the conclusions

[2] The values for LAES are for 2025 projections and thus used directly in equation D.1. If characteristics for LAES were missing, the characteristics for CAES are used.

$$\sum_{n=1}^{N}\frac{OPEX}{(r+1)^n} =$$

$$\sum_{n=1}^{N}\frac{C_{OPEX\,P} * P_{capacity} + C_{OPEX\,E} * (n_{an\,cyc} * DoD * E_{capacity})(1-cyc_{deg})^{(n-1)n_{an\,cyc}} * (1-t_{deg})^{(n-1)}}{(1+r)^{n+t_{constr}}} \tag{D.4}$$

$$\sum_{n=1}^{N}\frac{C_{charging}}{(r+1)^n} = \frac{C_{elec}}{\eta roundtrip} * \sum_{n=1}^{N}\frac{E_{discharged}}{(r+1)^n} \tag{D.5}$$

$$cyc_{deg} = 1 - e^{\frac{ln(0.8)}{cyc_{life}}} \tag{D.6}$$

D.3. Model boundary conditions and equations

This section contains the boundary conditions and the equations that are used in the optimization model that is described in 3.2.2.

$$\underset{x}{min} f^T(\mathbf{x}) = \begin{cases} \mathbf{A} * \mathbf{x} \leq \mathbf{b} \\ \mathbf{lb} < \mathbf{x} \leq \mathbf{ub} \end{cases} \tag{D.7}$$

$$\mathbf{A_{tril}} = \begin{bmatrix} 1 & 0 & \dots & \dots & 0 \\ 1 & 1 & \dots & \dots & 0 \\ \vdots & \vdots & \ddots & & \vdots \\ \vdots & \vdots & & 1 & 0 \\ 1 & 1 & \dots & 1 & 1 \end{bmatrix} \tag{D.8}$$

$$\mathbf{1} = \begin{bmatrix} 1 \\ 1 \\ \vdots \\ \vdots \\ 1 \end{bmatrix} \tag{D.9}$$

$$\begin{aligned} \mathbf{A_1} &= t_{step} * \mathbf{A_{tril}} \\ \mathbf{A_2} &= -t_{step} * \mathbf{A_{tril}} \\ \mathbf{A_3} &= \mathbf{I} \\ \mathbf{A_4} &= -\mathbf{I} \end{aligned} \tag{D.10}$$

$$\mathbf{A} = \begin{bmatrix} \mathbf{A_1} \\ \mathbf{A_2} \\ \mathbf{A_3} \\ \mathbf{A_4} \end{bmatrix} \tag{D.11}$$

$$\begin{aligned} \mathbf{b_1} &= SoC_0 * \mathbf{1} \\ \mathbf{b_2} &= E_{capacity} * (1 - SoC_0) * \mathbf{1} \\ \mathbf{b_3} &= P_{inframax} * \mathbf{1} - \mathbf{P_{OWF}} \\ \mathbf{b_4} &= \mathbf{P_{OWF}} \end{aligned} \tag{D.12}$$

$$\mathbf{b} = \begin{bmatrix} \mathbf{b_1} \\ \mathbf{b_2} \\ \mathbf{b_3} \\ \mathbf{b_4} \end{bmatrix} \tag{D.13}$$

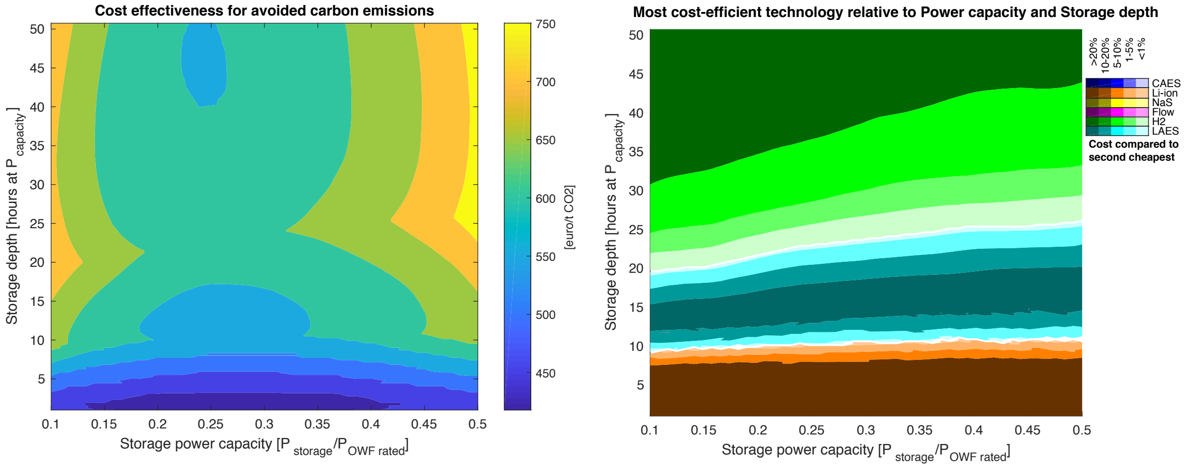
$$\begin{aligned} \mathbf{lb} &= -P_{capacity} * \mathbf{1} \\ \mathbf{ub} &= P_{capacity} * \mathbf{1} \end{aligned} \tag{D.14}$$

E

Sensitivity Analysis

In this section the results for the sensitivity analysis of the cost effectiveness for avoiding carbon emissions are shown. Multiple parameters are varied to analyze the robustness of the results in chapter 4.

Normal operation

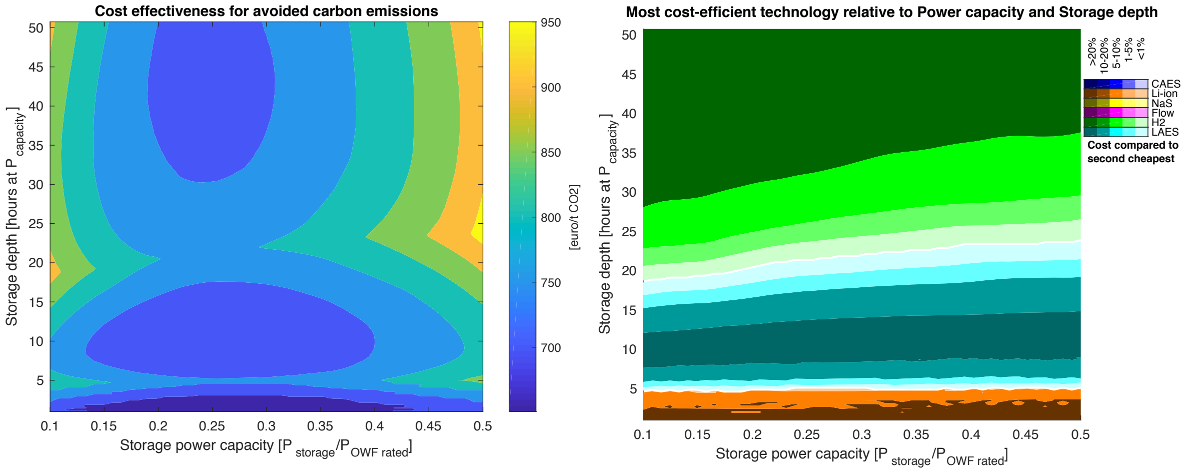


(a) Cost effectiveness for the storage facility as a function of the power capacity and the storage depth

(b) The most cost-efficient technique wrt the second best as a function of the power capacity and the storage depth

Figure E.1: A recap of the results that were generated in section 4.2.2.

Storage facility prices for a 2020 scenario

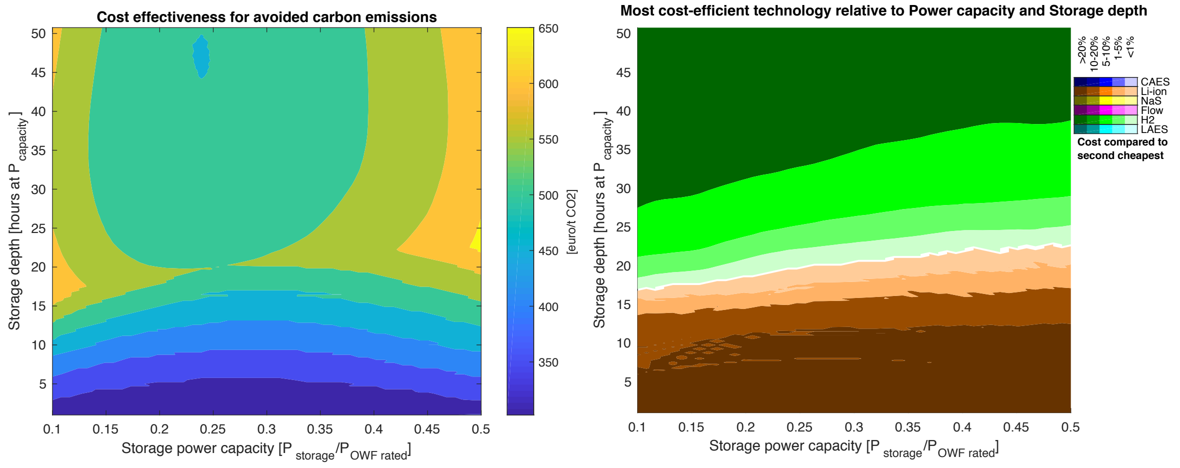


(a) Cost effectiveness for the storage facility as a function of the power capacity and the storage depth

(b) The most cost-efficient technique wrt the second best as a function of the power capacity and the storage depth

Figure E.2: Model run for the case where investment is made in 2020 by using cost model data expectations for 2020 [88]. Compared to the results in figure E.1 is the cost effectiveness significantly higher and is Li-ion storage the cheapest technology for a smaller part of the domain. From 2020 to 2025 Li-ion is expected to experience a significant reduction in investment cost.

Storage facility prices for a 2030 scenario

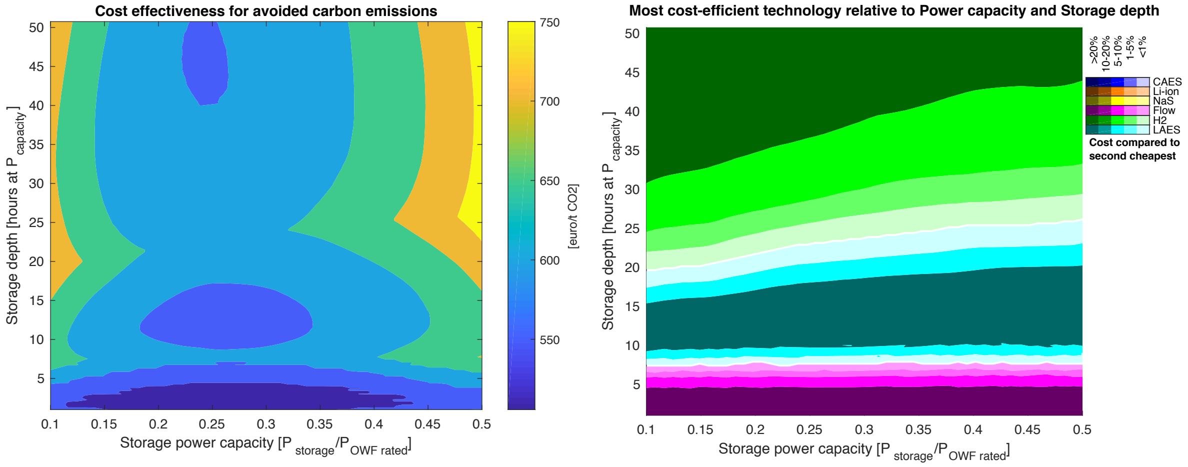


(a) Cost effectiveness for the storage facility as a function of the power capacity and the storage depth

(b) The most cost-efficient technique wrt the second best as a function of the power capacity and the storage depth

Figure E.3: Model run for the case where investment is made in 2030 by using cost model data expectations for 2030 [88]. Compared to the results in figure E.1 is the cost effectiveness significantly lower and LAES has disappeared as the cheapest technology in the domain. From 2025 to 2030 Li-ion and hydrogen are expected to experience a large cost reduction in investment cost, while LAES does not experience the same cost reduction.

Li-ion batteries excluded

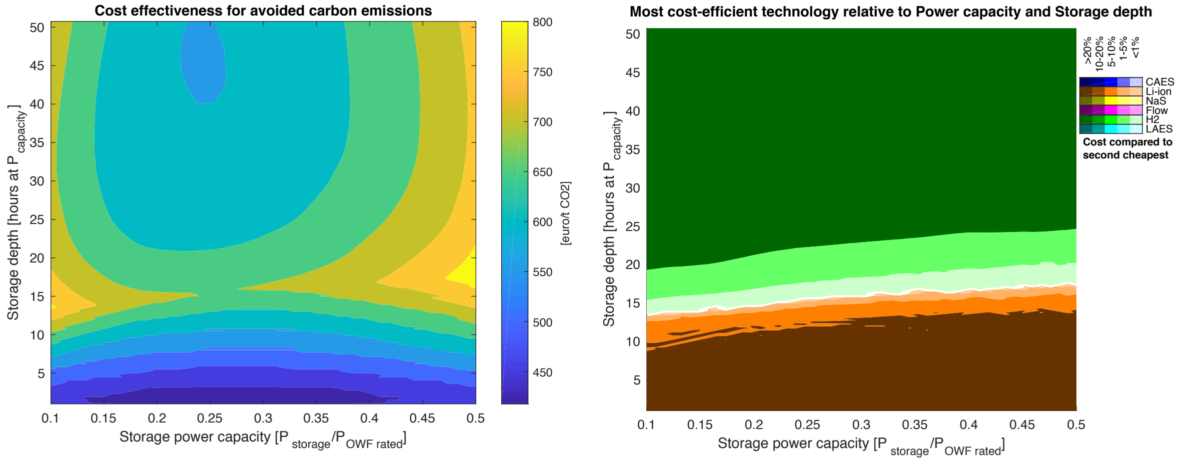


(a) Cost effectiveness for the storage facility as a function of the power capacity and the storage depth

(b) The most cost-efficient technique wrt the second best as a function of the power capacity and the storage depth

Figure E.4: Model run for the case where Li-ion batteries are excluded. When Li-ion batteries are excluded from the analysis flow battery storage largely fills the domain of Li-ion storage. In this case a small increase in the cost effectiveness is experienced for the domain which was dominated by Li-ion in figure E.1

LAES experiences no reduction in price



(a) Cost effectiveness for the storage facility as a function of the power capacity and the storage depth

(b) The most cost-efficient technique wrt the second best as a function of the power capacity and the storage depth

Figure E.5: Model run for the case where the LAES energy capacity experiences no price reduction up to 2025. If no price reduction for LAES is achieved, it will not be the cheapest technology anymore for the domain with the medium storage depth. The domain in which LAES is the cheapest technology will be filled by hydrogen storage an Li-ion battery storage. The cost effectiveness will experience an increase due to the absence of LAES.