# The extended LCOE calculation of internal hydrogen production, storage and reconversion for offshore wind turbines at remote locations


Delft University of Technology - MSc Sustainable Energy Technology

Sietze Naber

TU Delft

Van Oord

DELFT UNIVERSITY OF TECHNOLOGY

MSC SUSTAINABLE ENERGY TECHNOLOGY

# The extended LCOE calculation of internal hydrogen production, storage and reconversion for offshore wind turbines at remote locations

GRADUATION INTERNSHIP - VAN OORD

SIETZE NABER - 4291468 - MSC SET

SUPERVISORS TU DELFT:
E. SCHRÖDER
L. KAMP

SUPERVISORS VAN OORD:
E. VAN DE BRUG
D. KATTELER

30th November 2021

# Acknowledgement

First and foremost, I want to thank Enno, Linda, Edwin, Dirk and Daniel for their supervision and help during this thesis. Enno, Linda and Daniel have given me guidance on the path of LCOE's, discount rates, sustainable calculations and scientific research. Thank you Enno for taken over the baton from Daniel. Despite the fact that "the ship had already set sail", you managed to give me guidance during the last months of my thesis research.

Also, I want to thank Edwin and Dirk for the supervision at Van Oord. The guidance during Covid-19 times, when we were not able to meet for the first six months of the internship, was quite a challenge. Your enthusiasm about the topic and the input you gave me during the weekly meetings always gave me new insights or opportunities for this technology. Therefore, the first meeting at the office felt if we had known each other for months. Thanks a lot for all the laughs, music recommendations and professional input. I also want to thank my fellow interns/starters, Ids and Noor, for the many coffee drinks, advice and hours spent discussing sustainable solutions.

I also want to thank Demi, my friends and family for their help, support and understanding during the ups and downs of my thesis. Being available as a sounding board, to drink a beer or only to wish me luck was amazing. After my bachelor, I was not expecting to find a new group of friends during my masters which would be so close. However, it has been proven that I was wrong. After a week, I found in the 4J's a group friends which grew to the well know "folding boxes" group in the SET master. We had amazing times in the Bouwpub, even started training for the Ringvaart and went on a sailing trip during CoVid19. Thanks for the amazing few years and I hope we will stay together.

Sietze Naber

Rotterdam, 30th November 2021

# Abstract

This research will calculate the extended LCOE of internal hydrogen production and storage in offshore wind turbines at remote locations and will be done in collaboration with Van Oord. Van Oord is a global offshore marine contractor which is focused on dredging, land infra-structure, offshore wind and oil gas infrastructure.

To test the competitiveness of this technology a test location is selected; Grenada in the Caribbean. Grenada is selected because of its suitable conditions: the island is remote, which makes energy supply from outside the island not feasible. The current energy is generated with diesel generators, whereby the diesel is transported from onshore. This makes the electricity relatively expensive and creates excessive carbon emissions compared to sustainable energy systems. This high electricity price also makes renewable energies competitive in an early stage of development. Lastly, the location conditions are favourable for wind energy; high average wind speed, high capacity factor and water depths which are suitable for fixed bottom wind turbines.

To calculate the LCOE of this technology, first a base load calculation is made with the wind speed data from one year. The output of this calculation is the input for the technical component selection of the hydrogen system. The overproduction of the offshore wind turbine is used to produce hydrogen with an electrolyzer. For this process, fresh water is required, which is produced by a desalination system. The hydrogen is pressurized with a compressor and stored in a storage tank. If the wind turbine is not able to produce the required energy, the hydrogen is reconverted into electricity. All these components are located inside the foundation of the offshore wind turbine. The LCOE is calculated with the hydrogen component cost and the cost overview of the the wind turbine. This design is tested for the Grenada location, with various base load scenarios and number of wind turbine generators (WTG's). A sensitivity analysis on these input variables will show their impact on the LCOE and makes design optimization possible. The extended part of this LCOE analysis is the carbon emission decrease calculation between the current non-sustainable diesel generated energy and the offshore internal hydrogen wind turbine system. This sustainable impact is converted into financial input values which shift the financial competitiveness of the technology.

With the base load and LCOE models the following results are obtained. The extended LCOE for an internal hydrogen production and storage system depends on many variables and therefore is given as a range. The LCOE of the Grenada scenarios ranges between €604.03-246.53/MWh. If electricity is supplemented with diesel generated power, at the current energy price, the LCOE can drop to €230.09/MWh. For a single structure with generalized system design, Grenada location input, without the use of overproduction and a base load of 1.5 MW, a LCOE of €501.32/MWh is calculated. If this energy is used, this LCOE will drop to €390.46/MWh. With the addition of the hydrogen system, the security of supply of a traditional wind turbine is increased from 68% to 76%. Depending on the configuration and number of WTG the security of supply can increase to 100% for low base loads. The extended analysis of this LCOE calculation is the sustainable impact of the technology. According to the calculations, the assumed carbon emissions can be reduced up to 96% for a wind turbine system supplemented with diesel energy and up to 99% if the energy production is only generated with wind turbines. If carbon certificates need to be bought, the competitive financial break-even point of this technology will shift. For Grenada, the price of these certificates ranges between €42.03/kg tonnes of $CO_2$ up to €489.86, depending on the selected base load and configuration.

From the sensitivity analysis the influence of the parameters on the lCOE are obtained; an increase in base load, Number of WTG's, power output or storage volume will decrease the LCOE. However the LCOE will increase if the energy losses, discount rate, OPEX, CAPEX, decommissioning cost or growth rate are increased. Most of these variables are inter-depending, which requires iterations to decrease the LCOE.

Many stakeholders are involved in the roll-out of new electricity technology. For Grenada as remote location, the stakeholders are the electricity provider, electricity consumers, government, investors and secondary stakeholders. The competitiveness of a technology is not only depending on the LCOE, even with a sustainable impact analysis, but also on the implications for these stakeholders. Examples of these additional factors are view pollution, political incentives and benefits from byproducts.

Due to the early stage of development, many assumptions and simplifications have been made. These assumptions can be divided in four categories: technical, financial, location specific and stakeholders. Examples are; the foundation is assumed to be feasible for this technology, the carbon emissions are only based on the direct diesel emissions and the carbon emissions of the wind turbine and the base load calculation are based only on a data set of 2020. Therefore future research is recommended for detailed analysis on this technology.

# Contents

# Acronyms

An overview of the used acronyms in this research.

| | |
|---|---|
| **BEIS** | Business, energy and industrial strategy |
| **BoP** | Balance of plant |
| **CAPEX** | Capital expenditure |
| **CRF** | Capital recovery factor |
| **DMFC** | Direct methanol fuel cell |
| **DPB** | Discounted payback |
| **ED** | Electrodialysis |
| **HVDC** | High voltage direct current |
| **HVAC** | High voltage alternating current |
| **KPI** | Key performance indicator |
| **LCOE** | Levelized cost of energy |
| **LCOH** | Levelized cost of hydrogen |
| **MCFC** | Molten carbonate fuel cell |
| **MED** | Multi effect distillation |
| **MSF** | Multi-stage flash distillation |
| **NPE** | Net present energy |
| **NPV** | Net present value |
| **NREL** | National renewable energy laboratory |
| **O&M** | Operation and maintenance |
| **OPEX** | Operational expenditure |
| **PAFC** | Phosphoric acid fuel cell |
| **PEM** | Proton exchange membrane |
| **PtL** | Power-to-liquid |
| **PtG** | Power-to-gas |
| **RES** | Renewable energy source |
| **RMFC** | Reformed methanol fuel cell |
| **RO** | Reverse osmosis |
| **ROI** | Return on Investment |
| **SIDS** | Small island developing states |
| **SOFC** | Solid oxide fuel cell |
| **SoS** | Security of supply |
| **TP** | Transition piece |
| **TSO** | Transmission system operator |
| **VC** | Vapour compression distillation |
| **WACC** | Weighted average cost of capital |
| **WTG** | Wind turbine generator |

# List of Figures

# List of Tables

# 1 Introduction

The energy infrastructure and energy goals are changing. Due to the increase in global temperature, there is an increasing interest in new and more sustainable energy resources. One of these energy resources is wind energy. The energy from the wind is converted into electricity with the use of a wind-turbine and electricity generator. These wind turbines can be located onshore and offshore. Offshore wind has a higher and more constant wind speed, and therefore more wind energy, but also higher transportation and operational & maintenance costs compared to onshore wind energy (Van Oord, 2021).

Besides the positive environmental impact of sustainable energy technologies, compared to the conventional fossil fuels, there are also multiple new challenges due to these new types of energy resources (Energy Efficiency & Renewable Energy, 2017). One of the major challenges is the intermittency and distribution of renewable energies. With the use of fossil fuels, the generation and consumption of electricity does not need to be simultaneously; fossil energy, in the form of oil, can be stored in large tanks with a relatively high energy density. Electricity, on the other hand, needs to be consumed when it is generated. Otherwise, it needs to be stored, for example, in batteries which introduces high costs and lower efficiencies. Besides battery storage, one of these types of storage suitable for wind energy is hydrogen (Bloomberg NEF, 2019). Hereby, electricity, generated by a wind turbine, is converted into hydrogen with the use of an electrolyzer. This hydrogen can be stored, converted into different materials and transported. This makes it more suitable for our current energy grid and fluctuating energy consumption. Our current energy demand depends on a constant energy supply, whereby we have enough energy at any time.

In this graduation research, the opportunities for hydrogen production, storage and reconversion inside offshore wind turbines will be explored. An overview of this system design is given in figure 1. Offshore energy conversion can increase storage capabilities, secure the output supply of energy and decrease transportation costs (McDonagh, Ahmed, Desmond & Murphy, 2020). The aim of the research is to analyse the extended levelized cost of energy (LCOE) of this offshore production technology. The LCOE is the price per amount of energy (MWh) and makes it possible to compare renewable energies with each other. The extension of this LCOE calculation is the sustainable impact, focused on the carbon emissions, the transition from the current energy production system to this new technology will have. The system will be tested at Grenada, in the Caribbean Sea. This test location is selected because of its weather, non-sustainable energy generation and off-grid system conditions, as discussed in detail in chapter 5. An off-grid system is a system without; multiple suppliers, many internal connections or large storage capabilities, but often with only one electricity supplier and a limited ability for redundancy and security of supply. This lack of redundancy of electricity supply creates an opportunity for the internal hydrogen system. At this test location, the feasibility of the technology can be analysed on its technical and financial results.

Two calculation models will be created to calculate the extended LCOE of this system. The first model is the base load model. This model calculates the required base load selection, storage volume and security of supply. The second model is the LCOE model. This model uses the output of the base load calculation, location parameters, cost parameters and financial input values for the calculation of the LCOE. By using these models, the security of supply, electricity generation and the sustainable impact can be calculated and compared with the current diesel generation. The sustainable impact is measured as the reduction in carbon emissions. With the use of these carbon emission reductions, the theoretical price of a carbon certificate, for a financial break-even point, will be calculated. To set these values in context, these prices are compared with the certificate prognosis.

The graduation research will be conducted in collaboration with Van Oord. Van Oord is a global offshore marine contractor focused on dredging, land infra-structure, offshore wind and oil gas infrastructure. For offshore wind, the company focuses on the installation of wind turbine foundations (Van Oord, 2021). This graduation research is part of the master Sustainable Energy Technology at the Technical University of Delft and will be supervised by both the TU Delft and Van Oord.

First, the scientific relevance of the topic will be analysed in chapter 2. Subsequently, the analytic framework will be discussed in chapter 3. In chapter 4, the technical details of the system will be discussed. This includes the technology selection, product selection and cost overview of these components. Chapter 5 gives an overview of the selected test location and the relevance of this location. Chapter 6, discusses the financial parameters of the LCOE calculation and chapter 7 details the results of this extended LCOE. Chapters 8 and 9 consists of the conclusion, discussion and recommendations.

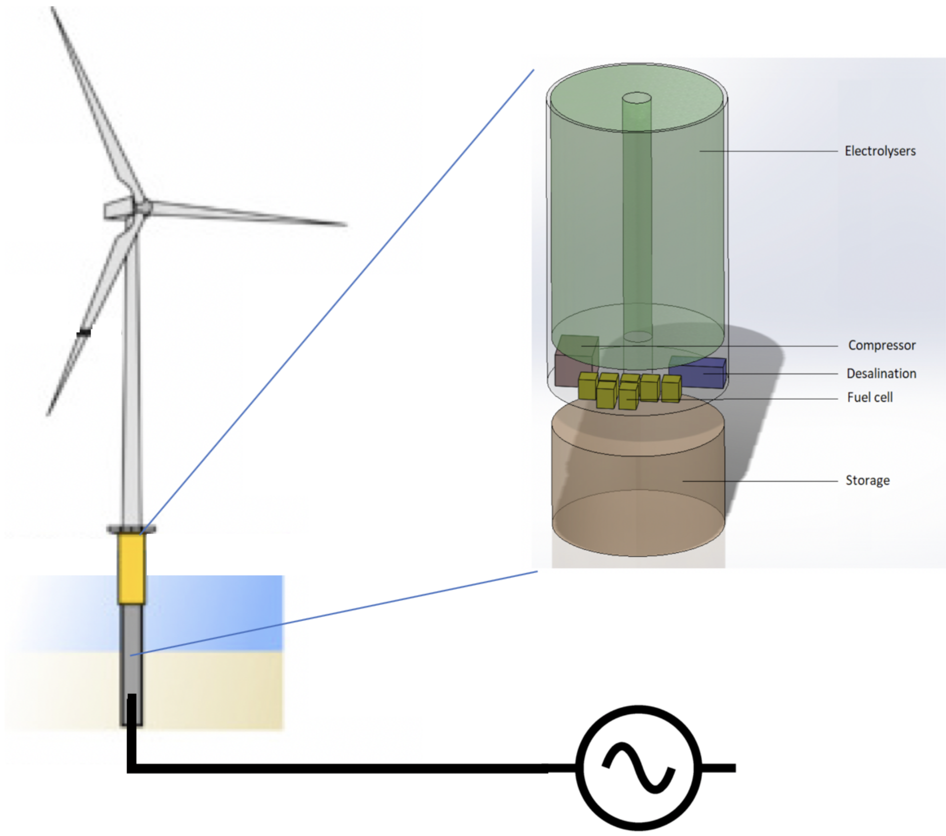



**Figure 1:** System overview of concept design, with location per component (Van Oord, 2021)

## 1.1 Current state of knowledge and knowledge gap

The current energy and sustainability goals are driving the need for renewable energy resources. Besides their lower sustainable impact, compared to current fossil fuel alternatives, these energy resources also create new challenges for transmission, distribution and security of supply. New technologies and solutions are required to address these challenges. One of these challenges is the way in which consumers are using energy: they require a constant energy supply, whereby there is enough energy at any given time. This minimal amount of required energy is called the base load. The percentage of time this base load can be generated is called the security of supply. Storage is one of the key elements in improving this security of supply and balancing of the energy generation and demand (Stram, 2016). As a result of the relative ease of conversion, the possible usages and the zero $CO_2$ emission, hydrogen is one of the big contenders in the race as main energy storage medium (Bloomberg NEF, 2019).

In this section, the current projects, which are available in the market, are discussed. Then the relevance of the topic and the added value will be analysed. Chapter 2 will discuss the scientific relevance and added value in more detail.

### 1.1.1 Current projects from market analysis

There are already multiple projects regarding energy storage solutions for offshore wind systems in the market (Van Oord, 2021). But most of these projects are in the developing phase and some in the test phase. They have each their own combination of storage system (e.g., PtG and storage on seabed), power output, transportation and conversion. Most of these projects are in the research or pilot phase and are not commercially available yet. These combinations of components create their own limitations regarding electricity output, costs (CAPEX or OPEX), feasibility, safety and reliability and needs to be adjusted to a specific location. These project are currently in the innovation phase, which make their technological and financial feasibility uncertain. A few of these projects are listed below:

- Deep Purple (Lindtvedt, 2019)
- Duwaal (HY-GRO, 2019)
- PosHydron (TNO, 2019)
- North H2 (Lee, 2020)
- Zero emission fuels (Zero Emission Fuels, 2020)
- Orstad & ITM (OffshoreWind.biz, 2020)(ITM-power, 2020)
- Floating wind-to-hydrogen (Lee, 2019)
- Utsira (StatiolHydro, 2009)
- Dolphyn (Dolphyn, 2019)

## 1.2 Relevance of the topic in the public market

The energy production is changing. Environmental issues require the change to a more sustainable energy generation. However, the transition to sustainable energies also creates new challenges regarding the balance between supply and demand. The ability to store sustainable energy is one of the important factors in this challenge. Hydrogen is one of the promising, large-scale, storage solutions viable of being implemented in the current human electricity behaviour. This increases the public interest in hydrogen. Wind energy is one of the large-scale energy providers, with offshore wind energy in particular (Bloomberg NEF, 2019). Adding storage to wind energy systems will increase the balance of supply and the capability of delivering base load.

Hydrogen storage and distribution is already in use with energy generated by offshore wind farms; the energy is transported to shore and hydrogen is generated onshore. However, locations where there is not enough available space onshore for hydrogen storage are looking for offshore stored alternatives. According to current research, centralised conversion and storage systems are mainly feasible for large-scale wind farms and decentralised systems are interesting for small-scale application (Singlitico, Ostergaard & Chatzivasileiadis, 2021).

There is also a specific interest from Van Oord in this research and the ground for this collaboration. As mentioned before, Van Oord is a global offshore marine contractor focused on dredging, land infrastructure, offshore wind and oil & gas infrastructure. As part of these specializations, the company has shifted its focus to the installation of offshore wind monopiles. Monopiles are the foundation for offshore wind turbines. The monopile is driven into the seabed to create a solid support for the wind turbine. Due to the changes in the energy sector, Van Oord is researching different topics to maintain their market share in the offshore market. The percentage of fossil fuels in the energy sector will decrease, which makes expanding of their competences important. New technologies such as offshore hydrogen, offshore solar and infrastructures for sustainable energy will increase their corporate opportunities and competitiveness in the market. Their focus on offshore foundation installation narrows their interesting in stand-alone systems, whereby the electricity from wind energy is internally converted into hydrogen and stored locally (offshore). Besides the technical aspects, increasing the number of stakeholders can also create a barrier for the roll-out of the technology. This is because of the possible different political and financial interests of these stakeholders (Van Oord, 2021). These topics will be discussed in more detail in section 3.4 and chapter 5.

## 1.3 Research questions

In this section, the main research question and the sub research questions will be discussed. The objective of this research is to analyse the levelized cost of energy and the decrease in carbon footprint with the use of an internal hydrogen storage system added to an offshore wind turbine. To test the technology, this research will focus on Grenada as selected remote island.

### 1.3.1 Main research question

The main research question of the thesis research is:

***What is the extended LCOE of a combined offshore wind, hydrogen production, storage and reconversion energy system in integrated single structures for remote locations?***

The main question will analyse the LCOE and sustainable impact of the internal hydrogen production, storage and reconversion of offshore wind turbines at Grenada. Grenada is selected as test location for this technology and to determine the suitable input parameters for the base load and financial calculations.

### 1.3.2 Sub research questions

The main research question is divided in several sub-questions. They are listed below and will be discussed in the following paragraphs.

1. What is the added value of an internal hydrogen production, storage and reconversion system for offshore wind turbines?
2. What is the most suitable technological setup, created with the current knowledge and state of technology, for internal hydrogen production, storage and reconversion for offshore wind turbines?
3. Which financial method will be used and which parameters are required in this cost analysis of internal hydrogen for offshore wind turbines?
4. What is the business case for small-scale internal hydrogen systems for offshore wind turbines?

5. What are the scenarios that need to be analysed for this technology?
6. What is the sustainable impact of the transition from the current energy generation to an internal hydrogen production wind turbine?

The first sub-question is related to the added value of the hydrogen production, storage and reconversion in the field of the energy transition. Which problem is solved and how can this technology improve the security of the offshore wind generated electricity? Sub-question number 2 is about the technological side of the system. Which components are required, what are their size/volume and how are they interconnected? This sizing will be used in the cost analysis for the financial part. The third sub-question focuses on the financial part of this research. Which financial model will be used? Therefore, the financial model and input parameters for the LCOE calculation are required. Sub-question 4 analyses the selected location and its comparability with other locations suitable for this technology. Here, the question is how a competitive business case can be obtained, with this technology. Therefore, several key performance indices are selected, such as the LCOE and carbon emission reduction. To calculate the LCOE and sustainable impact, a test case is selected, Grenada. The location selection will be substantiated and location specific values will be used for the calculations. To determine the influence of the location on the LCOE, a sensitivity analysis on these input variables will be performed. Sub-question 5 will give an answer to the question which scenarios are important for the LCOE comparison and optimization of this technology. Lastly, sub-question 6 will focus on the sustainable impact, the extended part of the LCOE, of the transition from the current energy generation with the use of diesel generators to an energy production with wind turbines, combined with this internal hydrogen system. With the current climate change and energy goals this part is essential to justify investments and possible higher costs.

# 2 Scientific literature research

The goal of this research is to calculate the LCOE of this internal hydrogen offshore wind turbine system and to determine the sustainable impact of this technology on a remote location; the extension of the LCOE. In this section the importance of the energy transition, the challenges of renewable energy resources, the LCOE calculation and the scientific researched projects, related to this technology, will be discussed.

## 2.1 Challenges of the energy transition to renewable energy resources

The climate is changing. Human activity has increased the amount of pollution, emissions and particles in the air. One of the major green house gasses is carbon dioxide, $CO_2$, which causes, in larger quantities, an increase in the average global temperature. The best way to counteract this increase in temperature is lowering the (carbon) emissions. One of the major carbon producers is the energy generation sector; burning fossil fuels creates $CO_2$ and pollution. Due to the size of the energy production industry, this is an important sector to decrease its carbon footprint. Due to the global aspect of this problem, the global energy production needs to be transitioned. Otherwise, examples, such as carbon leakage, which is the movement of carbon intensive production to other locations, will occur and the total global emissions will not be reduced. To achieve this carbon reduction several agreements, goals and alliances are started. One of the examples is the Paris agreement (UNFCCC, 2019), which sets sustainable targets for 196 parties with the goal to limit the global temperature increase to 2 degrees Celsius. Other agreements/initiatives focus more on a local group of parties, such as the SIDS Lighthouses Initiative (IRENA, 2021). With this initiative, the small island developing states, such as Grenada, have committed to the climate pledges.

These sustainability goals are driving the need for renewable energy resources. This necessity to transform the energy system generates interest from and creates opportunities for scientific research on sustainable topics. Renewable energy technologies are energy production methods without the use of non-replenishable products (over a human lifetime). Different sustainable energy technologies are: (offshore) wind, hydropower, solar energy (photovoltaic), tidal & wave energy, bio fuel, bio-gasses and geothermal energy. Between these technologies, solar and wind energy have the largest growth rates, as a result of their potential installation capacity (Bloomberg NEF, 2019)(Painuly & Wohlgemuth, 2021). Despite the potential growth of solar energy, wind energy has a higher potential as energy supplier for locations with lower irradiation levels and can be used for larger power outputs. Large solar electricity outputs still require large areas onshore. The alternative of offshore floating solar energy is still in the research and development stage which makes it currently not feasible for large power requirements (Hooper, Armstrong & Vlaswinkel, 2021).

The transition to sustainable energy technologies can reduce the carbon footprint of electricity production, but also induces new challenges: economical, technical, awareness for sustainability, regulatory & policy and social & environmental challenges, with arguably storage as one of the major challenges for RES's (Painuly & Wohlgemuth, 2021). Renewable energies are relying on renewable resources, such as wind, solar, etc., for energy production. These energy resources fluctuate, caused by changing weather/environmental conditions, which make the power output of renewable energies uncertain. To increase the security of supply by smoothing out the electricity supply, storage solutions are required. Excess production of electricity is stored and used when the electricity supply does not meet the demand. There are two types of storage for wind energy: long-term (seasonal) storage and short time storage. Long term storage will regulate the annual fluctuations; higher wind speeds during the winter, which results in more electricity production during these months and vice versa during the summer months. These fluctuations are expected to increase even further in the future as a result of environmental changes (Costoya, DeCastro, Santos, Sousa & Gómez-Gesteira, 2019). On the other hand, there are short term fluctuations; for wind these are the fluctuations in wind speed measured per 10 minutes.

Many types of energy storage have been researched: mechanical, thermal, electro-chemical, chemical and electrical, with the aim of examining the feasibility and advantages & challenges per technology (A.M. Othman, 2017). Many of these technologies induce new technological challenges, especially due to harsh offshore conditions, which make them not suitable for this research. The two most promising storage technologies are battery storage and hydrogen storage. Battery storage is already researched for remote locations and mainly used for short term energy storage (Serna & Tadeo, 2014). Currently, battery storage has a large share of the storage market and is a proven, reliable and long lasting technology. However, there are also two main challenges: to produce batteries, contaminating resources are required in the manufacturing process and batteries have a low energy capacity with high capital costs, which results in large and expensive storage systems. The alternative is hydrogen, which uses an electrolyzer to convert electricity into hydrogen. Hydrogen can be stored in a tank and partially eliminates the use of harmful materials. A side note on the required materials is the scarcity and high price of some of the used materials, such as platinum and iridium. The added benefit of using hydrogen as storage is the increasing interest in this storage medium. According to many recent studies, hydrogen will play a major role in the energy transition because of its storage capacity versus price and energy transportation rates (Bloomberg NEF, 2019). This makes hydrogen for offshore wind energy interesting for scientific research and will future proof the energy generation of remote locations. Hydrogen storage for offshore applications can be realised with multiple (hydrogen)carriers such as: metal hydrides, chemical hydrides, adsorption, liquefaction and compression (Franco et al., 2021). All of these storage mediums have their advantages and disadvantages, whereby compressed hydrogen, methanol and ammonia are showing the largest growth in the near future (Demirel, 2015) (Shatnawi, Qaydi, Aljaberi & Aljaberi, 2018).

An alternative for (large) storage systems is supply-and-demand management. In this kind of electricity control, the demand side will follow the changing supply of electricity. This system requires three important factors: up-to-date electricity generation information to give energy prognoses, the possibility to change the demand and an electricity system which is large enough to output base load energy for a continuous power demand. A lot of research has been conducted on this supply-and-demand management due to the opportunities for cost reduction, decrease requirement of installed capacity and increased security of supply (Dranka, Ferreira & Vaz, 2021). However, this system is more suitable for larger energy grids, which offer more opportunities for controlling the electricity flow due to the larger number of electricity providers and consumers. Including a short time storage system, as discussed in this research, gives the opportunity of also implementing this supply-and-demand system for smaller (remote) locations. This optimization of energy use will be out of the scope of this research, but is recommended for future research.

## 2.2 Introduction to the levelized cost of energy

The goal of this research is to calculate the levelized cost of energy (LCOE) in combination with a sustainable impact calculation. The LCOE is a metric that can be used to calculate the costs of an electricity production technology over its lifetime. With this metric, both the capital and the operating cost can be converted into the total net present value (NPV)

(US EIA, 2013). Because the capital costs are not the only cost driver, this makes a fairer comparison with a total lifetime cost analysis. The major advantage of using the LCOE is the comparability of electricity generation technologies for both renewable and non-renewable energy resources.

### 2.2.1 Components of the LCOE calculation

For the calculation of the LCOE, several cost components are required: capital costs, fixed O&M costs, variable O&M costs, decommissioning costs (Raikar & Adamson, 2020). Each of these components will be discussed in detail in the following paragraphs.

**Capital costs** The capital costs are the costs directly related to the development, production and installation of the system. For a wind turbine, these costs consist of the foundation, transition piece, tower, wind turbine generator and electricity cable. All these components needs to be designed, manufactured, managed and installed. Capital costs can either be fixed or variable. Variable costs will scale depending on the size of the project, whereby fixed costs, such as travel expenses, training, development, project management and surveys, will not change depending on the size of the project.

**Operation and maintenance costs** The operational and maintenance (O&M) costs can also be divided in two parts: the fixed O&M costs and the variable O&M costs. The fixed costs consist of insurance, administration, fixed grid access fees and service contracts for scheduled maintenance and the variable O&M costs consist of scheduled and unscheduled maintenance not covered by fixed contracts, as well as replacement parts and materials, and other labour costs (IRENA, 2012).

Besides the lifespan of a component, the efficiency or output of a component will decrease. This is called system degradation. Degradation will lower the theoretical maximum power output, which will increase the LCOE. An outage of a component is an extended form of degradation and will impact the reliability of the system. The occurrence of these outages are a probabilistic problem, which can be visualized as a normal distribution. To combine the risk of failure of all the components, for example, a Monte Carlo analysis can be used (Abdusamad, 2018)(Sun, Ye & Zhu, 2020). This analysis is a multivariate analysis which calculates the "What if" question by combining all failure distributions.

To increase the security of supply for this system, the components are selected based on their required number of components. A higher number of components will increase the reliability during a component failure. Therefore, the system components will have a minimal number of $n>1$ components, if possible. Other solutions are the use of a backup system or the storage of the required product, which can be used during an outage. Because of the uncertainties in lifespan and reliability of the components, the multivariate reliability analysis will be out of the scope of this research. In this research, the assumption is made that the failures do not influence the power output, due to the redundancy in components and the storage system which will function as a buffer.

**Decommissioning** After the lifetime of the system, the structure needs to be dismantled, transported and recycled. This is all part of the decommissioning costs of a project. Depending on the components and location, some components can be reused, refurbished or will be scrapped. This can generate an additional income stream which will be subtracted from the total decommissioning costs. An important note is the uncertainty regarding the demand for these components. Therefore, the total decommissioning cost will only be an estimation (Adedipe & Shafiee, 2021).

**Financial parameters within the calculation** Besides the project costs, there are several financial parameters which influence the cost structure over time. These financial parameters are the discount rate and financial growth rate. The discount rate will adjust for the value of money over time. The discount rate is the inverted value of the weighted average cost of capital (WACC). If a company has money, this money can earn interest which will increase the amount of money in the future. This money in turn can also earn interest, which results in an exponential growth of the amount of money. If a company is investing in a project or technology, the profit from this investment needs to be higher than the interest of a bank, otherwise it is often more financial interesting to save money at the bank. This principle of interest rate compared to project investment is integrated in the discount rate. In other words, an euro today is more valuable than an euro tomorrow, because the euro of today has the ability to gain interest. Besides the interest that money can earn, investing in a project creates a risk of not earning profit. This higher investment risk also needs to be taken into account in the discount rate when evaluating the financial feasibility of a project. Because of the impact of the discount rate in the LCOE calculation, it is important to use a realistic number. This is often an approximation due to the uncertainty factors for the investment risks, inflation rates and interest rates (Investopedia, 2013). The second parameter is the growth rate. The growth rate is used to account for the inflation rate. Inflation is the general progressive increase in the prices of goods and services in an economy.

**Annual electricity generation; capacity factor or utilization rate** The last parameter in the LCOE calculation is the total annual power output of the used technology. For the traditional wind turbine systems, the annual electricity generation is calculated with the capacity factor. This factor is the generated electricity divided by the theoretical total electricity generation of the wind turbine at maximum power output. This calculation will be discussed in detail in section 5.6.

## 2.3 Disadvantages of using the LCOE

However, the LCOE has a practical and simple application, it also has some disadvantages: variations in supply and demand, system integration costs and externalities (Sklar-Chik, Brent & de Kock, 2016)(Aldersey-Williams & Rubert, 2019). These disadvantages will be discussed in the following paragraphs.

The first shortcoming of the LCOE calculation is the allocation of daily variations in demand and supply. The LCOE calculation uses the annual power output, whereby dispatchable and non-dispatchable energy generation technologies are calculated in the same way. Most of the non-renewable energy resources are dispatchable, which means that they can provide electricity supply on demand. On the other hand, sustainable energy resources are non-dispatchable; they are depending on their energy resource. Because electricity only has a value if there is demand (Sklar-Chik et al., 2016), the percentage on which the supply meets the demand is more important than the total power. However, this metric is not taken into account when calculating the LCOE.

Integrating a new electricity supply induces costs; system integration costs. These costs are part of the profile costs and a responsibility of the transmission system operator (TSO) and include; transmission costs, distribution and marketing costs. However, these costs are not taken into account when calculating the LCOE of a new technology. Especially when the electricity supply is fluctuating, these costs can be significant due to added balancing and monitoring costs. These costs will be added to the electricity price and therefore need to be taken in consideration when comparing technologies (Hirth, Ueckerdt & Edenhofer, 2015). This will be discussed in more detail in base load pricing, section 3.2.1.

The third simplification of the LCOE is the integration of the externalities. Externalities are costs for a third party, which do not agree with it. Examples regarding wind turbines are manufacturing emissions resulting in climate change or view pollution for a hotel owner. For a traditional LCOE calculation these costs are not taken into account. However, they may have a significant importance in the comparison between technologies. To analyse the sustainable impact of this researched technology, a carbon footprint comparison is added to the LCOE calculation. However, this is only one of the many externalities which should be analysed for a realistic comparison between technologies.

In conclusion, the LCOE is a simple estimation which enables the comparison between renewable and non-renewable technologies. Nevertheless, it also has its limitations regarding energy fluctuations, system costs and the integration of externalities in the cost analysis. Because of these limitations, new metrics have been designed (Beiter, 2019). Examples are improved LCOE calculations which include security of supply or adding the sustainable impact by incorporating financial structures, as done in this research.

## 2.4 LCOE comparison of literature researches

The goal of this research is to calculate the LCOE of this technology. However, the determine the relevance of these results, they need to be compared with different technologies. In this section, first, the LCOE's of different currently available technologies will be compared, then the LCOE of new technologies which have been researched.

### 2.4.1 LCOE's of current electricity generation technologies

Because of the widespread use of the LCOE, many technologies have been evaluated with this metric. In this research the LCOE of the internal hydrogen technology for offshore wind turbines will be calculated. This value needs to be compared with LCOE's of alternative technologies, to get an understanding of the meaning of the LCOE result. An important nuance in this overview are the secondary factors; factors not directly related to the specific technology. The LCOE of a technology depends on many factors: national and local conditions, financial parameters and maturity of the technology due R&D. This results in a LCOE range instead of a specific value for each technology.

Non-sustainable energy resources range from 45 to 146 euros per MWh. Due to the development phases the LCOE value of these technologies has decreased over the years. However, there are two main cost drivers that are not taken into account in this LCOE value: the costs for the balance of plant, such as the infrastructure for transportation of the resources, and secondly the externalities of the technology. As discussed, the exact costs related to climate change are uncertain. This makes it difficult to directly compare non-sustainable and sustainable technologies on their sustainable impact. Therefore, the higher LCOE values for sustainable energy technologies, as seen in table 1, can financially be justified if the impact on the climate is higher than expected. Financial sustainable structures, such as the carbon footprint certificates used in this research, are an incentive to shift to a sustainable energy generation. An side note on these LCOE's is the discount rate. For this comparison a 10% discount rate is used in the following table. The same value as used in the LCOE calculation in this research. This will be discussed in more detail in section 6.

The main reason for the higher LCOE's of sustainable technologies is the early stage of roll-out of these technologies. Many of these technologies are still in development stage or are still scaling. Even for offshore wind turbines, which have been installed for many year, the maximum installation capacity is not reached and will be optimized in the future (Van Oord, 2021). This will lower the LCOE even further which makes sustainable technologies even more interesting in the future.

| **Non-sustainable** | |
|---|---|
| **Technology** | **LCOE (€/MWh)** |
| Lignite | 107-111 |
| Coal | 78-126 |
| Gas (CCGT) | 45-108 |
| Nuclear | 57-146 |

| **Conventional sustainable energy technologies** | |
|---|---|
| **Technology** | **LCOE (€/MWh)** |
| Wind onshore | 36-172 |
| Wind offshore | 58-237 |
| Solar PV | 42-277 |
| Solar thermal | 140-160 |
| Hydro | 56-203 |
| Geothermal | 103-163 |
| Biomass | 68-208 |

**Table 1:** LCOE values for different technologies, with a discount rate of 10% (IEA, 2021).

As discussed, the competitiveness of the LCOE of a sustainable technology depends on many factors (IEA, 2021). This point of competitiveness is called: Grid parity. Grid parity is when the LCOE of an alternative technology is equal to or lower than the current energy price (Tu, Liu, Li & Mo, 2021). When transitioning to a sustainable energy resource, this will have additional benefits such as lower emissions and less pollution. However, these added benefits are not taken into account in the LCOE calculation. To determine the competitiveness the LCOE of this researched technology will be compared with the current electricity price. With the addition of storage, the system profile costs can be lower, which will influence this LCOE comparison. This will be discussed in more detail in 3.2.1.

### 2.4.2 New sustainable technologies

In the last section, the LCOE's of currently available technologies are analysed, non-sustainable and conventional sustainable energy technologies. However, many conventional sustainable technologies have not solved the renewable challenges, as discussed in section 2.1. Because of technical, political and financial constrains, different technologies have their advantages and disadvantages, depending on the location. Therefore, there is not only one technology which will replace the current fossil energy production, but it will be a mix. In the following table, examples of literature research regarding the LCOE's of competitive technologies for remote/island locations will be given, whereas the next paragraphs give some background for these examples. Because of the wide variety of competitive technologies, these are only a few examples. However, these values sets the scene for the LCOE comparison of this internal hydrogen system with alternative technologies.

| Literature research | LCOE (€/MWh) | Reference |
|---|---|---|
| **Complete systems** | | |
| LCOE research on European islands | 100 - 580 | (Barney et al., 2021) |
| Case study in the North sea on PtG and PtL | 43 - 212 | (Crivellari & Cozzani, 2020) |
| Ometepe, Nicaragua, energy generation mix | 80 - 130 | (Meza et al., 2019) |
| Combining WTG and PV energy with batteries | 349 | (Jung, Jeong, Kim & Chang, 2020) |
| Sustainable energy transformation of Curacao | 232-393 | (Prochazka, 2012) |
| | | |
| **Addition of a hydrogen setup (increase in LCOE)** | | |
| $H_2$ generation for overproduced wind energy | 38.1 | (McDonagh et al., 2020) |
| Comparison on onshore, offshore or in-turbine hydrogen | 42-78 | (Singlitico et al., 2021) |
| Pathway of hydrogen for offshore wind turbines | 20-70 | (Franco et al., 2021) |
| Internal battery storage for offshore wind turbines | 75-100 | (Simpson, Hanrahan, Loth, Koenig & Sadoway, 2021) |

**Table 2:** Comparison of technologies on their LCOE, divided in complete energy systems and separate hydrogen setups, which can be added to existing systems ($1 = €0.83).

Extensive research has been conducted on the LCOE at European islands. Due to the Paris Agreement, these islands also need to comply with the sustainability goals. The goal of the first research is to develop an energy planning method for islands to transition towards a 100% renewable energy generation (Barney et al., 2021). These locations energy storage coupled to their energy generation, modern energy grid, the ability for electricity planning and supply & demand management. The LCOE's of these transitions to renewable energy differ between €100 and €580/ MWh. This research gives insights into the diversity of the LCOE depending on the location. Other European researches focus on different combinations of PtG for European islands (Crivellari & Cozzani, 2020). Both studies have a large range for their LCOE results. This is an example of the major influence of location, technology and financial values on the LCOE.

There are also several researches on developing state island. To comply with the sustainable goals and despite of their lack of financial funds, alliances have been initiated for these locations (IRENA, 2021). One of these renewable energy transformation researches focuses on Ometepe, Nicaragua. This island has the same environmental characteristics as Grenada, regarding fossil fuels, which are transported from shore to the island and wants to transition to a 100% sustainable energy generation. Therefore, a mix of energy generation, with a combination of solar, wind and biogas, have been researched. This research shows that wind energy alone, with a discount rate of 10%, will result in a LCOE of $80-$130 per MWh, depending on the installed capacity (Meza et al., 2019). Alternative technologies; tidal, hydro power and photovoltaic, have been researched on their feasibility for off-grid remote locations (Jung et al., 2020) (Serna & Tadeo, 2014) (Rahman, Oka & Shirai, 2010). These researches have shown several technological advantages and disadvantages.

One of the scientific researched options for offshore power hydrogen is the concept of a stand-alone wind powered offshore platform where hydrogen is generated centrally. This hydrogen is stored in an offshore underground hydrogen storage and will be transported by ship to shore. In these researches, the capital value will be analysed over time. For example, one of the researches analyses the cost projection of the Discounted Payback (DPB) and Net Present Value (NPV). Hereby, a hypothetical wind farm of 101.3 MW, located at the East Coast of Ireland, is analysed for its viability (Dinh et al., 2020). The research has focused on the output of hydrogen and therefore the LCOE is not calculated. Instead the a LCOH (levelized cost of hydrogen) of €5/kg of hydrogen is calculated as energy price. For this LCOH calculation, the same approach as the LCOE will be used, as discussed in section 3.3.1. Appendix figure 20 gives an overview of this offshore hydrogen production and storage system, used to transport energy by tanker to shore. This system requires secondary system (substation, vessels, etc.) which makes the roll-out less feasible and induces third parties. In this thesis research, the hydrogen system will be implemented inside the monopile/TP, which will eliminate the need for a substation or platform and therefore decreases the number of project stakeholders.

To set the internal offshore storage system in to context, the system needs to be competitive with internal battery storage systems. Therefore, a scientific research focus on battery storage of offshore wind turbines is added to the comparison. In this research, liquid batteries are used to level out the intermittency. The LCOE of this research ranges between €75 and €100/MWh. Three conclusions can be conducted on this technology; the storage CAPEX are a major part of the investment, the system has a low energy storage potential and there are still major emissions related to the manufacturing of batteries. However, due to the maturity of the technology, this is a feasible alternative for internal hydrogen production.

An alternative for offshore fixed bottom foundations are floating foundations. Within this technology, there are four types of floating structures: the spar-buoy type, the semi-submersible, tension-leg platform (TLG) and the barge type (ABN AMRO, 2021). The floating foundation has a large potential for deep-sea use. Due to the floating technology combined with anchors, instead of the fixed connections, the floating system can be financial feasible for a water depth of around 60 meters. However, this technology is in an early stage of development, with only a few pilot systems. Secondly, the volume inside the monopile is used for the hydrogen storage, which justifies the investment costs of a large monopile foundation. Therefore the floating bottom structure is not taken into account. Nevertheless, it may be interesting, due to the buoyancy construction which could be used as hydrogen storage, for future research (Linnenschmidt, 2021) (Myhr, Bjerkseter, Ågotnes & Nygaard, 2014) (Beiter et al., 2020).

Research has also been done on the frameworks for developing innovation systems in small island developing states, for example for Curacao (Prochazka, 2012). Within these frameworks, the main focus is on mixing the electricity generation. Therefore, appendix table 32 shows an additional overview of scientific research projects regarding mixed sustainable energy production for remote locations. However, this research will only focus on electricity generated with the current diesel generators, offshore wind generated electricity and offshore wind generated electricity with the additional internal hydrogen system.

In conclusion, many research has been done on the alternatives for non-sustainable energy technologies. The five main technologies are wind, solar, hydro, geothermal and biomass. Regarding these technologies, there have been many studies on sustainable transformation and LCOE research focused on remote/island locations. Due to the growing interest in wind energy and hydrogen, there is a large potential for a combined system which can be used in a decentralised offshore system, if the LCOE is financially competitive.

## 2.5 Decrease of levelized costs of energy for renewable energies

As discussed, the LCOE calculation consists of many parameters which can be changed to improve the LCOE. Due to the broad use of the LCOE, there have been many researches done on the improvement of this value. Driving down the levelized cost can be realised with four categories: market factors, technological factors, regulatory factors and financial structures (Agora Energiewende, Couture, Jacobs & Appleman, 2018).

The first category is to use market factors to decrease the LCOE. Economy of scale will improve the financial competitiveness. Examples of using these market factors are; gaining knowledge about the market of the technology, increasing the market share by standardization or using the broader macro-economic environment to determine new locations. Secondly, the technological factors can improve the LCOE of this technology. Examples are design optimization or increasing efficiencies with R&D of components. Thirdly, according to research, regulatory factors can improve the LCOE of a technology. Examples are streamlining the permitting and administrative procedures, improving the use of land which can decrease the survey costs and improving the grid connection procedure (Agora Energiewende et al., 2018). The last category of improvements are the financial structures. These financial structures consist of payment and contract structures such as the carbon certificates or emissions caps/allowances. These structures will increase the incentive to produce sustainable energies and induce added costs when the total carbon footprint allowances are exceeded. These added costs for $CO_2$ producing technologies give a financial advantage for sustainable technologies. This concept will be discussed and calculated in section 28.

Looking specifically at the wind technology, there is a clear decrease in the LCOE: the global average LCOE for wind energy is decreased by 20% between 2010 and 2018. This can a result of 3 factors: increased market interest, technological development or economy of scale. An increasing interest from the market creates more trust in technology. This will be reflected in a lower discount rate, as discussed in section 6.4. Secondly, the evolution in technology can decrease the LCOE, for example, an increase in capacity due to an improved nacelle design or higher hub heights (Energy Information Administration [EIA], 2021). The economy of scale could have improved the LCOE by allocating the costs (CAPEX and OPEX) over a larger number of turbines (IRENA, 2018) (Fernández-Guillamón, Das, Cutululis & Molina-García, 2019). Lastly, these financial structures can create a financial advantage for wind turbines, compared to non-renewable energies.

Within these factors, two separate developing visions can be determined: learning-by-doing or learning-by-thinking. The first is based on developing a technology and improving it during the lifetime. Hereby, the gained knowledge during operation can be used. The second type is learning by thinking, which is based on collecting knowledge and improving the technology before the technologies roll-out (Van Poeck, Östman & Block, 2020). These visions are visualized in the life-cycle model, whereby there is approach for market entry during the adaptation phase and market entry during the stabilization phase. In the first approach, the technology will enter the niche market when it is still developed. This results in a less optimized system, but creates the opportunity of learning-by-doing. The second approach optimizes the technology and enters the stabilized market with an optimized system (Ortt & Schoormans, 2004). Both visions are reflected within the four improvement factors. A researched example of this is the learning curve analysis for wind and photovoltaics in the US. This research analyses the importance of R&D for the reduction in costs (Zhou & Gu, 2019).

## 2.6 Carbon trading schemes and allocation of social costs

Besides the absolute electricity price, as expressed in the LCOE, the externalities must be taken into account when comparing technologies. To allocate these costs, there are several ways to stimulate the decrease in emissions. Within these emissions, the main focus is on carbon emissions, due to the Paris agreement. However, recent agreements, such as the Glasgow agreement, also focus on the decrease of methane emissions (of Regions, 2021).

To stimulate the sustainable improvement, emissions certificates can be bought, emissions can be capped, contracts can be signed, and emissions allowances can be bought. Long-term contracts, such as feed-in tariffs, can be offered to renewable energy providers to positively encourage investments in sustainable energy technologies. On the other hand, emission permits must be purchased and represent the right to produce an amount of emissions or greenhouse gas, expressed in tonnes of kg. Within these permits, there are two approaches: prescriptive and market-based (Nordhaus, 2009). Prescriptive allowances can be permitted for free, called "grandfathering". Market-based approaches are structures whereby allowances can be traded via an auction and the price of the trade is based on the supply and demand of the allowances.

Tradable permits, also called cap-and-trade, set a specific total amount of emissions that is allowed to be emitted by power plants, industry factories and the aviation sector (EC, 2016). These permits can be allocated (prescriptive) or auctioned (market-base). With these permits providers of electricity are encouraged to increase the sustainability of their electricity generation technology. By improving the technology, less permits need to be bought or the excess of permits can be sold, which creates an additional income stream (Nordhaus, 2009). The disadvantage of this permit system is the sensitivity of the emission cap and the difficulty to determine this supply and demand. If the cap is too high, too much emissions will be emitted, set the cap too low and the electricity price will be (too) high, which will induce new social economic challenges.

Carbon taxes are the second method to create a sustainable incentive. Electricity providers will analyse the profitability of new technologies, compared to these taxes. They will either pay taxes or invest to avoid these tax costs. The advantage of this system is the simplicity of the system. The permit controller does not need to analyse the supply and demand of permits, but only set a tax price. The disadvantage is the uncertainty in the total amount of emissions. The decision of sustainable investment depends on the energy provider (Nordhaus, 2009). Besides these taxes, carbon offsets can be bought as an addition to these certificates for the further reduction in the amount of emissions emitted. This will demonstrate the companies willingness to decrease their emissions (Native, 2017). Carbon subsidies are the inversed approach of carbon taxes. In this approach, a positive incentive will be given to increase the sustainable impact. These subsidies can be used to decrease the CAPEX of the project, which decreases the total costs and therefore the LCOE of a technology (Perdan & Azapagic, 2011).

In this research, the price of the financial certificates is calculated at which the technology/scenario has a break-even point with the current electricity generation system. Theses certificates can be seen as tradable permits, with a specific price or carbon tax, which will increase the price of the non-sustainable technology. The calculation, assumptions and results are discussed in section 28.

## 2.7 Conclusions from scientific literature research

To summarize, climate change requires renewable energy technologies and (new) energy goals. These goals are driven by agreements and alliances between parties. Within the renewable energy resources especially wind and solar energy are increasing their market share. However, with new renewable technologies will also arise challenges, with intermittency problems as one of the major hurdles. The current scientific research covers the energy transition, new technologies and challenges, but lacks in the field of leveling the intermittency of offshore wind energy for small-scale applications.

Storage can give a solution for this intermittency, whereby hydrogen and battery storage are seen as the major players in the near future according to current research. Combining renewable energy resources with integrated storage systems will improve the feasibility of these technologies and create new opportunities. Therefore, this research focuses on a new technology: internal hydrogen production, storage and reconversion for offshore wind turbines. The higher purpose is to decrease the emissions, the pollution and in order to slow down the climate change. The challenging short-term fluctuations of wind energy supply are leveled with hydrogen storage. This makes higher security of supplies of up to 100% and therefore conversions to a 100% renewable energy supply feasible. Sustainable performances which are not able to achieve with traditional wind turbines. The internal and offshore placement of the hydrogen components makes the technology suitable for locations with area scarcity. An other solution for this intermittency problem is supply-and-demand management, which will level out the fluctuations in electricity. However, this solution still requires a storage solution within the energy grid. The combination of hydrogen storage for short-term balancing in combination with sustainable electricity is the missing link in the energy transition of these remote locations.

To determine the competitiveness, the levelized cost of energy of this technology is calculated. Several approaches to decrease the LCOE and to increase the competitiveness of this internal hydrogen system have been analysed in this section. These will be taken into account when designing the system. Because of the shortcomings of the LCOE, the calculation is complemented with a sustainable comparison for the carbon emissions, whereby the theoretical price of the carbon certificates will be calculated to achieve a financial break-even point. Therefore, a positive sustainable impact will be beneficial for the LCOE competitiveness. This extended LCOE gives a better understanding of the social economic aspects of this technology, whereby not only the financial but also sustainable parameters have a major influence will have on its feasibility. Therefore, LCOE results will be compared with the listed LCOE's of alternative technological solutions for energy generation at remote locations, as discussed in the following sections.

# 3 Analytical framework

In this research, the internal hydrogen production and storage inside the foundation (monopile and transition piece) of an offshore wind turbine will be researched. The analysed concept is shown in figure 1. In this research the LCOE and the sustainable impact, expressed in the reduction of carbon emissions, of this system will be calculated. For this calculation, a base load model and financial (LCOE) model will be used. First, the research design will be discussed in this chapter, then the outline of the two models. Subsequently, the social and environmental effects of the system will be analysed. Lastly, the approach for the extended framework will be analysed.

## 3.1 Research design

This research will focus on the extended LCOE of internal hydrogen production, storage and reconversion for offshore wind turbines at remote locations. An overview of the research method is shown in appendix figure 2. In the first stage, knowledge regarding technologies, available components and electricity data will be gained with the use of literature research, market analysis and input from Van Oord. The market research gives insights into the components, manufacturers and the current state of technology. To determine the selected components a base load calculation model is created. This model calculates the hourly generation of electricity, the status of the hydrogen storage and the total electricity output per wind turbine. To create the LCOE model, input from Van Oord, the base load calculation model and manufacturers of the selected components are combined with the knowledge from literature research. With these models a first LCOE calculation can be made per base load. The results will be compared and in a dialogue with experts and component manufacturers, the output can be validated and optimized regarding future components and financial input parameters. For this iteration different scenarios are selected, based on their output parameters. These specific selected scenarios will be part of sub question 6. With the two models, selected scenarios and a design iteration, the LCOE and sustainable impact will be analysed. For this sustainable impact, the carbon emissions are compared and will be taken into account in the LCOE value by calculating the required carbon certificate price for a break-even point of the energy price.

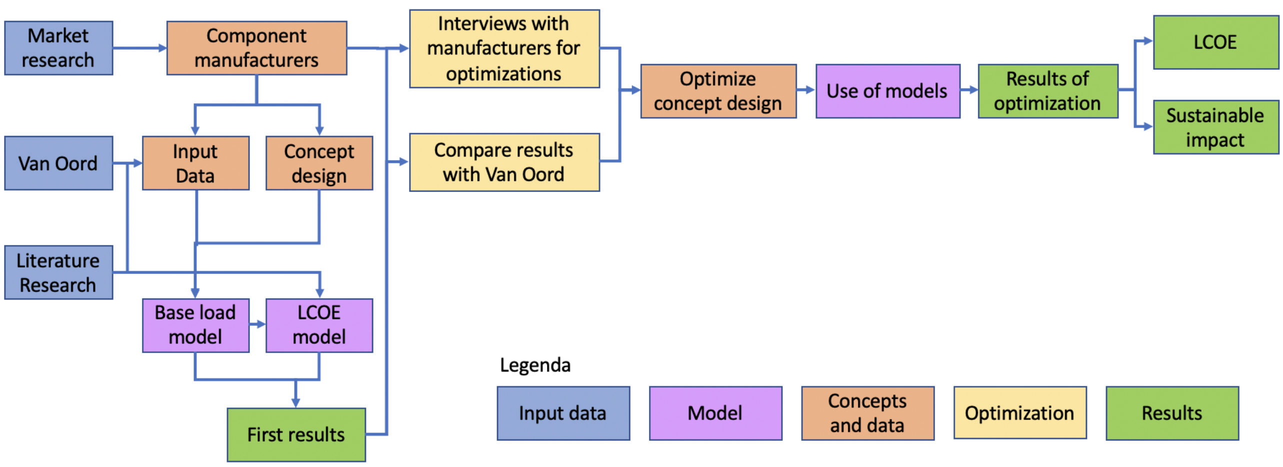



**Figure 2:** Overview of the research method with design iteration.

The research approach for the analysis of internal hydrogen storage for offshore wind turbines consists of the following steps. A visual overview of these steps is given in appendix figure 21.

- Literature research
- Market analysis
- Calculate technical and financial feasibility
- Optimize component layout and setup
- Interviews with third party manufacturers and Van Oord
- Optimize the concept design to improve the KPI's

**Literature research** Scientific literature research will be done on the currently available knowledge regarding the sustainable importance of sustainable energies, challenges induced by sustainable energies, researched technologies for electricity storage, alternative solutions for these challenges, LCOE's of related projects and the opportunities for decreasing the LCOE. This research will dive deeper into the scientific relevance of this technology and its place in the scientific research field. With the LCOE's of the researched projects, the results of this technology can be placed in context and determined on their relevance.

**Market analysis** Besides the scientific research, the market of offshore wind combined with hydrogen will be analysed. This market analysis is done for three reasons: to validate the system with other pilots, to substantiate the location selection and to use as input for the system and component selection. The existing projects will be used as knowledge input for this technology. This is important for the verification of the uniqueness of the system and to gain knowledge on competitive projects. For the test location selection, a detailed political, sustainable and electricity analysis will be done, based on public available information. This selection will be the start of sub question 2; what is the most suitable technological setup? The component selection will be based on the products available in the market. This is because of two reasons: the components require a technological maturity for an offshore application and to be able to validate the technical details for a possible roll-out. Therefore, components, which are still in the development phase, are not suitable for this research and will not be taken into account.

**Base load and LCOE calculation model** To determine the extended LCOE of the system, two models are used. The first model is the base load model. This model uses the hourly wind speed to calculate the electricity production, storage status and total electricity output. The second model is the LCOE model, which uses the output of the base load model and the component selection to calculate the electricity price. With these two models, the sustainable impact can be analysed and the connection and input values of these models will be discussed. The results of the calculation models will be assessed on the following performance parameters, also known as key performance indices (KPI):

- Levelized cost of energy (LCOE), with the underlaying parameters:
  - Costs of the project (CAPEX and OPEX)
  - LCOE for different base load scenarios
  - Investment costs of hydrogen components
  - LCOE comparison with traditional wind turbines
- Sustainable performance; with the parameters:
  - Decrease of carbon footprint
  - Security of supply, which will determine the percentage of sustainable energy production

– Percentage of sustainable energy generated on the selected location
– Financial break-even point with financial structure for $CO_2$, compared to the current system

**Interviews** The first results will be challenged by experts. The vast knowledge of Van Oord, related to offshore development, will be used to eliminate future technological barriers. To validate the used (technological) input data and get feedback from the market, interviews with component manufacturers are included in the research method. This information will be used for the optimization of the component selection, to discuss the feasibility of the technology and the prognoses on these components. During these interviews, the first results of the base load and LCOE calculations are reviewed. The product of these manufacturers will also be challenged for their usability in this system. These interviews have also added value for the component companies: they have the opportunity to discuss the usage of their products with a major player in the offshore market, which might give them new insights for innovation strategies. This technological innovation will be beneficial for all stakeholders and might improve the feasibility of the system. The minutes of each meeting and updated models and information will be shared only with the participants.

**Optimization** As mentioned above, iterations of the LCOE calculation by improving the input data and the size of the selected components will improve the KPI's of this technology. Examples of these KPI's are: LCOE, base load, security of supply, and sustainable impact. With the use of the interviews and input from the engineers, the scenarios and input variables will be adjusted for an improved LCOE and feasibility of the technology (Hou et al., 2017). This optimization is combined with the use of the sensitivity analysis on the different input parameters. This sensitivity analysis is an important factor due to the developing stage of the technology; assumptions are made regarding the input parameters. Hereby, this analysis gives insights into the influence of these parameters on these KPI's.

## 3.2 Base load model

In this section, first, the definition of the base load energy pricing will be discussed and then the base load calculation model will be analysed.

### 3.2.1 Base load electricity pricing

Energy providers can provide two different types of electricity generation: a variable output or a base load electricity. Variable output is a fluctuating electricity generation, often depending on the energy resource. Base load electricity generation needs to meet the set minimal electricity demand at any given time. In fossil fueled energy generation, the energy resource can be varied by the amount of fuel it is consuming. However, renewable energies are depending on their energy resources (wind speed, irradiation, etc). Therefore, a renewable energy generation, without storage, can not provide base load energy: there are instances of zero wind or no irradiation. On the other hand, if there is too much wind, this generated electricity needs to be balanced over the system to prevent damage and outages.

Electricity prices are depending on this supply and demand balance. A higher demand will increase the price of electricity. This fluctuating electricity price is called the market value, with €/MWh as electricity price. A base load energy is more interesting for energy users (consumers & industry) due to the predictability of the energy supply; the minimum power output requirement is always met. This predictability increases the electricity price compared to the fluctuating energy. This is caused by two factors induces by the transmission system operator (TSO): the balancing costs and the profile costs, as seen in appendix figure 23. The "balancing costs" are the costs of the balancing of the system: the distribution of overproduction and increasing the energy supply (supplementing), if the base load is not met. For fossil energies more fuel can be converted and for sustainable energies storage capacities, such as the hydrogen system in this research, can be used. The "profile costs" are the costs induced to counteract these fluctuations in power generation, for example, backup storage (Matek & Gawell, 2015). Appendix figure 23 also shows the increase in electricity price when supplying base load. This will offset the higher initial investment cost and higher operational and maintenance costs for the hydrogen wind turbine, compared to a conventional offshore wind turbine system. In this research, the base load pricing for the hydrogen system for offshore wind will be analysed, whereby the market value pricing will be compared. However, due to the single energy provider at Grenada, there is not a real fluctuating market electricity price, as would be the case in a matured energy grid.

### 3.2.2 Base load calculation model

To calculate the required storage volume, the energy mismatch of supply and demand for Grenada is calculated with the base load model. The following states of supply and demand (mis)match for the hydrogen storage system are:

| **Electricity generation compared to the base load** | **State of hydrogen storage** | **Conditions of change of state** |
|---|---|---|
| Electricity generation = base load | No change in state of hydrogen storage | - |
| Electricity generation < base load | Hydrogen is used for supplementing electricity supply | If there is hydrogen available |
| Electricity generation > base load | Overproduction is used for production of hydrogen | Only if there is storage volume available |

**Table 3:** States, used in the base load model, of mis(match) in supply and demand power generation.

The model uses the hourly wind speed, at the selected location, as input. This is converted with the wind turbine power curve to calculate the electricity generation. According to the electricity supply and the selected base load, the system will be in one of the three states. If the electricity generation of the wind turbine can provide the required base load, the electricity is always directly transported to shore, instead of converted to hydrogen. Otherwise, the amount of electricity will decrease due to the conversion efficiencies. If the electricity generation is lower than the required base load, the stored hydrogen is reconverted and will supplement the electricity generated by the wind turbine to meet the base load requirement. If the electricity generation is higher than the base load, the overproduction of electricity is converted into hydrogen and stored in the storage tank. For the third state, storage volume is required. If there is no storage volume available, the electricity is not converted into hydrogen and the wind turbine is stopped, which is called curtailment.

During the year, there can be instances where the base load is higher than the electricity production combined with the stored energy, in the form of hydrogen. During these instances, there is a shortage of supply. Depending on the selected base load, storage volume and hydrogen components, the annual frequency of these shortages changes. Security of supply (SoS) is the inverse of the shortage of supply. Both are expressed in the percentage of hours, over a year, during which the supply is not met. There are three SoS which will be analysed: the 100%, the 80% and the optimum between base load versus SoS. The 100% will always supply the required base load, which is important if there is no redundancy in the system. However, the LCOE will be higher as a result of the higher initial investments or lower power output. Therefore, the 80% SoS will probably be a more viable option, which will be a balance between a reliable SoS and lower LCOE. The last setup is focused on the combination between a high base load and high SoS. To determine the selected input values, a first concept design will be calculated, after which the optimized scenarios will be analysed.

Within this base load calculation, there are three input parameters added for a realistic analysis. The first two are the ramp-up and ramp-down values for the fuel cell and electrolyzer. These values will be used in the selection criteria. The last value is the status of the storage tank at the start of the year. Before the first operational year, the system is tested extensively. During these tests, the storage tank will be filled to 100%. Therefore, for this calculation the tank will start completely filled. This will be seen in the results, such as figure 7.1. However, the capacity at the end of the year can be lower than 100%. This is not taken into account, which might change the results of this LCOE analysis slightly. In reality, the storage tank will be filled with the overproduced electricity which is not used in this research or can be refilled during outages and maintenance. Both situations will counteract this assumption and are therefore recommended as a topic for future analysis.

## 3.3 Levelized cost of energy model

The second model calculates the LCOE of the internal hydrogen production, storage and reconversion for offshore wind turbines. The input of the calculation depends on the input from the selected (remote) location and therefore the base load calculation. The focus of this research will be on remote locations without a mature grid-connection. These locations often use non-sustainable energy resources with high energy prices. Grenada is selected as the test location. The decision to test at this remote location is induced by the high electricity prices, their sustainable goals regarding the transition to a more sustainable generated base load, the potential for sustainable resources and the suitable weather conditions for wind energy. Due to these conditions, a potential relative high LCOE, compared to onshore energy prices, can still be financial competitive. In future feasibility analysis for new locations, the results of this test location can be used for dedicated LCOE calculations, a more optimized design and development of the technology.

### 3.3.1 Concept of the levelized cost of energy

To determine the financial competitiveness of the hydrogen storage technology, the LCOE will be calculated. The LCOE is a powerful comparative measurement between technologies and projects. However, the input variables and calculation need to be consistent throughout the different projects to be comparable. The advantage of the LCOE, compared, for example, to the return on investment (ROI), is the lower influence of company values in the output value. This makes the LCOE a more scientific foundation for an electricity price comparison and less dependent on the company requirements. The LCOE method is also used to calculate price-based support instruments, such as premiums, feed-in tariffs, contracts and green certificates (Badouard, Moreira de Oliveira, Yearwood, Torres & Altmann, 2020). This property will be used for the carbon certificate calculation in this research. Besides the advantages, there are some considerations that need to be taken into account when comparing technologies with the LCOE. First, a consistent approach needs to be used throughout the projects. Using different calculation methods or input variables, company or technology related, can have large impact on the LCOE value. Therefore, a sensitivity analysis will be performed on these input variables.

The LCOE uses input variables such as capital costs, operating costs, decommissioning costs and financing parameters. The general definition of the LCOE is given in formula 1. Hereby the $I_t$ are the investment costs, including financing. The $M_t$ are the operating and maintenance expenditure, $F_t$ are the fuel costs. $E_t$ is the electricity generation, r the discount rate and n the lifetime of the system. All these variables are summed over the number of years (n), whereby t is the year (Awalom, Tesfa, Kidane, Ghebremedhin & Teklesenbet, 2015).

$$LCOE = \frac{Sum\ of\ cost\ over\ lifetime}{Produced\ energy\ over\ lifetime} = \frac{\sum_{t=1}^{n} \frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{1}$$

### 3.3.2 Selected LCOE method

For this research, the Department for business, Energy and Industrial Strategy (BEIS) method will be used. This method originates from the UK governmental Department of Business and was first used by the Department Energy and Climate change (DECC) in 2016 (BEIS, 2016). This method accounts for the discounted costs over the lifetime (installation, ownership, generation and decommissioning) of a project. The BEIS method divides the discounted sum of costs by the discounted sum of energy generated, which can be defined as the net present energy (NPE) (Myers & Ridge, 2008). By definition the following formulas are used:

$$NPV_{project} = NPV_{revenues} - NPV_{costs} = 0 \tag{2}$$

$$LCOE = \frac{NPV_{revenue}}{NPE} \tag{3}$$

The formula used for this BEIS method is:

$$LCOE_{BEIS} = \frac{NPV_{costs}}{NPE} = \frac{\sum_{t=1}^{n} \frac{C_t+O_t+V_t}{(1+d)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+d)^t}} \tag{4}$$

To answer sub research question 3, the selected LCOE calculation method will be analysed. In this research, the BEIS method will be used. There are several other variations on the LCOE calculation. One of these variations is the Department of Energy's National Renewable Energy Laboratory (NREL) method (Aldersey-Williams & Rubert, 2019). Both methods show the minimum price at which the energy needs to be sold to be break-even between the expenses and energy generated. The difference between the methods is the varying output value. The BEIS method gives a value over the total lifetime of the project as output, whereas the NREL method calculates an energy price per year (Aldersey-Williams & Rubert, 2019). More details on this NREL method and the differences between these two methods are discussed in appendix A.2.1. Because of the uncertainties of the annual fluctuations and therefore mainly an interest in the average electricity, the BEIS method is selected. If more information was available on electricity and technological prognoses, the LCOE might have been optimized with a different LCOE method.

## 3.4 Social and environmental effects of internal hydrogen storage for offshore wind turbines at remote locations

Besides the financial incentive of renewable energy resources, there are multiple social and environmental benefits of this energy transition at remote locations (Renewable & Agency, 2016). These effects are divided into three topics: electricity generation, electricity availability and environmental effects.

The first and maybe most important argument for the installation of this system at a remote island is the availability of renewable energy. This availability make islands less depending on fossil fuels from shore or other islands. The transportation of resources can be hindered due to bad weather, low supply at the supplier and political reasons. To be independent of external energy providers, an alternative electricity generator needs to have a high security of supply. However, renewable energy resources have a relatively low security of supply due to the fluctuations in renewable resources (wind, irradiation, etc.). By adding storage to the system, the security of supply can be increased, especially when currently existing diesel generators are used as backup system. However, the operational and maintenance costs of these diesel generators will be much higher due to the lower total number of running hours over a year. Thus, diversifying the energy generation mix will counteract these sustainable fluctuations and will increase the security of supply and protect the electricity sector from oil price volatility and scarcity. A larger energy generation will increase the importance of energy balancing, but will also give more people excess to (sustainable) electricity, which improves the quality of life, education, health, comfort, protection, entertainment and productivity (Stenhouse, Hanania & Donev, 2018).

With the transition to sustainable energies, a decrease in electricity price could be realised in the future. The installation of offshore wind turbines will give new opportunities in the energy market. The influence of the (privatised) electricity company at these locations is high. Often there is only one supplier of electricity, which results in little force of a free market. This is because there are no competitors in the energy market who will lower the energy price. An example of the lack of free market for Grenada is visible in the realisation rate of sustainable projects; legal actions were required to change the company's vision and goals to a more sustainable future. These sustainable alternatives create opportunities in two ways: current energy providers will lower their prices because of the lower LCOE of these renewable energy resources. If not, new competitors will enter the market, which will lower the electricity price due to the free market. A lower energy price will also create additional business opportunities (Bulbaai, 2019). For example, low energy prices create new opportunities for (micro) businesses due to lower overhead costs. The energy price of the current wind turbine with hydrogen system will probably be higher than the current energy price. However, this can shift in the future due to rapid technological development of the technology. Furthermore, the current electricity price in remote locations is fluctuating, as seen in appendix figure 62, which makes the future prices uncertain. Delivery of a constant electricity price, with the use of wind turbines, will be beneficial for consumers. All these factors will support the island's economic growth.

The third aspect of this technology is the environmental impact of this transition. This aspect will answer sub question 5. By implementing sustainable resources, less fossil fuels will be used. This will lower the greenhouse gas emissions, especially the carbon footprint. Besides the emissions, the turbine foundations will also have a positive impact on the marine life and biomass, by creating a save environment. However, there are also disadvantages with the installation of wind turbines. Marine birds are vulnerable to collisions with (offshore) wind turbines (Kelsey, Felis, Czapanskiy, Pereksta & Adams, 2018). Especially on locations where birds gather for the breeding season, this will have a large impact. A second disadvantage is the noise pollution. This type of pollution is the reason for relocation of wind turbines to offshore locations, because of human criticism, but will not decrease the effects on marine life. The noise pollution is not only present when the wind turbines are installed, but also when the turbine is operational. During operation, wind turbines produce low frequency noises, which interfere with the communication of marine life (Tougaard, Hermannsen & Madsen, 2020). Besides noise pollution, wind turbines also create view pollution, which is, of course, a subjective issue. Grenada's economy, and most other islands in the Caribbean, are depending on tourism. Large wind turbine farms, even offshore, can cause a decline in tourism, which will negatively affect the islands economy (AGI, 2019).

The disadvantage characteristics of SIDS islands make these locations sensitive to changes. Factors like small population size, isolation from international markets, high import costs for fuel and goods with a narrow resource base, vulnerability to exogenous economic shocks and fragile land and marine ecosystems make SIDS particularly vulnerable to biodiversity loss and climate change due to the lack of economic alternatives. (United Nations, 2021). However, as discussed, these characteristics can also be used in their advantage for the development of new technologies. Examples are; the remote location makes it difficult for new electricity suppliers to enter the market, which results in less competition. High import costs results in early grid parity and the vulnerability regarding changes in the climate will increase the incentive for the development of sustainable technologies. Therefore, the adaptation of these islands is relatively high. An extended analysis on the specific advantageous characteristics of Grenada will be conducted in this research.

## 3.5 Extended framework

As described by the main research question, the research is about the extended LCOE of this internal hydrogen production and storage system for offshore wind turbines. A conventional LCOE calculation indicates the price of electricity and makes comparison of energy generation technologies possible. However, due to emission restrictions and energy goals, a low energy price is not enough. Countries need to apply to regulations regarding emissions and pollution. This makes the sustainable impact, besides the energy price, an important output parameter. The extended part of this LCOE calculation is therefore a sustainability analysis in which the current carbon emissions of diesel generated electricity will be compared with the situation with a hydrogen storage wind turbine system and the traditional wind turbine system. In this comparison, the security of supply and therefore the potential added usage of the current diesel generators will be taken into account to provide the annual electricity requirement.

The current electricity is produced with the use of diesel generators. Diesel, transported from shore to the island, is used as fuel for these diesel generators. With the combustion of diesel carbon dioxide ($CO_2$), nitrogen oxide ($NO_x$) and particular matter is emitted. Because of the environmental impact of $CO_2$, this research focuses on the production and potential reduction of $CO_2$. The extension of this LCOE calculation is the sustainable impact of the replacement of diesel generators for this hydrogen wind turbine system. Section 7.4 will discuss the calculation and results for this carbon emission comparison between the current diesel generated electricity generation, traditional wind turbines and wind turbines including this hydrogen system.

With these carbon emissions, the financial break-even point of the technology can be calculated. Emissions also embody social costs which are not taken into account with only a LCOE comparison. Therefore, the difference in carbon emission needs to be taken into account when comparing the values. To determine the increase in social welfare, the price of $CO_2$ certificates are taken into account in the LCOE comparison. There are several financial structures which can be used to allocate the sustainable costs into the electricity price or to increase the sustainable incentive, for example; carbon certificates, carbon allowances and subsidies. These can be permitted for free by ”grandfathering” or auctioned. These trading structures and allocations of sustainable permits are analysed in more detail. However, in this research, the operation of these trading schemes is not taken into account. However, the price per tonnes kg of carbon emissions for a break-even point with the current electricity generation is calculated. The results and assumptions of this comparison will be discussed in further detail.

# 4 Components for the internal hydrogen production and storage system

As discussed in the introduction; the balancing of energy generation from renewable resources is important for the energy transition and decarbonisation. Internal storage of hydrogen inside the transition piece (TP) of an offshore wind turbine has the potential to increase the ability to balance the electricity generation. Figure 3 gives an overview of the energy flows between the different components of this researched system. The wind turbine converts wind energy into electricity with the use of a generator. If this electricity exceeds the energy demand, the overproduction is used to produce hydrogen. In this research, the electricity supply will be set as a fixed power output: the base load. For this hydrogen production, a desalinator and electrolyzer are required. The desalinator converts seawater into fresh water and the electrolyzer uses this water to create hydrogen. This hydrogen is compressed and stored in a storage tank. If the electricity production of the wind turbine is lower than the demand, the stored hydrogen is reconverted into electricity with the use of a fuel cell. In this section, the components required for this hydrogen system will be discussed. With these components, a technological setup will be designed, depending on the input variables. This setup will give an answer to sub-question 2. First, the foundation of the wind turbine will be analysed, secondly, the different components, after which the products per component will be selected with input and validation from experts and manufacturers.

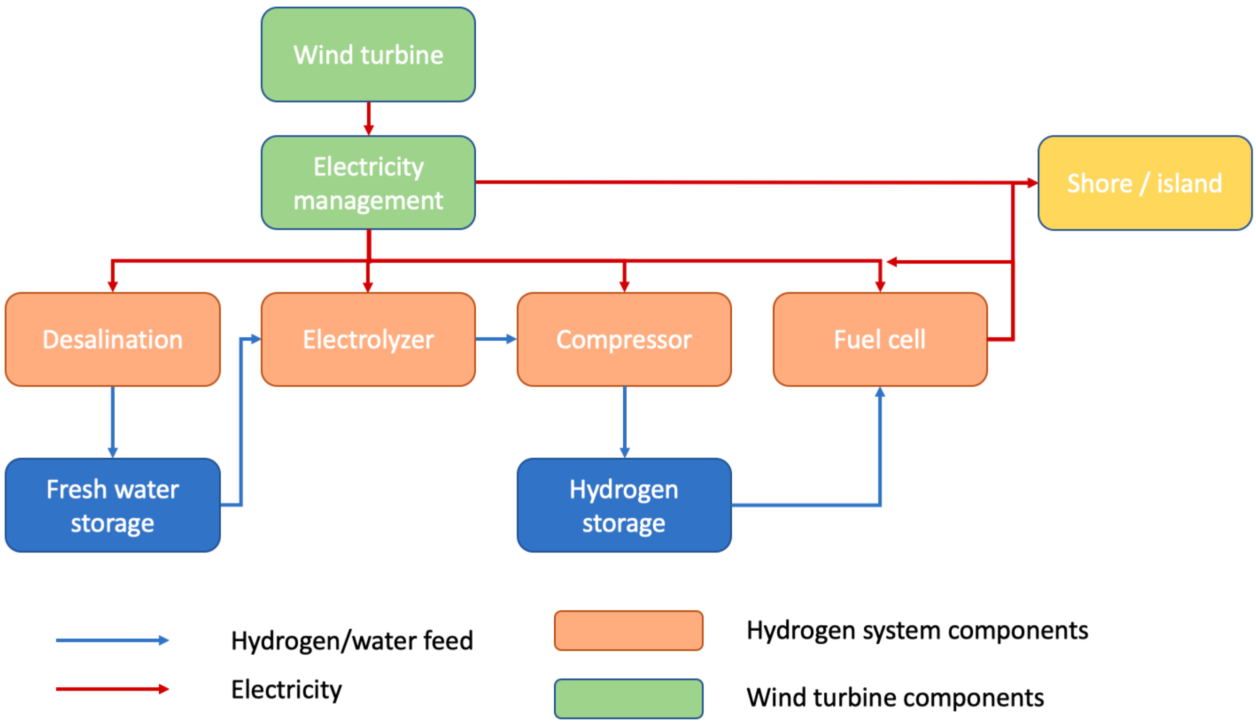



**Figure 3:** Schematic system overview with the different energy/feed flows within the system.

## 4.1 Foundation and transition piece of an offshore wind turbine

An offshore wind turbine consists of several components: the foundation with the monopile and the transition piece (TP), as seen in figure 4, the tower and the blades, rotor and nacelle (Jaax, 2016). In this research, the opportunities for hydrogen production, storage and reconversion, within the available space of the monopile and TP, will be discussed.

The monopile is the foundation of the offshore wind turbine and contains the connection with the electricity cable. This cable, which lays on the seabed, transports the electricity to shore or substation. In this hydrogen system, the monopile will also be used for (hydrogen) storage. On top of the monopile and between the tower and the monopile is the transition piece (TP). The TP includes various functions: access for maintenance, the cable connection for the wind turbine and the corrosion protection for the entire foundation (Gemini, 2021). The TP consists of the following components: the steel outside tube, which encases the monopile, the J-tube for the power cable connection and the boat landing and work platform for the maintenance access (Van Oord, 2021). In this system, the hydrogen components; desalination system, electrolyzer, compressor and fuel cell, will be located in the TP. This is due to the sensitivity of these components and the damage which can occur during the pile drive installation. During this installation, the monopile is hammered into the seabed, which induces large forces on the construction. The top of the monopile is below sea level which makes the watertightness of the (hydrogen) storage tank before the installation important. Also, the connection between the tank and the other components needs to be designed accordingly. The second option, of using the volume of the tower for equipment and storage space, is not used in this research. The reason for this decision is the ownership of these components. Van Oord is responsible for the installation of the monopile and the TP. The wind turbine company installs the tower and wind turbine installation (rotor, blades and nacelle), which makes the installation of equipment inside the tower, installed and owned by a second party, more complex (Van Oord, 2021). The second reason for this decision is the increased difficulty of installation and maintenance of components high above sea level. Larger crane vessels will be required if the components are located high in the tower. This will increase the OPEX costs, which will have a negative influence on the energy price.

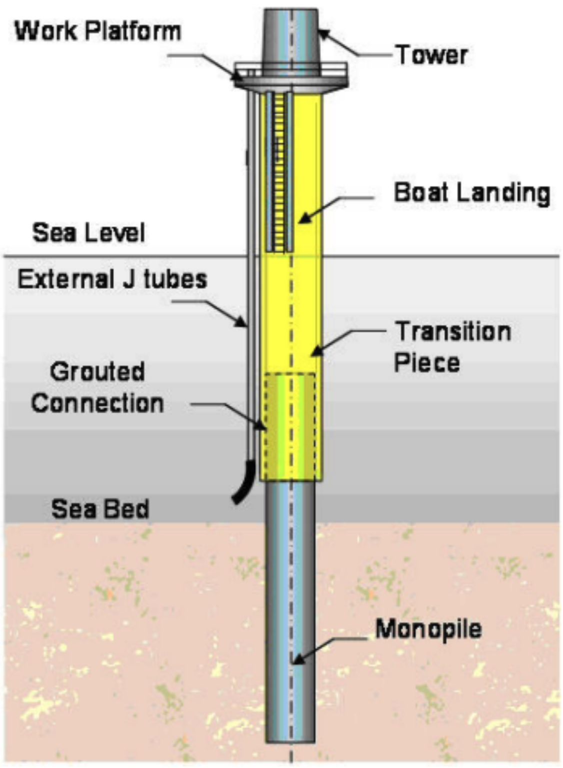



**Figure 4:** Overview of the foundation of an offshore wind turbine, with monopile, transition piece and tower (Tomlinson, 2012).

## 4.2 Technology selection for hydrogen production, storage and reconversion

This section will discuss the technologies available for the required hydrogen production, storage and reconversion components of this system. Subsequently, the required technologies are selected. The system consists of the following components, whereby each of the components depends on each others input/output. The components which will be discussed are listed in order of use during the production, storage and reconversion of the technology.

1. Desalinator
2. Electrolyzer
3. Compressor
4. Storage
5. Fuel cell

### 4.2.1 Desalination

For the production of hydrogen in an electrolyzer, as discussed in 4.2.2, clean and fresh water is required. Seawater consists of a large composition of elements. These elements can cause contamination, damage to the equipment or undesirable electrochemical byproducts (Heather, Peter H & Gary, 2006). Some research has been conducted on using seawater for hydrogen production, without desalination of this seawater, but this technology is in a very early stage and it is not suitable for larger offshore applications with high maintenance and operation constraints (D'Amore-Domenech, Santiago & Leo, 2020). Furthermore, there are studies on crystallization, solvent extraction and ion-exchange as desalination methods. However, these technologies are still in the R&D phase or not suitable for offshore use (He, Li & Gu, 2010)(Cheboxarov, Yakimovich, Abd Ali & Al-Rufee, 2019). Therefore, these technologies will not be used in this comparison.

There are various methods to make fresh water from seawater in an offshore industrial application. Each of these methods have their own advantages and disadvantages (Curto et al., 2021). Depending on the other components in the system and the design constrains, a specific type can be selected. Desalination can be divided into two sections, with variations on each of these desalination methods:

- Membrane desalination
  - Electrodialysis (ED)
  - Reverse osmosis (RO)
- Thermal desalination
  - Multi-stage flash distillation (MSF)
  - Multi effect distillation (MED)
  - Vapour compression distillation (VC)

**Membrane desalination** In a membrane desalination, the salt water is forced through a membrane, the salt molecules are blocked and clean water will exit the desalinator. There are two types of membrane desalinators: the electrodialysis (ED) and the reverse osmosis technology (RO). Electrodialysis uses an electric current to move the salt ions through the membrane. The remainder is clean drinking water. This type of desalination is mainly used with low salt-concentration water (brackish water) and is not able to clean pure salt water.

Because of the much higher salt-concentration of sea water, this type of desalination is not suitable for offshore hydrogen production. The second type is the reverse osmosis process. This process forces salt water through a semi-permeable membrane, whereby the salt ions are blocked and fresh water will exit the system. The advantage of this technology is that it does not require heating or a phase change of water. This decreases the energy consumption, compared to the thermal desalination method, which increases the overall efficiency of the system. The major energy consumption of the membrane technology is used by pressurising the feed water.

**Thermal desalination** The second type of desalination uses heat to separate the salt ions. Seawater is heated to its boiling point, which changes the phase to a gas. This gas is captured and condensed as fresh water. When the seawater heated, a scale will form in the piping, which decreases the efficiency. This scaling can be reduced by coatings in the pipelines, which on the other hand increases the investment costs. The first thermal desalination type is the multi-stage flash distillation. In this technology, the seawater is pressurised and heated to a near boiling point in multiple stages. The second type is the multi-effect distillation. Seawater is heated in several stages, whereby the steam flows into the next stage. This type has the advantage of reusing the heat from the previous stage. Two types of thermal desalination; MSF and MED, are mainly used in large volume applications. Depending on the layout and scale of the internal hydrogen production system, these types might be interesting. The third type of thermal desalination is the vapour compression (VC) distillation technology. Seawater is heated with the heat from the compression. This type of thermal desalination is mainly used for smaller applications, compared to the MSF and MED types.

**Comparison of desalination technologies** The different types of desalination technologies are compared in table 4. The technologies are compared on required energy, emissions, the ability of handling sea water and the costs of the produced water. Appendix table 33 gives the explanation of this data and the related input values (Youssef et al., 2014) (Shahzad et al., 2019) (Curto et al., 2021).

| **Desalination method** | | **Membrane desalination** | | | | **Thermal desalination** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Technology | | Electro-dialysis | | Reverse Osmosis | | Multi-stage flash | | Multi effect | | Vapour Compression | |
| Required energy | $\frac{kWh}{m^3}$ | <5 | ++ | 5-8 | + | >15 | - - | >15 | - - | 8-15 | - |
| Emissions | $\frac{kg}{m^3}$ | 2-5 | + | 2-5 | + | 5-10 | - | 5-10 | - | 5-10 | - |
| Handling sea water | ppm | <10E3 | - - | >70E3 | + | >70E3 | ++ | 35-70E3 | + | 35-70E3 | + |
| Water production costs | $\frac{\$}{m^3}$ | 0.5-1.0 | + | 0.5-1.0 | + | 0.5-1.0 | + | 0.5-1.0 | + | 0.5-1.0 | + |
| Total | | | 2 | | 4 | | 0 | | -1 | | 0 |

**Table 4:** Comparison overview of different desalination technologies (Youssef et al., 2014) (Curto et al., 2021) (Shahzad et al., 2019) (Kim et al., 2016)

As seen in table 4, the reverse osmosis technology is the most suitable for the internal hydrogen production system due to its capability of handling salt water (up to 45000 ppm) and relative low energy requirement and emissions. The RO technology is commonly used for small applications which makes it suitable for use inside the TP. The electrodialysis technology is a good alternative, with a lower energy requirement compared to the RO, if the system is located on locations with low salt concentration in the water (brackish water) or fresh water locations, such as lakes. In conclusion, the best desalination system for this internal hydrogen system is the reverse osmosis technology. In section 4.3, the specific manufacturers and products will be compared.

An important note on the production is the outflow of salt from the desalinator. When producing fresh water by desalination, the outflow of salt is dumped into the sea. This outflow is discharged outside of the foundation to minimize the corrosion effects of the high salt concentration on the foundation. This increases the salt concentration around the wind turbine foundation, which decreases the efficiency due to the higher salt concentration in the feed flow. Mixing this water by, for example, currents will restore the salt concentration and is one of the advantages of offshore locations instead of fresh water locations. Higher salt concentration can be harmful for marine life and can cause corrosion on offshore installations (Dols, 2019). Therefore, it needs to be taken into account when selecting suitable locations. Because of the offshore nature of Grenada, this problem is assumed as negligible in this research.

#### 4.2.2 Electrolyzer

The second component in the system is the electrolyzer. In the electrolyzer the water molecules are split into oxygen and hydrogen. In this section, the different electrolyzer technologies will be discussed and compared on their advantages and disadvantages. Hydrogen is required for the storage of energy. This hydrogen can be produced with multiple technologies and processes, as seen in figure 25 below. Currently, up to 96% of the hydrogen production uses fossil fuels as a resource, by which steam reforming and hydrogen from methane, which both use fossil fuels, are the most used conversion processes (Shiva Kumar & Himabindu, 2019). Due to the sustainable angle of the system, this research will only focus on renewable energy resources and conversion methods. As seen in appendix figure 25, this results in two options: hydrogen from biomass and water splitting. The offshore wind energy creates the opportunity to use sustainable generated electricity for the electrolysis water splitting process, which excludes the thermolysis and photolysis process. However, these technologies are recommended for future researches on the combination of processes in this system. There are three established electrolysis water splitting processes available: Alkaline, proton exchange membrane (PEM) and solid oxide. In this section, the different processes will be discussed and compared on their advantages and disadvantages. The electrolyzer will use the largest part of the energy in the system, which makes an optimized selection important for the efficiency and LCOE of the system (Steilen & Jörissen, 2015). Figure 5 gives an overview of the advantages and disadvantages of each of these three technologies.

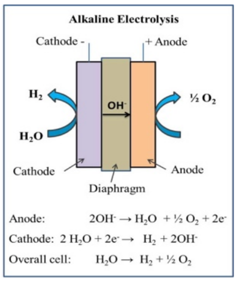
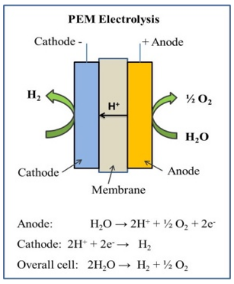
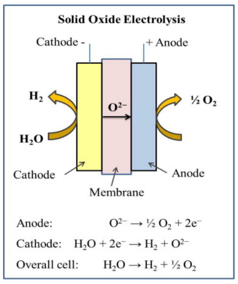
<table>
<tr><th></th><th>Alkaline</th><th>PEM</th><th>Solid oxide</th></tr>
<tr><td>Electrolysis</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Efficiency</td><td>70-80%</td><td>80-90%</td><td>90-100%</td></tr>
<tr><td>Temperature</td><td>30-80 ˚C</td><td>20-80 ˚C</td><td>500-850 ˚C</td></tr>
<tr><td>Advantages</td><td>+ Established technology<br>+ Commercialized<br>+ Low operating temperature<br>+ Non-noble electro catalyst<br>+ Low cost</td><td>+ Lower gas permeability<br>+ High energy efficiency (80-90%)<br>+ High proton conductivity<br>+ Low operating temperature<br>+ Lower thickness<br>+ High operating pressure<br>+ High purity hydrogen (99,99%)<br>+ Compact design, small footprint<br>+ High current density (2 A/cm2)<br>+ Fast response<br>+ Ease of balancing</td><td>+ Very high efficiency (90-100%)<br>+ Non-noble electro catalysts<br>+ High working pressure<br>+ High purity hydrogen</td></tr>
<tr><td>Disadvantages</td><td>– Relative low energy efficiency (70-80%)<br>– Low current density (400 mA/cm$^2$)<br>– Low operating pressure<br>– Formation of carbonates (on electrodes)<br>– Low purity of gases<br>– Low operational pressure (3-30 bar)<br>– Low dynamic operation</td><td>– More expensive than Alkaline<br>– Noble materials are required</td><td>– Laboratory stage<br>– High operating temperature<br>– Large system design<br>– Low durability (stability and degradation)<br>– High costs</td></tr>
</table>

**Figure 5:** Overview of three electrolyzer technologies (Pitschak & Mergel, 2016)(Dincer et al., 2018)(Shiva Kumar & Himabindu, 2019)(Akinyele et al., 2020)(ABN AMRO, 2021)

The alkaline electrolyzer is the most established electrolyzer technology. Due to its low operating temperature, commercialized application and low cost, this technology is suitable for remote offshore applications. The downside of this type of electrolyzer is the relative low performance (efficiency and current density), compared to the PEM and solid oxide. Due to the large energy demand of the electrolyzer within this overall internal hydrogen system, the efficiency of the electrolyzer is an important factor for the overall efficiency of the system, especially because this efficiency is directly related to the sustainable impact and the LCOE of the system. A second disadvantage of the alkaline electrolyzer is the low purity of the created hydrogen. This lower purity can induce problems in the component selection for the storage and fuel cell, because higher purity is required, and can create contamination in the system. Despite the low energy efficiency and low gas purity, the alkaline electrolyzer will be used in the electrolyzer comparison due to its established technology and low cost (Shiva Kumar & Himabindu, 2019) (ABN AMRO, 2021).

The second type of electrolyzer is the proton exchange membrane, abbreviated PEM. This technology has a better performance, compared to the alkaline technology, which results in higher efficiencies, fast dynamic response and a compact design. This dynamic response is important when there are large changes in the required output of the electrolyzer and gives the opportunity for 15-minute optimization, instead of day-to-day forecasting. The disadvantage of this higher performance is that the PEM technology is more expensive and uses noble materials. However, the higher capital costs are expected to be counteracted during the lifespan of the wind turbine due to the increased efficiency. This is why the PEM technology will be used in the component selection comparison (Dincer et al., 2018) (Shiva Kumar & Himabindu, 2019) (ABN AMRO, 2021).

The third option is the solid oxide electrolyzer. Compared to the alkaline and PEM, this technology has an even higher efficiency, working pressure and purity of the produced hydrogen. However, due to the laboratory stage, large system volume and higher costs, it is currently not expected to be feasible in this internal offshore system. It is recommended to explore the opportunities of this technology in future comparisons, when the technology is more matured, reliability is proven and capital costs are lowered (ABN AMRO, 2021).

In conclusion, although the solid oxide electrolyzer has the highest efficiency, it is also the least matured technology and less reliable, from the three. Offshore maintenance is costly due to required equipment and expertise. Therefore, only the alkaline and PEM electrolyzer technologies will be used in the product comparison in section 4.3.3. According to this comparison the most suitable technology will be selected.

### 4.2.3 Storage of hydrogen

Storage of energy is important for the security of supply, due to the current usage of electricity. The society is accustomed to the fact that there is always a sufficient supply of energy, because electricity produced with non-sustainable energy resources can easily be stored, for example, oil in barrels or coal in bulk storage. The fluctuations in supply and demand can be covered by using more or less energy from this stored energy. However, the storage of renewable energies introduces new challenges. High energy losses, when storing electrons, create the need for new technologies. The future of energy use will change in two ways: sustainable energy resources will advance to adjust for supply and demand fluctuations and consumers will change their energy demand (Ghasemian et al., 2020). Consumers will increase their demand if there is more energy available; during higher wind speeds and increased irradiation. This will result in the so-called smart grids, for example, your fridge will cool during high energy production (and low energy prices). This supply and demand management will decrease the fluctuations between the supply of energy and the usage of the consumers and will decrease the storage requirements (Lazarou & Makridis, 2017).

Currently, offshore wind produced electricity is directly transported to shore where it needs to be consumed instantaneously. A mismatch in energy supply and demand can cause breakouts, instabilities in frequency or damage to the energy system (Giraldo, Cardenas & Quijano, 2014). Storing large amounts of energy induces high energy losses and requires large storage volumes. One of the future large storage solutions will be hydrogen storage in empty gas or salt fields at the seabed. This type will be used mainly for long time (seasonal) storage. The solution which will be discussed in this research is using the internal volume of a monopile for short time storage, which makes outputting base load power possible. The foundation size limits the system in storage volume and available products.

Energy can be stored in several ways: mechanical, thermal, electro-chemical, chemical and electrical. Each of these technologies have their pro's and cons, such as power output, efficiency, suitability for offshore application and durability (A.M. Othman, 2017). This research will focus on hydrogen and conversion products of hydrogen. The reasons for the selection of hydrogen, instead of other energy carriers, are the energy which can be stored, the sustainable aspect and the future proofing of a location by using hydrogen as an intermediate storage solution. If there is more demand, the reconversion of this system can be eliminated and hydrogen can be supplied to the location. Other technologies are out of the scope of this research, but are recommended for future research, because these technologies may have the ability to improve the system if they are further developed.

To store hydrogen from wind energy, several techniques are available. A visual overview of these technologies is given in appendix figure 26 (Andersson & Grönkvist, 2019)(Wolf, 2015). Each of these techniques will be discussed in the following paragraphs and validated on their feasibility within this system.

- Compression
- Liquefaction
- Adsorption
- Metal hydrides
- Chemical hydrides

**Compression** Compression of hydrogen will increase the stored energy per volume. This pressurized hydrogen, viable up to 700 bar, will be stored inside a tank. The advantage of compression, compared to other techniques, is the lack of extra steps or added components. On the other hand, compression of hydrogen is very expensive and only practical for smaller scale (short term) systems. The energy density is also relatively low compared to other methods, as seen in appendix figure 26. Compression is also required for the transportation of hydrogen, however with lower compression rates. Due to the reconversion of the hydrogen into electricity, this is out of the scope of this research, but can be used in future applications with centralized fuel cell systems. This can have a positive impact on the system efficiencies if the hydrogen can be used at shore.

**Liquefaction** Liquefaction is the process of cooling a gas below its boiling temperature. For hydrogen the boiling temperature is -253°C, which requires a lot of energy to cool the gas. Therefore, the storage tank needs to be well insulated, otherwise the hydrogen will undergo a phase change from liquid to gas. The advantage of liquefaction is the higher volume density of 70 $\frac{kg}{m^3}$, which makes storage of large energy volumes possible. An additional advantage is that no energy is required to reuse the energy (Andersson & Grönkvist, 2019)(Franco et al., 2021). Liquefaction is considered too expensive for this researched hydrogen system and will be out of the scope. However, new technologies, which are more efficient, can make liquefaction suitable for future systems.

**Adsorption** Adsorption is the bonding of hydrogen to a material with a large specific surface area. For this process, a high pressure and low temperature is required. The advantage of using adsorption for hydrogen storage is the efficiency and higher energy storage compared to compression. The disadvantage is that adsorption is an exothermic reaction, whereby a lot of heat is released. This requires cooling (below -196 °C) during the adsorption process, which is usually done with liquid nitrogen. For 1 kg of hydrogen 10 kg of liquid nitrogen is required (Andersson & Grönkvist, 2019). The ratio of nitrogen for 1 kg of hydrogen and the volume required for this nitrogen system makes adsorption not suitable for this internal hydrogen system.

**Metal hydrides** The fourth process which is analysed, is the use of metal hydrides for hydrogen storage. In this process, metal additives are bond to the hydrogen atoms. This creates a stronger bond, compared to adsorption, which allows hydrogen to be stored at a higher density even at ambient conditions. Metal additives which can be used in this bond are: magnesium hydride ($MgH_2$), aluminum hydride ($AlH_3$), intermetallic hydride ($AB_2$), sodium tetrahydridoalanate ($NaAlH_4$), lithium borohydride with magnesium hydride ($LiBH_4$ - $MgH_4$), sodium borohydride ($NaBH_4$), lithium amide with magnesium hydride (2 $LiNH_2$ -

$MgH_2$). The disadvantage of this process is the energy which is required to release the bond between the hydrogen and the metal additives. Releasing this hydrogen (dehydrogenation) can be realised by using one of the following methods: heating (thermolysis) and by reacting (hydrolysis) (Andersson & Grönkvist, 2019). An other disadvantage is the requirement of these additives, which can also cause environmental damage. These disadvantages make metal hydrides not suitable for this hydrogen system.

**Chemical hydrides** The last hydrogen storage method is the use of chemical hydrides. This method is similar to the metal hydride method, but uses usually liquids. This makes it easier to store the hydrogen, compared to the metal hydrides. The two most used chemicals for this process are methanol and ammonia. The advantage of these liquids is that they are stable fluids, easy to store & transport and can be used directly, without reconverting into hydrogen. The added advantages of methanol are the total dehydrogenating; all the $H_2$ can be recovered. Specific methanol engines, combustion and fuel cell types, will increase the storage efficiency. A disadvantage is the requirement of $CO_2$, which needs to be captured. Ammonia has as disadvantage that it requires $N_2$ for the conversion from hydrogen to ammonia. However, the synthesis of ammonia is a matured technology which is reversible and has a small impact on the environment. Other promising technologies are perhydrodibenzyltoluen (PDBT) and formic acid, but these technologies are not matured enough to use in an offshore application with harsh offshore conditions and low availability of maintenance (Andersson & Grönkvist, 2019).

| | Advantages | Disadvantages |
|---|---|---|
| Compression | - Simple<br>- No additional energy needed for release<br>- Low energy cost for storage | - Low storage densities<br>- Expensive high pressure tank needed<br>- Storage in gas phase |
| Liquefaction | - High storage density<br>- No additional energy needed for release<br>- Reasonably well established method<br>- Storage in liquid phase | - High capital costs<br>- High energy cost for storage<br>- Unavoidable boi-off rate |
| Adsorption | - Reasonably good storage density<br>- No additional energy needed for release | - Needs to be stored under high pressure<br>- Intensive heat management needed<br>- Low efficiencies (<80% hydrogen to hydrogen) for short term storage<br>- Storage in solid phase |
| Metal hydrides | - High storage density at ambient conditions<br>- Intermetallic hydride most promising, but can get expensive | - Sluggish kinetics<br>- Additional energy needed for release<br>- Irreversible<br>- Storage in solid phase |
| Methanol | - High storage density<br>- Storage in liquid phase<br>- Utility goes beyond hydrogen storage<br>- Well known commercialised technology<br>- Reversible | - Additional energy needed for release<br>- Conversion to methanol |
| Ammonia | - High storage density<br>- Storage in liquid phase<br>- Utility goes beyond hydrogen storage<br>- Well known commercialised technology | - Additional energy needed for release and<br>- Extremely high temperatures<br>- Conversion to Ammonia |
| Formic acid | - High storage density<br>- Storage in liquid phase<br>- Utility goes beyond hydrogen storage<br>- Well known commercialised technology | - Additional energy needed for release<br>- Energy intensive to store |
| PDBT | - High storage density<br>- Storage in liquid phase<br>- Dehydrogenated form also in liquid phase<br>- Reversible | - Additional energy needed for release |

**Table 5:** Overview of hydrogen storage technologies (Andersson & Grönkvist, 2019)(Franco et al., 2021)(Wolf, 2015).

In conclusion, each of the methods have their advantages and disadvantages, as seen in table 5. Due to the security and reliability requirements in combination with the ease of conversion, this research will focus only on the use of compression for the storage of hydrogen. Other technologies have the potential to store more energy, but have disadvantages that make them currently not suitable for this offshore system. Nevertheless, higher energy densities can increase the storage capacity and will therefore lower the LCOE. Because of the potential decrease in LCOE, it is recommended to analyse these technologies in future research.

#### 4.2.4 Compressor

As discussed before, the hydrogen will be stored under compression. This compressor depends on the required compression in the tank, which will be discussed in section 4.3.5. Higher pressure creates a higher energy storage, which results in the ability of generating a higher base load or higher security of supply. There are multiple types of compression technologies: mechanical compressors, cryogenic compressors, metal hydride compressors, electrochemical compressors, adsorption compressors (Sdanghi, Maranzana, Celzard & Fierro, 2019). Each of these compressors is related to a storage technique, as listed in the previous section. With compressed hydrogen as the selected storage technique, a mechanical compressor is required in this system setup. Within the mechanical compressor technology, there are three main types of compressor technology; reciprocating piston compressors, rotary screw compressors and rotary vane compressors. Each of the compressor types has its own advantages as listed in table 6.

| Mechanical compressor technology | Advantages | Disadvantages |
|---|---|---|
| Reciprocating piston compressor | - Low initial purchase price | - Low efficiency<br>- Large compressor volume |
| Rotary screw compressors | - Relative long life<br>- High air flow delivery<br>- Smaller volume<br>- High energy efficiency<br>- Less noise | - Higher initial investment compared to reciprocating |
| Vane compressor | - Continuous duty cycle<br>- Smaller size<br>- Even higher efficiency compared to rotary screw | - Higher initial investment compared to rotary screw |

**Table 6:** Comparison between mechanical compressor technologies (Compressors, 2018)(The Titus Company, 2021)

According to this comparison, there is not a preferred mechanical compressor technology which should be used for this system. Mainly because of the interdependency of the components within the system; the constrains regarding the other components, such as the available volume of compression rate, are not yet analysed. Therefore, all three technologies will be taken into account for the product comparison in section 4.3.5.

### 4.2.5 Fuel cell

The stored hydrogen is reconverted back into electricity and is transported to shore by cable. As discussed in chapter 2, hydrogen could also be transported to shore, but this requires reconversion equipment on shore or a demand for hydrogen. However, this hydrogen supply option will make the island's energy production future proof for a change to a hydrogen economy (Franco et al., 2021). For the conversion from hydrogen to electricity, a fuel cell is required. In this section, the different fuel cell technologies will be discussed and the suitable technology for this system will be selected.

A fuel cell converts hydrogen combined with oxygen into power and water. This is the reversed step of the electrolyzer, as described in 4.2.2. The hydrogen ions ($H^+$) pass through a membrane and create an equilibrium with the $OH^-$, which results in water as output. The electrons, which do not pass through the membrane, are redirected and create an electric current. A visualization of the process is shown in appendix figure 27. In this process, oxygen is added to create electricity out of the stored hydrogen. This oxygen is extracted from the air outside the wind turbine. Wind turbines are designed to be sealed to protect the components inside the tower and nacelle from the salt air, which is highly corrosive. Using the outside air will protect the components. To protect the fuel cell from the salt air, an air module, which filters the air from salt, gasses and small particles, is installed (Nedstack, 2021). Otherwise these elements can contaminate the fuel cell process, which decreases the efficiency and causes damage to the system (EH Group, 2021)(Garzon et al., 2007).

There are several fuel cell technologies: Alkaline electrolyzer (AFC), Proton Exchange Membrane (PEM), Molten carbonate (MCFC), Solid oxide (SOFC), Phosphoric acid (PAFC), Direct methanol (DMFC) and Reformed methanol (RMFC). Table 7 gives an overview of the advantages and disadvantages of the different fuel cell technologies.

| Fuel cell Technology | Advantages | Disadvantages |
|---|---|---|
| AFC | - Low operation temperature (60°C)<br>- Hydrogen as fuel<br>- High efficiency | - System needed to keep KOH and carbonate concentrations within the right boundaries<br>- Low power density |
| PEMFC | - Lower operation temperature (<80°C)<br>- Hydrogen as fuel | - Lower power density compared to SOFC |
| MCFC | - High power density | - Very high operation temperature (650°C)<br>- $CO_2$ must be fed to the fuel cell<br>- Cooling system needed<br>- More advanced fuel needed |
| SOFC | - High efficiency<br>- High power density | - Very high operation temperature (>700°C)<br>- Suffers under thermal cycling<br>- Cooling system needed<br>- More advanced fuel needed |
| PAFC | - Hydrogen as fuel | - High operation temperature (180°C)<br>- Lower power density<br>- Use of phosphoric acid |
| DMFC | - Low operation temperature (<80°C)<br>- High power density | - Methanol as fuel<br>- Limited in power output<br>- Only for small applications |
| RMFC | - Low operation temperature (<80°C) | - Methanol as fuel<br>- Lower power density |

**Table 7:** Advantages and disadvantages of fuel cell technologies (Steilen & Jörissen, 2015)(Gencell, 2018)(Akinyele et al., 2020)(ABN AMRO, 2021).

With the overview of table 7, the following technology selection can be made. The Direct methanol fuel cell and reformed methanol fuel cell can not be used for the internal hydrogen system, because the fuel cells use methanol as fuel. As discussed in 4.2.3, compressed hydrogen will be the storage medium due to fewer conversion steps in the process, maturity of the technology and the volume available in the TP. The molten carbonate, solid oxide has a very high operation temperature. This makes the use of these two types of fuel cells more complex, expensive and possibly dangerous, especially in an offshore environment with less access for maintenance. However, these technologies also have high power densities and therefore higher operation performance, which can lead to a decreased LCOE. This makes them interesting for future research, but due to these disadvantages not suitable for this research. The phosphoric acid fuel cell has an aggressive electrolyte, a higher operation temperature compared to alkaline and PEM and relative low power density, which makes this technology not feasible for this hydrogen system. The two options which remain are the alkaline fuel cell and the proton exchange membrane. Both have low operation temperature, which makes them easier to use in harsh offshore conditions and both use hydrogen as input. The lower power density and, for AFC, the required potassium hydroxide (KOH) and carbonate concentration boundaries are the disadvantages and will be discussed in the product comparison in section 4.3. In future research, new innovations and developments in these fuel cell technologies can be used for better optimization and possible lower LCOE results.

In conclusion, the alkaline fuel cell and proton exchange membrane fuel cell technologies will be compared in the product selection. These two technologies are selected because of their low operating temperature which simplifies operational constrains, hydrogen as the required input fuel and commercial availability. According to the selected product, challenges regarding disadvantages will be taken into account.

#### 4.2.6 Conclusion of component selection

The internal hydrogen production, storage and reconversion system consists of multiple components. For each of these components, a pre-selection is made with the discussed constrains taken into account. In the following sections, the manufacturers and their different products will be analysed and compared for the internal hydrogen system for offshore wind turbines. With these products, the sizing and costs of these components will be calculated.

| Components | Selected technologies for each component |
|---|---|
| Desalinator | Reverse osmosis |
| Electrolyzer | Alkaline electrolyzer & PEM electrolyzer |
| Storage | Compression of hydrogen |
| Compressor | Mechanical hydrogen compressor |
| Fuel cell | Alkaline fuel cell & PEM fuel cell |

**Table 8:** Overview of the selected technologies per component for this technology.

### 4.3 Product selection, cost overview and system design of hydrogen components

With the output data from the location selection, in chapter 5, a first system setup can be designed. Table 9 gives an overview of these values and chapter 5 gives the calculation and argumentation of this data. In the first system design, a lower storage pressure of 300 bar will be used. In future designs, a higher pressure system, with lower storage volume, can be analysed on its LCOE and sustainability, but this will be out of the scope of this research due to the uncertainties in safety. To calculate the required volume, storage pressure, reconversion rate and base load, the first efficiency assumptions are made with the input from appendix table 34, and inputted into the base load model.

| Specification for first design iteration | Value |
|---|---|
| Required base load | 1.5 MW |
| Maximum mismatch (supply/demand) | 2.5 MW |
| Storage volume | 314 $m^3$ |
| Storage pressure | 300 bar |

**Table 9:** Overview of the selected parameters used in this hydrogen production, storage and reconversion system.

#### 4.3.1 Foundation design and sizing of storage tank

The produced hydrogen is stored, in a compressed state, in a storage tank. This storage tank is located inside the bottom part of the foundation of the offshore wind turbine; the monopile. For the sizing of the tank, the diameter and length of the monopile are key factors. Therefore, first the sizing of the monopile will be discussed and then the available volume for the storage tank.

The length of a monopile depends on the water depth at the selected installation location. According to the feasibility analysis of Van Oord, the water depths at Grenada, with suitable wind turbine locations, range between 30 and 50 meters (Van Oord, 2021). Depending on the seabed conditions (type of soil, rocks etc.), a part of the monopile is driven into the seabed. This length of the monopile is not taken into account as available storage volume, because it will be below the seabed. For this research, a minimal storage tank length of 25 meters will be taken into account. This will give 5 meters to accommodate for tank design deviations (thickness and shape of the tank) and structural components. At larger depths (up to 50 meters), larger tank volumes can be installed, but this will be not taken into account to make the system also applicable for smaller water depths. The second parameter is the diameter of the monopile. This depends on the installed wind turbine capacity. In this design, a capacity of 4 MW is used. This installed capacity requires a minimal monopile diameter of 4.5 meters (vestas, 2021). Increasing this diameter will largely affect the foundation costs (procurement and installation) and is therefore not assumed to be feasible (Van Oord, 2021). To accommodate for wall thicknesses and cables, 0.5 meter is reserved. This gives an available storage diameter of 4 meters (radius of 2 meters). All these numbers are validated by foundation experts from Van Oord, as discussed in the paragraphs below.

To calculate the storage volume, this tank is assumed as a cylindrical volume, with the input parameters as above. This will give the following storage volume, with r is the radius and l is the length:

$$Storage\,volume = \pi * r^2 * l = \pi * (2)^2 * 25 = 314.16\,m^3 \approx 314\,m^3 \tag{5}$$

As discussed, the monopile will be driven into the seabed, which results in large stresses on the monopile. To prevent the storage tank from being damaged, the tank will be lifted in the monopile after the pile drive installation. This will also be beneficial for the installation vessels maximum lift capacity. This will make it feasible to install larger storage tanks, at locations with larger water depths or larger monopile diameters.

**Expert validation** To validate this design and feasibility, this hydrogen technology is discussed with foundation experts of Van Oord and Vestas. In the following paragraphs, the foundation design, prognoses on wind turbine capacity and operational questions will be discussed.

Wind turbines and their foundations are increasing in size. Due to the economy of scale, wind turbine generators (WTG's) with larger outputs will have a positive effect on the LCOE of offshore wind turbines. This prognosis of an increase in the installed capacity will also affect the wind turbines with hydrogen system. If the price of wind turbines (per MW) will decrease, there will be less small WTG's (<6 MW) installed. This results in more availability for installation vessels for smaller WTG's. Because these vessels are already paid off, these can be operating at lower cost than newer vessels with larger installation capacities.

A second operational question is the maximum installation weight of the system. The weight of the monopile and TP will be higher due to the already installed hydrogen components, whereby the maximum installation capacity of 1500 tons needs to be taken into account. In general, the TP is lighter compared to the monopile, which makes the weight of the monopile decisive in the installation. Due to the pile driven installation, the storage tank will be installed afterwards. Because the storage tank will be lighter than the monopile, this will not cause problems with the maximum installation capacity. A second operational question is the lifetime of the components inside the foundation and TP, which can be affected by the humidity and salt in the air. According to the foundation expert, this can be solved by a dehumidifier and by pressurizing the TP. Because of the positive feedback from the hydrogen component manufactures and experts in the hydrogen market about the lifetime of these components in offshore conditions, the addition of a dehumidifier is not taken into account in this research. According to the component manufactures, these conditions are expected to have only a negligible impact on the system and therefore does not need to be taken into account for this research (Frames Group, 2021)(Hua et al., 2011).

After validation with foundation experts, the conclusion can be made that there are no major barriers regarding the foundation of an offshore WTG which can hinder the feasibility of this technology.

### 4.3.2 Fuel cell

With the input from table 9, the required number of fuel cells and the related volume of this equipment can be calculated. For the fuel cell selection, there are a number of requirements: the specific volume and mass of the required fuel cell system, the volume the system uses and the efficiency of the selected fuel cell. These selection criteria are selected because of the volume restriction of the TP and the influence of the efficiency on the system. As discussed, an increased conversion and reconversion will have a major impact on the total annual electricity production and therefore the LCOE. To get insights into the influence of the annual electricity production, the sensitivity of this parameter on the LCOE is analysed in section 7.3.

Appendix figures 28 and 30 give an overview of the available hydrogen products. An important note is that this information is based on publicly available information. Therefore, non-commercial products or products that are still in the testing phase are not taken into account. As discussed, the first requirements of the fuel cell are the size and mass. According to these two figures, there are major variations between the different hydrogen components. This is due to the application and scaling of the different products: in general, larger output power units have a better performance for larger power requirements, because smaller units have overdimensioned components or parts that can not optimized when used at a smaller scale. However, these variations can also be a result of overoptimism from the manufacturer. Therefore, the values of the selected product are validated on their trustworthiness during the interviews. The products with a higher power output/ volume ratio, lower number of fuel cells and required volume are suitable options: Beijing Nowogen, Bosch Powercell, Elringklinger, EH Group - EH81, Ballard FC-gen, etc.

The fuel cell efficiency is one of the most important parameters for the overall efficiency of the system. This is due to the fact that the fuel cell is the last component in the system. A low fuel cell efficiency will directly require higher input feeds for the storage, electrolyzer and desalination. Improving this efficiency, also with a higher volume requirement, will directly result in a more optimized system and therefore a lower LCOE. Appendix figure 30 gives an overview of the publicly available efficiency values. Due to the early stage of development of fuel cell and therefore the limited available data, not every fuel cell product has given its efficiency and may therefore not be taken into account in the comparison.

With the information from the previously mentioned figures and the importance of the efficiency of the fuel cell in the hydrogen process, the fuel cell with the highest value will be selected: EH Group - EH 81, with the data from table 10. A side note on this fuel cell selection is that this is the best performing fuel cell between the analysed products and with these input values. The assumption is made that the manufacturer is able to produce the required number of fuel cells times the number of WTG's for this system. The second assumption is the scalability of the specifications of the fuel cell, hereby the volume is linear scaled. In practice, this volume can be different due to added piping or can be smaller due to the removal of the casing. For this reason, the best design concept is selected to decrease the LCOE and make the concept feasible. A detailed fuel cell design is recommended for future research (H2-view, 2021).

| **Specifications single fuel cell: EH Group - EH 81** | |
|---|---|
| Fuel cell technology | Low temperature PEM (LTPEM) |
| Maximum single power output | 0.1 MW |
| Efficiency | 60% |
| Weight single fuel cell | 65 kg |
| Maximum theoretical volume | 0.0325632 $m^3$ |
| Weight/volume ratio | 1996.12 kg/ $m^3$ |
| Power output/volume ratio | 3.1 MW/$m^3$ |
| **Required for base load power** | |
| Power conversion capacity | 1.5 MW |
| Number of fuel cells required for base load | 15 |
| Weight (theoretical) | 975 kg |
| Volume required for base load fuel cells | 0.5 $m^3$ |

**Table 10:** Specifications of the EH Group - EH 81 (EH Group, 2021)

**Expert validation** To gain detailed knowledge about the fuel cell, an expert from Nedstack has reviewed the hydrogen concept. Nedstack is specialized in fuel cells used in the maritime and offshore sector (Nedstack, 2021). With Nedstack, the following topics are discussed: usage and suitability for offshore use, CAPEX, volume, life-time, maintenance, power output and sustainable impact. The second interview is with the EH group. In this interview, the feasibility and values from table 10 are validated.

Because of the developments of the technology and the increasing demand, the CAPEX of fuel cells is decreasing. Prognoses show an even faster decrease in costs in the future. This decrease in CAPEX will be favourable for the roll-out of this technology and the hydrogen economy in general. According to Nedstack, a CAPEX of €2500-3000 per MW of installed capacity is achievable. Due to the stackability of the fuel cells (stacks), the design can be optimized to decrease the required volume. For the LCOE calculation, the upper-limit of €3/watt is taken into account, which increases the financial scope for this optimized system design. Economy of scale is required for these developments and therefore multiple hydrogen wind farms need to be scoped.

Regarding maintenance, life-time and offshore use there are no major challenges. The system is designed for this application, whereby the lifetime of the components can be stretched even further than the 10 years, used in the LCOE model. Furthermore, the start/stop cycles will be negligible for this system efficiency. However, the system volume is advised to be overdesigned; fuel cells which operate at maximum level degrade faster.

The sustainable impact of the fuel cell manufacturer is uncertain. The company is not using a 100% sustainable power supply, however the manufacturing process of the fuel cell is mainly human capital and not energy intensive. Therefore the carbon footprint of the fuel cell is not taken into account in the $CO_2$ emission. The assumptions for the sustainable impact of this energy transition will be discussed in detail in section 7.4.

### 4.3.3 Electrolyzer

With the storage requirement from the location selection, chapter 5, and the fuel cell input requirements, as described in the previous section, the electrolyzer can be selected. The electrolyzer will be selected based on the following criteria: energy usage per kg of hydrogen, minimal system volume, high efficiency and number of components. These criteria are selected because of the energy usage which is used in the base load calculation. The restricted volume inside the TP will make products not feasible. A higher efficiency will have a positive effect on the annual electricity production and therefore the base load. For the number of electrolyzers, it would be beneficial to have more than one fuel cell system. This will improve the security of supply during maintenance or outages; if one fuel cell system is defected, the system can still convert a part of the electricity into hydrogen. The data of the electrolyzer, as shown in the graphs in the appendix, is retrieved from publicly available information. This results in some missing information (efficiencies) and differences in the calculation of the values, as discussed if applicable to the graph.

Appendix figure 31 shows for the different electrolyzer products the maximum power output and the power usage accordingly. As discussed in chapter 5, the maximum required power mismatch for the first design iteration is 2.5 MW per hour (frequency over 2020 of 83). The wind turbine can produce a maximum of 4 MW and, minus the base load power demand of 1.5 MW. gives this mismatch of 2.5 MW. This figure gives the amount of hydrogen that can be produced with this power mismatch of 2.5 MW. The energy usage (in kWh/h2) is reversed proportional to the hydrogen generation. A lower efficiency, thus higher energy usage per kg of hydrogen, will result in a lower hydrogen production. Higher hydrogen production and lower energy requirements are required, which will shift the focus to the electrolyzers on the left of this graph.

The second constraint of the electrolyzer system is the required volume. Appendix figure 32 gives an overview of the required number of electrolyzers and volumes per product. To make it easier to compare the figures, the same order as in the last figure is used. An important note on this information is the definition of volume in the market analysis; the used volume is the total outside measurements, including casing, of the product. Many of these electrolyzer products are designed for a stand-alone system which can easily be transported. For example, some components are combined inside a container. This creates spikes in the specific volume for a few of the electrolyzers. This may eliminate electrolyzers which would be interesting without casing, but due to the lack of detailed volume information, these components are not selected. Smaller volumes are preferred; because the available volume is restricted due to the wind turbine components, which are already in the TP. More free volume in the TP will also improve the ability to maintain and replace the components. To be able to analyse the data even further, the appendix figure 33 gives the required volume and quantity of electrolyzer for this first design. Because the volume is limited and the available volume inside the TP will not more than 500 $m^3$, the electrolyzer with higher volumes are not shown. Otherwise this would require a TP length of 40 meters only used for electrolyzers. This TP length is already more than the average TP length for a small wind turbine foundation of 4 MW, which has an approximate length of 25 meters. This results in a total volume of 314 $m^3$ as seen in the monopile calculation. The products with the lower number of electrolyzer and volume are desired for the system design. The electrolyzers with the lowest volumes (Plugpower Allagash and Plugpower Merrimack) are only stack components, without the balance of system. Therefore, these systems will not be taken into account in this design phase. In future research, this type of electrolyzer will be an interesting option for a single system, with a possible decrease in volume requirement. With these assumptions and figures, possible electrolyzers are the Frames 10, 5, 2 & 1 MW, ITM Power HGAS3SP/HGAS2SP, and NEL C30.

Appendix figure 35 gives an overview of the available efficiencies per electrolyzer. Higher efficiencies are beneficial for the overall system. Increasing the efficiency will increase the power output, decrease the required number of components and decrease the storage volume. This will decrease the total LCOE and improve the opportunities for the technology. In this figure, the products with volumes above 500 $m^3$ are also not shown due to the volume restrictions of the TP.

Concluding, all these graphs taken into account, the Frames 1 MW electrolyzer is selected. Table 11 gives the detailed data for this Frames 1 MW system. The selection is made with the following arguments:

- The volume is below 500 $m^3$
- The electrolyzer requires a relatively low volume
- The system requires more than one electrolyzer. The Frames 5 or 10 MW has a lower required volume (124.92 $m^3$ vs 187.23 $m^3$), but also consists of 1 electrolyzer. Using multiple systems will increase the security of supply and make partial maintenance when the system is in use possible
- A minimum load of 0%; the electrolyzer is able to work at low production rates. This makes optimization of the hydrogen production possible. Electrolyzers with a minimum production rate can be damaged by constant switching of the required output
- A relatively high efficiency compared to the other electrolyzer products, which will be beneficial for the overal efficiency of the system

| **Specifications single electrolyzer: Frames - 1 MW** | |
|---|---|
| Technology | Proton exchange membrane (PEM) |
| Hydrogen production rate | 453 kg/day |
| Hydrogen production output/volume ratio | 7.26 kg/$m^3$ |
| Efficiency | 75 % |
| Dimensions | 6090 * 2440 * (2800 + 1400) mm |
| Volume | 62.41 $m^3$ |
| Energy usage | 47.68 kWh/kg $H_2$ |
| Maximum hydrogen production | 52.43 kg/hour |
| Produced hydrogen | 2065.73 MWh |
| Water requirement for maximum production | 555.56 L/hour |
| Minimum production range | 0% |
| Output pressure | 40 bar |
| **Required for base load** | |
| Number of electrolyzers (theoretical) | 3 (2.5) |
| Volume of electrolyzers | 187.23 (156.03) $m^3$ |

**Table 11:** Specifications of the Frames 1 MW (Frames Group, 2020)(Frames Group, 2021)

**Expert validation** To validate this analysis, the data is discussed with an expert from the market and electrolyzer manufacturer. In this conversation, the following objects are discussed:

- Lifetime and maintenance of an electrolyzer

- Volume optimization
- CAPEX of the electrolyzer
- Use of an electrolyzer in an offshore setting
- Safety

One of the important parameters in the CAPEX calculation are the replacement costs of the hydrogen system. Due to the lifetime of the components, part of the system is completely replaced after 10 years (Schmidt et al., 2017). According to Frames, many parts can be reused and mainly the mechanical rotary components, such as pumps, and electrolyzer stack need to be replacemened. This will decrease the replacement costs and therefore the LCOE. According to the state of the electrolyzer stack, these can be refurbished, which will decrease the LCOE even further. As discussed in the component selection, the life time of electrolyzers and fuel cells can be reduced by turning the system off when the components are not in use. However, this lifetime increase is assumed to be not sufficient to elimate the replacement of the components. Therefore, the replacement costs are still taken into account in the financial overview, as discussed in section 6.4.

The electrolyzer system, besides the storage tank, has the largest share of the total hydrogen system volume (187 $m^3$). This volume calculation is based on the container size in which the current electrolyzer system is designed. An analysis of the separate component volumes will optimize these volume values. This will improve the design out, between the WTG and hydrogen components, inside the TP. In this volume design, the added weight besides the bare electrolyzer needs to be taken into account. This will probably result in additional support beams and separate spaces (see also safety) for the hydrogen components, inside the TP. This total weight of hydrogen components and added structure needs to be compared with the maximum lifting capacity of the installation vessel. This detailed design is outside the scope of this research.

This volume optimization is also linked to the CAPEX. The €1.2/watt, which is used in the LCOE model and will be discussed in section 6.1, is appropriated for a current electrolyzer system (Frames Group, 2021). Technological development will decrease the CAPEX, which will create financial scope for the electrolyzer optimization phase. Standardization of a hydrogen system inside a TP will decrease the costs over time.

The use of hydrogen technology in an offshore environment is still in an early phase. This makes operational questions about the use of the components inside a salty environment with a limited space interesting. According to Frames, the components which are used in the system are; water treatment system, electrolyzer stack, power control system, after-treatment of $H_2$, pressure regulating system and unit control. These components can be designed to withstand the harsh offshore environment. This covers the movement during installation, movement of the TP during operation (due to wind and waves), the salt environment and the operating parameters (such as on/off cycles). Therefore, the system is assumed to be able to operate in these offshore conditions and no additional measurements are required to protect these components.

The biggest issue with using a hydrogen system inside a confined space is the safety. The TP of a wind turbine is closed from the outside to protect the components against the salty air and seawater. This makes possible leakages of hydrogen, in combination with the high voltage gearing inside the TP, a safety issue. This issue needs to be addressed in more detail during the design phase and can be solved, for example, by adding different compartments for the electrical components and the hydrogen system. Due to the complexity of this question and the connection with the detailed design phase, this is out of the scope of this research.

### 4.3.4 Desalination system

The selection of the desalination system is based on the capacity of the electrolyzer. The selected electrolyzer has a maximum water production requirement of 555.67 $^3$ per electrolyzer at maximum capacity. This results in a total of 1667 liter fresh water per hour for the 3 electrolyzer. The selection criteria for the desalination system are: it needs to meet the fresh water demand of the electrolyzer, low volume and low energy usage. These criteria are selected because the electrolyzers can not function at peak power, if the fresh water demand is not met. The low volume criterion is selected because of the volume restriction inside the TP, whereby more remaining space will improve the maintenance operations. Lastly, the energy usage criterion is selected as a measurement for efficiency. If less energy is used in the conversion process, more electricity can be outputted by the system.

Appendix figure 36 gives an overview of the required number of products to meet the water demand and the system volume. Hereby, the products are sorted by their total volume; a lower volume is preferred, because of the limited space inside the TP. The third selection criterion for the desalination system is the amount of energy used to convert seawater into fresh water, which can be used in the electrolyzer to produce hydrogen. Figure 37 gives an overview of the energy usage, in kWh/m$^3$ of produced water, sorted in the same order as in the information in figure 36. In this overview, a lower value (less energy usage) is preferred.

According to these graphs, the best option for this internal hydrogen system seems the Lenntech - BWRO desalination system; high efficiency and low volume. However, this desalination is designed for brackish water (BWRO = Brackish Water Reverse Osmosis), which makes it unsuitable for offshore use. The second best option is the Lenntech SWRO-L 5, which is made for small desalination; SWRO = Small Seawater Reverse Osmosis Plant. The trade-off in this selection is the slightly larger volume and higher energy usage, compared to the BWRO. However, this system still meets the low volume, high output and high system efficiency (low energy usage) requirements. A disadvantage of this desalinator is the number of desalinators; a minimum of 2 would increase the redundancy if there is maintenance or a component outage. However, this problem is solved by the added water tank in the electrolyzer system which will function as a buffer. A third option is the Lenntech SWRO-L 10, which has the same volume and efficiency, but is more expensive, due to the larger output capacity, as a result of the larger installed pump. Therefore, the second option; Lenntech SWRO-L 5 will be selected. Table 12 shows the specifications of the selected desalination system.

| **Specifications of single desalination: Lenntech - SWRO-L 5** | |
|---|---|
| Dimensions | 4000 * 1000 * 1600 mm |
| Volume | 6.40 $m^3$ |
| Output capacity | 5.00 $m^3$/h - 120 $m^3$/day |
| Energy usage | 4.00 kWh/$m^3$ of water |
| Installed pump | 20 kW |
| Rinse Tank | 300 L |
| **Required for base load** | |
| Number of desalination products | 1 |
| Total volume | 6.40 $m^3$ |

**Table 12:** Specification of the Lenntech - SWRO-L 5 (Lenntech, 2021)

### 4.3.5 Compressor

The last component in the system is the compressor. As discussed, the compressor pressurizes the hydrogen to increase the energy density of the storage: a higher pressure will result in more hydrogen stored and therefore more energy storage. As discussed, the hydrogen will be stored at 300 bar with a volume of 314 $m^3$. The data in the following graphs is obtained from publicly available information. This results in differences in data and the lack of specific values.

The selection criteria for the compressor are: the capacity requirements need to be met, a low energy usage which results in a high efficiency, discharge pressure of 300 bar and the number of compressors. These criteria are selected because the total volume of produced hydrogen needs to be pressurized for storage. Therefore, the delivery rate needs to meet the supply of the electrolyzer. A high efficiency will decrease the total system losses and will therefore increase the annual electricity output of the system. The compressor needs to be able to pressurize the hydrogen at 300 bar. A higher pressure would be beneficial for future high pressure applications, but is not a requirement for the current system. Lastly, a larger number of compressors than one will improve the operational reliability during outages and maintenance of one of the compressors.

In appendix figure 38, the power output per hour is given. The maximum overcapacity of the single hydrogen system is 2.5 MW (4 MW WTG - 1.5 MW base load). Compressors are rated in kg of $H_2$, whereby a kilogram of hydrogen is approximately 39.4 kWh. These values are the input for the number of required compressors. A higher output rate will result in less compressors, which makes the installation and maintenance of the system less complex. On the other hand, less compressor components will decrease the security of supply during a component failure or during maintenance. In this overview, the compressor types for onshore large-scale use are not taken into account. This is because of the limited space inside the TP. Due to the optimized equipment, these compressors have a relatively high efficiency, compared to small-scale products. However, they also have two downsides. They output a higher delivery rate than required and require higher power input capacities, which exceeds the power output of this wind turbine setup. The figure shows that the compressors with the highest delivery rate, compared with a low number of compressors, but still higher than 1 for the redundancy, are: Ventos compressors, Linde Ionic 90 double, Pure energy centre and Linde Ionic 90 double.

Besides the power output and therefore the number of compressors, the discharge pressure of 300 bar needs to be reached. A higher discharge pressure will be beneficial for future applications, because of the higher energy density. This higher energy density results in more energy stored in the form of hydrogen and therefore a smaller storage tank or more storage capacity. But in this current design, the lower pressure of 300 bar will be used because of safety regulations and a less expensive tank. Appendix figure 39 shows the maximum discharge pressure per compressor product. These compressors are sorted in the same order as graph 38. This criterion gives the following possible compressors: Ventos compressors, Linde Ionic 90 double, Pure energy centre, Linde Ionic 90 double, Haskel AG, AGT and AGD 152 series.

With these two graphs, the compressor can be selected. The selected compressor is the Linde Ionic Compressor 90 - single line. This is, with the Pure energy centre - H2 compressor, the best performing compressor with a requirement of at least 2 compressors and a power output of 2.65 MWh/hour. lthough the double line version has a higher delivery rate, it would be overdesigned and too expensive to install two of these compressors. The use of 2 compressors will increase the redundancy and security of supply of the system; during maintenance or outages of a single compressor, the second compressor can take over the load. This will result in a lower output, but the electrolyzers can still be turned on. This will be beneficial when the second compressor is turned back on, because there are no starting times for the components throughout the process. The security of supply is slightly more important in this selection than the higher delivery rate of the double line version: outages will reduce the outputted power more than small efficiency gains.

Table 13 gives an overview of the specifications of the Linde - Ionic Compressor 90 - single line.

| **Specifications of single compressor: Linde - Ionic Compressor 90 - single line** | |
|---|---|
| Dimensions | 4200*2700*2600 mm |
| Volume | 29.48 $m^3$ |
| Delivery rate | 33.6 kg/h |
| Maximum discharge pressure | 700 bar |
| Energy consumption | 2.7 kWh/kg of hydrogen |
| Weight | 17,000 kg |
| Target fuelling pressure | 30-50 bar |
| **Required for base load of 1.5 MW** | |
| Number of compressor products | 2 |
| Total volume | 59 $m^3$ |
| Full delivery rate | 67.2 kg/h (2.647 MWh) |
| Maximum delivery requirement | 2.5 MWh |

**Table 13:** Specification of the Linde - Ionic Compressor 90 - single line (Linde, 2014)

## 4.4 Conclusion

In this section, the different technologies are discussed for the five components in the hydrogen system. The specific products are selected per component. Hereby selection criteria such as volume, output, redundancy and efficiency are used accordingly. As seen, there is a strong interconnection between these components and the location input variables. Therefore, the products and number of components can not be changed without validating the variables with the other components. The table below gives an overview of the selected components which are the base of the first iteration design of the internal hydrogen system.

| Component | Selected product | Reference |
|---|---|---|
| Fuel cell | EH Group - EH 81 | (EH Group, 2021) |
| Electrolyzer | Frames - 1 MW | (Frames Group, 2020) |
| Desalination | Lenntech - SWRO-L 5 | (Lenntech, 2021) |
| Compressor | Linde - Ionic Compressor 90 - single line | (Linde, 2014) |

**Table 14:** Overview of the selected hydrogen products for the first design iteration

# 5 Business case selection

To test the selected internal hydrogen design, the LCOE and sustainable impact will be calculated for a test location. First, the selection criteria will be discussed, then the location specific details, such as weather data, electricity demand and power mismatch. With this information, the base load calculation and therefore decisions in the components for the hydrogen system can be made.

## 5.1 Selection criteria for the business case

To determine the required energy generation and security of supply of this researched hydrogen production, storage and reconversion system for offshore wind turbines, a test location, with viable conditions, is required for input. If the technology is not feasible at this location, the opportunities will be even lower at other locations with less favourable conditions. With the following constrains, sub question 4 will be answered.

For this test location selection, location constrains are selected. These requirements are selected with the knowledge gained from the scientific research, conversations with experts from Van Oord and by comparing current offshore hydrogen projects.

- Suitable weather conditions: steady wind with a relatively high average wind speed to generate enough energy (vestas, 2021)
- The location needs to have a relatively high energy price. If the energy price is low, the technology will not be competitive due to the higher investment costs for hydrogen compared to traditional wind turbines (Van Oord, 2021)
- There needs to be a suitable location for fixed bottom structures; for example waters that are not too deep. The decision to choose for fixed bottom, instead of floating, is based on the fact that this will drive the initial investment costs even further due to the less matured technology and because of the interest of Van Oord in fixed bottom structures (Van Oord, 2021)(Linnenschmidt, 2021)
- The location needs to have a separate electricity grid. If the location is able to import electricity from another supplier, the advantage of an internal storage system is diminished
- Currently, only a small amount of electricity needs to be generated with sustainable energies, otherwise a new sustainable technology has less added value for the location
- The location needs to have interest in or the necessity to change their electricity generation to a more sustainable system. This change can have a financial incentive, such as the need to apply to new renewable regulations or a lower energy price, or a more idealistic incentive; to lower their emissions

With these constrains, the island Grenada, located at the West Indies of the Caribbean Sea, as seen in appendix figure 40, is selected as test location. Besides these constrains from this list, Grenada is already a location of interest for Van Oord, which increases the available knowledge, opportunities and the feasibility for a future roll-out of the technology. Within the broad location portfolio of Van Oord, Grenada is selected for the renewable energy properties, weather conditions, current non sustainable energy generation by diesel generators and energy pricing. These aspects of Grenada will be discussed in more detail in the following sections. Besides these conditions, the selection of Grenada makes it possible to compare the offshore wind turbine system with the feasibility analysis from Van Oord, as discussed in chapter 7.

## 5.2 Equivalent locations

Grenada is a suitable location regarding its environmental constrains. However, if the technology is competitive for Grenada, there are numerous other locations suitable for this offshore hydrogen wind turbine technology. These locations do often also have a diesel generated electricity supply, high(er) energy prices as discussed in section 5.3 and high emissions. This makes this hydrogen technology suitable for more projects, which will increase the interest in the development of this technology. Increasing the number of projects/locations will allocate the development costs over more projects, which will decrease the LCOE. Examples of these locations are nearby located islands in the Caribbean, such as Dominica, Martinique and Barbados, all part of the Small Island Developing States (SIDS). These SIDS and their opportunities are discussed in chapter 2. Besides locations nearby Grenada, the technology can also be used at UNESCO protected locations or locations with ecological importance, such as the Galapagos Islands, Socotra and New Caledonia. These locations have an interest in shifting to more sustainable resources for their electricity supply. The last potential location category are islands with financing from onshore, which lags behind in their national sustainability goals. Examples of these potential locations are Madeira for Portugal and islands in Japan, such as Yakushima, (center for energy policy, 2020). These locations are recommended for future research.

## 5.3 General information of Grenada

Grenada is a suitable location for renewable energies: abundant sunshine for solar energy because of its location nearby the equator, a steady wind for wind energy due to its offshore location and three active volcanoes, which make up the different islands of Grenada and create a good geothermal resource (Climatechangenews, 2021). Grenada is one of the islands of the Grenadines, which consists of Grenada, Carriacou and Petite Martinique, as well as a number of smaller islands. These islands have a combined land area of 340 $m^2$, with a population of 112,003 in 2019 (Worlddata.info, 2021) and a minimum power requirement (base load) of 20 MW (Energy Transition Initiative, 2015), which will be discussed in section 3.2.1. 90% of the population lives on Grenada and a third in the national capital of St. George. An overview of the Grenada general data is given in table 15.

| Data | Value |
|---|---|
| Population | 112,003 |
| Area | 340 $m^2$ |
| Total installed capacity | 45.59 MW |
| Required total base load | 20 MW |
| Peak demand | 30.2 MW |
| Total electricity generation | 185.1 GWh |
| Renewable share | 1.4 % |

**Table 15:** Overview of general data and electricity data of Grenada in 2019 (Energy Transition Initiative, 2015) (Worlddata.info, 2021).

| Average electricity tariffs (2019) | |
|---|---|
| Residential | $ 0.32 / kWh |
| Commercial | $ 0.32 / kWh |
| Industrial | $ 0.28 / kWh |
| Street lights | $ 0.30 / kWh |

| | |
|---|---|
| Average electricity tariffs over 6 years for Grenlec | €0.195 / MWh |

**Table 16:** Average electricity tariffs in Grenada (Grenlec, 2019)(Initiative Energy Transition, 2020).

Similar to other remote islands in the Caribbean, Grenada's energy generation is mainly based upon diesel. This diesel is transported by tanker to Grenada and burned to produce electricity. The diesel fuel costs are approximately 60% of the overall energy production costs (Grenlec, 2019), as seen in appendix table 62. In 2013, the imported diesel and petroleum products accounted for 93% of the total energy supply. Whereby, 41% (of the 91%) was used for electricity generation. Furthermore, Grenada used 6% of its GDP on oil imports (IDB, 2016). This results in relatively high energy tariffs compared to non-remote locations (Statista, 2021), but still lower compared to the Eastern Caribbean average oil import costs, as seen in appendix figure 41. This makes the technology also suitable for Eastern Caribbean islands, if their renewable goals and resources are suitable. As seen in table 16, the consumer energy prices in 2019 were around €0.30 per kWh, with an average energy price for the energy provider of €0.195 / kWh. This last value will be used in the LCOE comparison to account for the profit margins.

### 5.3.1 Background of Grenada's electricity provider and sustainable goals

The electricity at Grenada is produced and regulated by a privatised electric utility company, Grenlec. The privatisation of the company, nearly 30 years ago, resulted in relatively high energy prices compared to non-remote locations. Between 2011 and 2015, Grenada's energy costs per kilowatt hour were between 4 and 10 times more expensive than those in the USA, although similar to some Caribbean neighbours. The company tried to maintain their monopoly position; the commercial use of renewable energy resources was hindered. For the use of rooftop solar panels, a licence from Grenlec was needed to be approved. Originally, the overproduction of electricity from these rooftop panels was sold to Grenlec, through a net-metering scheme, for a 10-year fixed price of $0.17 /kWh. However, it was replaced with a net billing system, which accounts for the diesel fuel it had used otherwise. These licences and electricity prices by this net billing system restricted the installation of new rooftop solar systems due to the high investment risks (Climatechangenews, 2021)(Government of Grenada - National Plan Secretariat, 2019). Despite these licences, Grenada had set high renewable goals in 2010:

- 0.6% of the electricity from renewable resources (mainly small-scale solar photovoltaic system) in 2015
- 10% of all buildings equipped with renewable energy technologies by 2015
- 20% of its electricity from renewables by 2017
- 20% of all electricity and transportation energy from renewable energy sources by 2020
- 20% reduction of greenhouse gas emissions by 2020 and a 100% renewable energy by 2030, whereby 10% of the consumers benefit from solar water heaters

However, due to the low commercial use of sustainable energies and problems with renewable projects, only a 10% realisation rate of the Grenada renewable energy transition goals was realised in 2020 (Climatechangenews, 2021). Examples of these delayed projects were a 2 MW solar photovoltaic plant, the 10-20 MW geothermal plant and the 2 MW wind farm on Carriacou (IDB, 2016).

This low realisation rate and the influence of the privatisation deal resulted in legal actions, a changed company vision and new sustainability goals (United Nations Framework Convention on Climate Change, 2015) (Climate Change Laws of the World, 2021):

- 30% reduction in emissions through electricity production in 2025
- 20% energy efficiency gains by 2025
- 100% of electricity to be generated renewable by 2030

Hereby, the estimations from the US National Renewable Energy laboratory, as seen in figure 6, are used. Grenada has the technological potential for 20 MW of wind power, 25-50 MW of solar power and more than 50 MW of geothermal, whereas the current electricity generation capacity is around 46 MW, with mostly diesel power plants (Europa.eu, 2018). A combination of wind, hydro-power, geothermal, tidal power, biomass and solar power can induce a 100% sustainable generated energy supply. Combining different energy supplies will increase the security of supply by decreasing fluctuations in supply. An example of this combination is the inversely proportional connection between sun hours and wind power; if there is more wind power, during the winter months, there is less sun power and vice versa for the summer months. This will level the power generation and decrease the required installed capacity and the supply-demand-management. Grenada has planned multiple small-scale efforts to diversify the energy system. The new sustainable goals of Grenada's National Energy policy for the transition to a low-carbon future are based on three key goals. First, achieving energy independence by reducing reliance on imported energy resources. Secondly, securing long-term socioeconomic development by making efficient and sustainable energy in an effective market. Thirdly, to ensure that all sectors have equal and reliable access to energy at affordable prices (IDB, 2016) (Initiative Energy Transition, 2020).

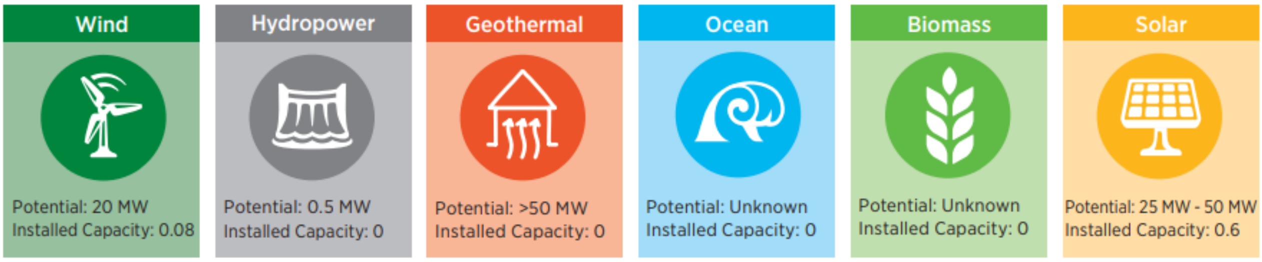



**Figure 6:** Realised installed capacity and potential sustainable energy resources of Grenada in 2015 (Energy Transition Initiative, 2015).

The combination of a high electricity price, renewable energy resources, renewable energy goals and a remote energy grid without an additional supply of electricity makes Grenada an ideal location for this offshore internal hydrogen production and storage system. These factors make a new technology, with often higher LCOE compared to a matured technology, competitive in an earlier stage.

## 5.4 Wind turbine selection

To determine the electricity output from the wind data, a wind turbine needs to be selected. This wind turbine selection will be based on the site conditions of remote offshore locations and focused on the Grenada conditions. With this selected wind turbine and the wind data, the electricity generation can be calculated with the base load model. This is discussed in more detail in sections 3.2.2 and 5.6.

For the wind speed analysis, a wind turbine of 4.2 MW will be taken into account. This turbine capacity is selected because of three reasons. First, small offshore wind turbines will have an advantage regarding the availability of installation vessels; WTG's are increasing in size, which decreases the demand for small installation vessels. Secondly, the wind turbine foundation is not linear scaled with the capacity of the wind turbine. However, larger scale WTG's require larger storage capacities. Thus, a smaller scale WTG will have relatively more storage capacity. And lastly, the base load electricity demand of Grenada (20 MW) will be supplied with these offshore WTG's. These remote locations only require a small-scale wind farm, whereby a higher number of WTG's decreases the outages due to maintenance. Therefore, a smaller WTG is preferred. An overview of the specs of this wind turbine is given in table 17. According to the site conditions, the wind turbine has a maximal output of 4.2 MW, but due to the uncertainty of future site conditions, the 4 MW rating will be used in the base load model (Vestas, 2017). This type of wind turbine is selected because of the following reasons: the model is often used in small-scale offshore applications, the WTG is part of the matured 4 MW platform of Vestas (Vestas, 2017) and the WTG parameters are applicable for this offshore location. For example, a relatively high cut-out wind speed.

| | **Vestas 4.2MW offshore wind turbine** |
|---|---|
| Rated power | 4000 kW/ 4200 kW (site specific) |
| Cut-in wind speed | 3 m/s |
| Cut-out wind speed | 25 m/s |
| Re-cut in wind speed | 23 m/s |
| Hub height | 90.5 m IEC IB, 84 m IEC IIA |

**Table 17:** Specification overview of the Vestas 4.2 MW offshore wind turbine (Vestas, 2017).

## 5.5 Wind data of Grenada

For the feasibility of hydrogen wind turbines at Grenada, an analysis of the wind speeds is required. With these wind speeds, the potential electricity production can be calculated. For this research, an additional storage analysis is required. This analysis is based on the frequency of mismatch in electricity supply and demand and the duration of this mismatch. The wind speed of this analysis is based on a hourly wind speed measurement at St. George over 2020. This data set is provided by Meteoblue and is only available for research purposes (Meteoblue, 2021).

For the wind speed analysis, the mismatch in electricity is divided in three states, as discussed in more detail in section 3.2.2. To recap, two periods are important for the storage system: the times of using stored energy to provide or supplement to the base load and the time of refilling the hydrogen storage. First, if there is not enough wind energy, a wind speed below the cut-in speed, the wind turbine will not provide electricity. Otherwise, if there is too much wind, the cut-off wind speed, the wind turbine will stop to prevent damage (Dupont, Koppelaar & Jeanmart, 2018). These cut-in and cut-off values are discussed in section 5.6. Because the island also requires electricity during periods of no wind, the stored hydrogen inside the transition piece needs to be reconverted for electricity output. Besides the periods with too much or too less wind, there is a second period during which hydrogen is reconverted; if the wind turbine is not able to provide the required electricity demand, hydrogen is reconverted and added to the energy output of the wind turbine. Secondly, generation which exceeds the demand will be used to refill this hydrogen storage, by converting electricity into hydrogen. This is why the duration of energy production below the base load can not exceed the stored hydrogen energy.

Appendix figure 42 gives an overview of the wind speed fluctuations of 2020 and the average wind speed of 6.54 m/s at St. George, the capital of Grenada, at a height of 80 meters. This height is the height of wind turbine hub, as seen in table 17. As will be discussed in section 5.6, a wind turbine produces a different output power per wind speed. To analyse this wind speed distribution, the wind speed fluctuations are divided monthly into wind speed categories: 0 - 15 m/s, as seen in figure 43. In this figure, the number of hours per wind speed category are stacked per month. This visuals clearly that the majority of the wind speeds is between 5 to 8 m/s per second during the winter and 3-6 m/s during the summer months. This result will also be visible at the power output graphs in section 5.6.

As seen in appendix figure 43, there are zero occurrences of wind speed higher than 25 m/s, which is the cut-off point of the analysed 4MW wind turbine. Therefore, only the low wind speed fluctuations need to be analysed, as seen in appendix figure 44. This figure shows the duration of low wind speeds and therefore outages for traditional wind turbines. Besides the outages, this graph also shows that the lower wind speeds occur during the summer months. This result is in line with the expectation. The electricity supply can be supplemented with solar energy. This is out of the scope of this research, but will be interesting for future research because of the less installed capacity that will be required. With the wind speed distribution, the outage frequency over 2020 can be analysed. Figure 7 gives the hours of outages, whereby the maximum outage duration was 26 hours. This figure will be used when comparing the traditional wind turbine with the wind turbine with hydrogen system.

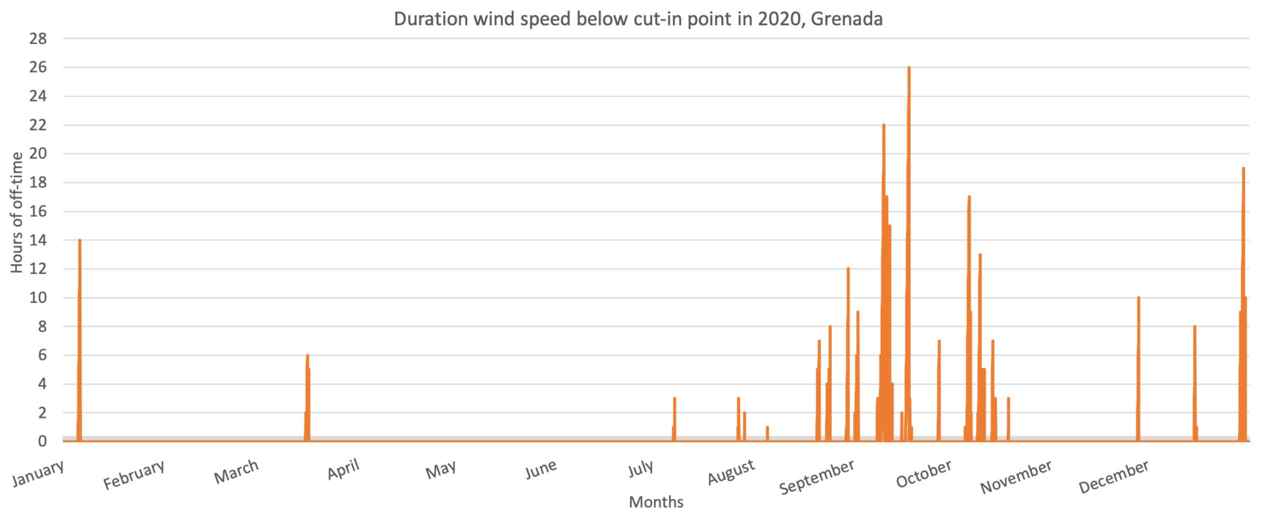



**Figure 7:** Duration wind speed below cut-in point at Grenada in 2020 (Meteoblue, 2021).

In this research, the assumption is made that the wind data set of 2020 is representative for each year. However, improvements in the security of supply between a traditional wind turbine and this technology can differ depending on the wind speed distribution over the year. Appendix A.4.2 gives an overview of the wind data between 1985 and 2021 for more insights into these yearly fluctuations. However, this input data will be out of the scope of this research and is recommended for implementation in future research. An other simplification which is made is the installation location for the wind turbines. Appendix A.4.3 gives details on the wind speed measurement and wind distribution around Grenada. This research focuses on the extended LCOE of the technology and therefore, the location selection is not taken into account. This also includes wind direction, mean wind speed distribution, hub height optimization and the presence of marine traffic lanes.

## 5.6 Electricity generation at Grenada

As discussed in the previous section, a wind turbine does not generate the same electricity output at any wind speed. Appendix figure 48 shows the 3 wind speeds of a wind turbine, which define the 4 phases: cut-in speed, rated output speed and cut-out speed. First, the wind speed below the cut-in speed. At these wind speeds, the wind turbine is not generating any electricity. The second phase are wind speeds at which the wind turbine is generating electricity but below its rated power output. The third is the phase in which the wind turbine is generating maximum power output. The last phase are wind speeds above the cut-out wind speed, in which the wind turbine is not rotating to prevent damage to the wind turbine components. Appendix figure 49 gives an overview of the power curve for a 4 MW wind turbine. Hereby, the cut-in wind speed is 3 m/s and the cut-out wind speed is 25 m/s.

With this power curve and the wind speed overview of St. George from figure 42, the power output over the last year can be calculated, as seen in figure 8. This power output is calculated with the base load model. Hereby, the wind speed is divided in steps of 0.5 m/s and the corresponding output power of the wind turbine, which explains the incremental power output from this figure. To visualize this data in more detail, the power output in MWh is divided per wind speed category per month, as seen in appendix figure 50. This base load calculation is discussed in more detail in section 3.2.2.

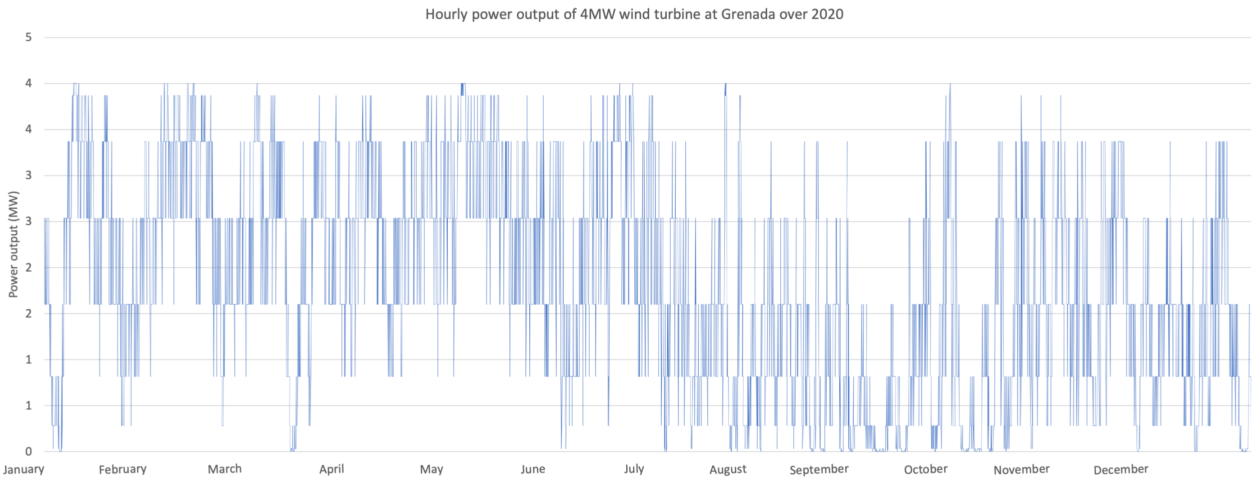



**Figure 8:** Hourly power output of 4MW wind turbine at St. George, Grenada over 2020.

With the hourly power generation, the wind speed data can be validated and checked with the calculated wind capacity factor of the global wind atlas (Global wind atlas, 2018). The wind capacity factor is the energy generated over a set period compared to the theoretical total energy which can be produced by a certain wind turbine (Zappa & van den Broek, 2018). In this case, the energy generation is compared for a 4 MW wind turbine. The calculated total generated electricity output is divided by the theoretical power output of a 4MW wind turbine times 8784 hours (for 2020). This power output will be the theoretical electricity generation of a traditional wind turbine, if system losses and maintenance are not taken into account. This calculation gives the following equation (over a year):

$$Capacity\ factor = \frac{Total\ energy\ generated}{Total\ theoretical\ power\ output} = \frac{15,965.77\ MWh}{35,136\ MWh} = 0.45 \qquad (6)$$

Compared to appendix figure 51, this value is similar to the wind capacity at St. George of the Global Wind Atlas, which shows a wind capacity of 0.43 (Global wind atlas, 2018). This difference in output can be a result of a different wind turbine (different output, cut-in speed, etc), annual hours of maintenance or the step size in the base load calculation, but will not be significant in the system design or LCOE calculation.

# 6 Parameters of the LCOE model

In this section, the cost parameters and input parameters of the LCOE model will be discussed. In the previous sections, the technological details are discussed, components selected, dimensioned and the hourly electricity generation is calculated with the base load model. In this section, first the hydrogen component costs will be analysed with the selected products from chapter 4, then the fixed and variable costs, which gives an insight into the scalability of costs of a wind turbine farm. Lastly, an overview of the financial input values will be discussed. Appendix figure 57 gives a detailed expensive overview used in the LCOE model.

## 6.1 Hydrogen technology pricing

In this section, the cost per hydrogen component will be analysed. The hydrogen technology for offshore use is not in a matured phase yet. Therefore, the price of these components will only be an approximation determined by public available information, manufacturers and scientific research. Due to this early phase of development, component manufacturers will not determine a set price for the components in this system, but only an estimation based on capacity. In the next paragraphs, the cost analysis and justification for each of the components is outlined, whereby the components are analysis in the order in which they are used in the hydrogen process.

The first component in the hydrogen process is the desalination system. As described in chapter 4, the reversed osmosis (RO) technology will be used. For the price analysis of desalination systems, the price per $m_3$ of fresh water daily production capacity is calculated. According to research the costs are between \$900 - \$1200 per $m^3$ (Khawaji, Kutubkhanah & Wie, 2013). For this hydrogen system desalination equipment is selected which is capable of producing 5 $m^3$/hour, which results in 120 $m^3$ per day. Because of the best case selection, the \$900 value will be used in the calculation. The required rinse tank is taken into account for this cost analysis.

The price of the electrolyzer system is calculated with a price/power in watt (W) output ratio. The price per watt and the price forecast are analysed by several research institutions. However, due to the development stage of the technology, the price analysis difference between these studies. The Bloomberg research differentiate Western and Chinese electrolyzers, because of the differences in production costs. As discussed in 4.2.2 the price between the Alkaline and PEM electrolyzer technology differs, because of the maturity and availability of materials. The Bloomberg research states for small electrolyzers (50 kW) a price of 14 \$/W of installed capacity and 1.4 \$/W (€1.2/W) for a large-scale system (2-3 MW) (Bloomberg NEF, 2019). An even more optimistic price analysis is the research from Irena. This research has analysed a 700-1000 \$/kW in 2020 and a price forecast of <200 \$/kW in 2050, but this is only for the electrolyzer stack and not for the entire system (IRENA, 2020a). For this research the electrolyzer price (stack and BoS) of the Bloomberg research is used. The total power output of the selected components is 3 times a 1 MW Frames system. Therefore, the large-scale system price of €1.2/kW is used. According to market analysis the electrolyzer price can easily be reduced by 45%. By scaling up to 70 GW of total installed electrolyzer systems can already lead to unit costs of \$400 per kW (0.4 \$/w), hereby the costs for the balance of system needs to be added (Bloomberg NEF, 2019). The initial investment costs are challenged with the electrolyzer manufacturer for validation of the input data. Their feedback on price a cost of €1.2/w was positive; they expected it to be around 0.8-1.0 for a standardized system. However, with the development costs for a dedicated wind turbine electrolyzer, these costs indeed would increase up to the used €1.2/W (Frames Group, 2021).

The costs overviews for compressors are wider public available. This is due to the fact that hydrogen compression is already in use, also in larger output systems. According to (Richardson, Fisher, Frome & Smith, 2015) and (Pure Energy Centre, 2021), the costs for a compressor system are between €40,000 and €140,000 per compressor, depending on the compression. This price will drop even further if the technology is even further matured and the demand will grow (Rivard, Trudeau & Zaghib, 2019). Because of the overdimensioned compressor system the €40,000 should be sufficient. These input variables will also be challenged in the sensitivity analysis, whereby the influence of this decision will be analysed.

The costs of the hydrogen storage tank are determined by the amount of stored kilograms of $H_2$ and per kWh of stored energy of $H_2$. As discussed before, the maximum storage requirement of the tank is 6,447 kg of hydrogen. Small hydrogen tanks would not be financial feasible for a hydrogen storage system, with prices up to $1400 / kg of hydrogen (Hormerenergy, 2016). This is due to the economy of scale and the non-linear volume increase by small increases of construction material. For large scale storage tanks there are 3 materials types: all metal, metal with composite overwrap and metal-liner full composite tanks. The costs for the first type, with an all metal construction, start at $83/kg of stored hydrogen. The second type of storage tanks are the metal tanks with composite overwrap. These tanks have a higher energy density for the overall system, due to the lower tank weight, but are not capable of storing hydrogen at pressures above 200 bar. These hybrid-composite tanks are more expensive, with $86 / kg of stored hydrogen. The last types are the metal-liner and full composite tanks, which are capable of operating pressures up to 700 bar in combination with lower weight. The downside of these tanks are the costs: $700 / kg of stored hydrogen (Rivard et al., 2019). For this research the full metal storage tank will be used, with the lowest cost/kg price of €69.72/kg of $H_2$. This is because of the lower initial investment and the lower impact of a heavier tank on the total system compared to, for example, vehicles.

The price of fuel cells is fluctuating per research and per forecast. The reason for this fluctuation is the technological development and the increasing demand of fuel cells. This increase in the economy of scale is decreasing the costs. According to research from Berkeley, the stack costs for a low temperature PEM fuel cell are between $556.13 and $238.22 per kWh (Gosselin, 2014). In this CAPEX value, the operating and maintenance costs ($14.60 and $5.25 respectively) could be eliminated, because these costs are converged in the O&M value in the LCOE, as seen in appendix section A.5. After validating with a fuel cell expert from Nedstack, a price per installed capacity of €3/W instead of outputted power is recommended (Nedstack, 2021). This makes the system scalable and independent of the operational hours, which will be used in the LCOE calculations.

Table 18 gives an overview of the used unit prices per component, the required unit size and the total prices per components. These costs are applicable for a single wind turbine structure, but can be scaled with the number of WTG's in the system.

| Component | Unit price | Required output (per WTG) | Subtotal price (per WTG) | Reference |
|---|---|---|---|---|
| Desalinator | € 756/$m^3$ of daily production capacity of produced water | 5 $m^3/h$ | € 90,720 | (Khawaji et al., 2013) |
| Electrolyzer | € 1.2 / watt | 2.5 MW | € 3,600,000 | (Bloomberg NEF, 2019) |
| Compressor | € 40,000 per unit | 2 units | € 80,000 | (Pure Energy Centre, 2021) |
| Storage tank | € 69.72 / kg of stored H2 | 6,447 kg of H2 | € 449,510 | (Rivard et al., 2019) |
| Fuel cell | € 3 / watt | 1.5 MW | € 4,500,000 | (Nedstack, 2021) |
| **Total hydrogen component cost per WTG** | | | € 8,720,230 | |

**Table 18:** Overview of the hydrogen component costs (€1 = $0.83).

## 6.2 Fixed cost of the system

The LCOE calculation consists, besides the hydrogen component cost pricing, of multiple parameters. Some of these parameters are fixed and do not change when the project size is scaled. Some simplifications are made in this LCOE calculation whereby the values are set as a fixed price, but can scale if the farm size is changed a lot. This will be explained in more detail in the following paragraphs.

**Development and project management** The first fixed costs are the development and project management costs. These costs consist of surveys for environmental, geological and hydrological analysis. This cost element also consists of the development costs, which are required for the engineering and design of the hydrogen and wind turbine system, optimized for the selected location. Because these surveys and designs are required to be executed, independent of the size of the project, these costs are fixed. However, if the scale of the project is really large, some costs can be shifted. For example, really large wind farm areas will have more expensive surveys. However, the project size of the different scenarios in this research are quite similar and therefore, the scaling does not need to be taken into account.

**Installation and commissioning** A part of the installation and commissioning costs are fixed. These costs consists of travel and transport expenses, project management during the installation and the insurance, weather forecasting and other prerequisites required for the installation.

**Operation, maintenance and service** For the operation and maintenance of wind turbines, fixed costs such as training, logistics and health and safety inspections are implemented. In the LCOE model the assumption is made that these costs are independent of the size of the maintenance. This is true if the scale is not really different from the smaller farms, which is applicable for these remote locations.

## 6.3 Variable costs of the system

Besides the variable costs of the hydrogen system there are multiple other costs which are scaled with the number of WTG's, the length of cable or the power output. In the following paragraphs, these variable costs will be discussed.

**Wind turbine and foundation procurement and installation** The foundation and the wind turbine generators are scaled per MW. Larger wind turbines, with larger power outputs, require a more expensive foundation and a more expensive rotor, nacelle and tower. However, in this research, the installation costs of these wind turbines are scaled with the number of

WTG's. This is because the important parameter in this phase is the number of installations, instead of the size. If the wind turbine is much larger, this assumption is not valid anymore. This is due to the more expensive vessels which will be required.

**Operation and maintenance wind turbine and hydrogen components** The variable operational and maintenance (O&M) costs are divided in the WTG O&M and the hydrogen O&M. A simplification in the model is that the annual costs are taken as a constant value over the lifetime. Therefore, the average value will be used annually to take the O&M fluctuations into account. The variable O&M of the WTG's costs are scaled with the number of WTG's. In the LCOE model, per 3 WTG's one engineer is calculated. This is relatively high, but necessary due to the added hydrogen components. After the installation, the operational and maintenance are the main costs during the lifetime of the wind turbine.

The OPEX values of the hydrogen components are variable with the output or connected to the CAPEX of the component. The following O&M costs are determined without the required engineers, as discussed. For both the electrolyzer and the fuel cells an O&M costs of €0,0042/kW is used (Steward, Saur, Penev & Ramsden, 2011) (Mongird et al., 2020). Hereby only the basic O&M costs are taken into account because of the replacement of the total hydrogen system every 10 years and therefore replacement costs are allocated in these investments. For the hydrogen compressor and the desalination system, a percentage of their CAPEX is used; 3% for the compressor (Jepma, Kok, Renz, Schot & Wouters, 2018) and 2% for the desalinator (Gao, Yoshikawa, Iseri, Fujimori & Kanae, 2017).

**Decommissioning costs** After the lifetime of 25 years, the wind turbine, foundation and related components for the hydrogen system and transport of electricity need to be decommissioned. Therefore, a set price per WTG and hydrogen component is calculated. For the hydrogen system these decommissioning costs are taken into when the system is replaced. In addition, the decommissioning costs are adjusted for the interest rate with the growth rate value. Depending on the scale, location and number of wind turbines, this decommissioning price can alter. An important note on the decommissioning cost of the hydrogen is that it is uncertain if components can be reused or recycled, which will have a major impact on the decommissioning costs and is therefore recommended for future research.

**Pricing of electricity cables** The electricity cables, used to transport electricity from the wind turbines to shore, are a variable cost depending on the number of WTG's and the WTG layout. Transportation of energy induces large losses in the energy system. Decreasing these losses can have a major impact on the feasibility of a technology. Wind generated energy can be transported by pipeline, vessel or cable, depending on the energy carrier. Each of these transportation methods have their challenges andopprotunities (Franco et al., 2021) (Dinh et al., 2020). In general, remote locations do not have the infrastructure or demand for hydrogen as energy supply. Therefore, only electricity by cable will be analysed in this research. However, transportation of hydrogen by pipeline with a conversion station onshore can decrease the losses and costs, but also requires cooperation from third parties, which makes the technology roll-out more complex, as discussed in chapter 1. Currently, there are already multiple researches on offshore wind-to-hydrogen with local storage systems for onshore applications. These onshore systems can be used in a grid-connected system, where they supply electricity or hydrogen, and can be used in an off-grid system for storage (Yang & Aydin, 2001). Different transportation are out of the scope of this research, but are recommended for future research. In the following price calculation, the layout is assumed as parallel strings whereby the number of strings depends on the number of WTG's. Optimizing this WTG layout is recommended for future research.

There are multiple types of offshore cables: high voltage direct current (HVDC), high voltage alternating current (HVAC) and array cables. HVDC has the lowest transportation losses, but also the highest CAPEX (>€1m per meter), due to the invertor, required for the AC-DC-AC conversion, and cable costs. This makes DC interesting for distances to shore of more than 60 km (Xiang, Merlin & Green, 2016). HVAC cables have a lower CAPEX compared to HVDC, but higher than array cables and are used as a single electricity cable for substation-shore connection. These cables cost between €1,200,00 and €2,500,000 per kilometer depending on the specifications (Van Oord, 2021)(Blix Consultancy, 2020). Array cables are used for the interconnection between the wind turbines in a wind farm and the substation. They can also be used for low power transmission from the wind farm to shore. Depending on the type of cable, an array cable cable can connect up to 6 wind turbines in series (Mokhi & Addaim, 2020). In this research, the array cables are used in between the wind turbines, connected in series of 4 with a distance between the turbines of 5 times the rotor diameter of 117 m, and to connect to shore (Van Oord, 2021). The price of cables depends on the thickness of the cable and therefore the amount of copper which is required. Cable thicknesses range from 300 $m^2$ to 2000 $m^2$ for HVAC cables. The required cable depends on the maximum amperage which needs to be transported. This amperage can be calculated with equation 7, whereby the $P_n$ is the nominal power, $V_{LL}$ is the cable voltage and $\cos(\phi)$ is the power factor which accounts for the load losses in AC cables (Schachner, 2004).

$$I_s = \frac{P_n}{\sqrt{3} * V_{LL} * cos(\phi)} \tag{7}$$

In the researched scenarios, a voltage of 66 KV is used, which will give an amperage per array cable of 147 amperes. For this amperage, a cable with a thickness of 300 $mm^2$ and a CAPEX of €150/meter will be sufficient (Abb, 2010)(Van Oord, 2021). For a single wind turbine an amperage of only 37 amperes is required. This cable is overdimensionized for the single wind turbine scenario and will heavily impact the LCOE of a single structure.

## 6.4 Financial input variables

**Energy losses in the system** The total efficiency of a wind turbine will have a major impact on the energy production and therefore the LCOE of a wind turbine. The efficiency will be impacted by the following factors, whereby not all these factors will be applicable for the Grenada location:

- Substation, BOP and Grid availability
- Electrical losses
- Blade Degradation
- Performance degradation due to icing
- High wind speed hysteresis
- Power curve performance
- Sub optimal operation
- Curtailment - noise, visual and environmental
- Curtailment - Maximum rated capacity
- Future improvements

For the Grenada scenario, the total energy losses are around 5% of the total energy production, which is used in the LCOE model (Van Oord, 2021). One of the larger system losses are the transportation efficiency. Transportation of energy induces losses in the amount of energy. These losses are in the range of 0.8% of the transported electricity per 100 km for a cable with alternating current (AC). In this research, a distance to shore of 10 km is taken into account, which result in an electricity loss of 0.08% of the total generated energy. Direct current cables (HVDC) will decrease these electricity losses to 0.04% of the total energy generation, but this difference will not be financial feasible to justify the higher CAPEX, as discussed before (Blix Consultancy, 2020).

**Percentage of unforeseen** As discussed before, this technology is not matured and still in the development phase. Testing this technology in a real-life situation, as a pilot, will decrease these uncertainties. To accommodate for this new technology, a relative high percentage of unforeseen cost expense of 10% will be taken into account. This percentage is calculated over the total of capital investment costs, such initial investment and installation costs.

**Operation and maintenance growth rate** Due to the financial interest the O&M costs are increasing each year. The growth rate is used to account for this interest rate. For the LCOE calculation, a growth rate of 2% per year is used. This is relatively high, but will also take into account financial uncertainties. Therefore, the growth rate will be analysed with a sensitivity on its influence on the LCOE, as discussed in section 7.3.

**Lifetime of the wind turbine and hydrogen system** Currently, wind turbines have a lifetime of 25 years. Improvements in technology, the availability of new materials and the positive effect of a longer lifetime for an offshore wind turbine increase this lifetime even further. However, hydrogen production and reconversion components have a limited lifetime, as discussed in section 4.3. Therefore, these components (desalination, electrolyzer and fuel cells) will be replace after 10 years. If these components prove to withstand the constant use and do not need to be replaced, the LCOE will be lower than this calculation. However, due to the current maturity of technology this replacement is taken into account in this research.

**Discount rate** As discussed in chapter 2, the discount rate will adjust for the value of money over time (Investopedia, 2013). The costs weighted with the discount rate give the net present value of these costs. The amount of produced electricity is also converted with the discount rate, as seen in equation 1, into the NPE of the total energy output. Due to the high investment risks related to the new technology and the assumed 100% own equity, a discount rate of 10% is used in the LCOE calculation of this research.

The assumption to use 100% equity is used because of the independency of the financial parameters. If financial debt structures are taken into account this will have a major impact on the LCOE, as seen in the results. Therefore, a 100% own equity will minimize the influence of the stakeholders and will emphasis the competitiveness of the technology. In reality, a project is seldom financed with 100% equity. Mainly because of the lack of financial assets and to mitigate risks. Depending on the financial structure and the repayment time the LCOE can be increased or decreased.

## 6.5 Conclusion

In the previous paragraphs the costs for the hydrogen production, storage and reconversion system are uncertain. Economy of scale, technological developments, supply and demand of components and long-term contracts will have a large influence on the initial investment costs. Therefore, there are no assumption made on a decreasing LCOE by major cost reductions. In section 3.3 the LCOE method selection is discussed. In section 6.1, an overview of the costs of the hydrogen production, storage and reconversion components is given. The components of the hydrogen system are part of the initial investment. Besides these components costs several other elements Within the LCOE calculation will influence the final LCOE value. Within these investments costs the wind turbine generator (WTG), the foundation and export cable are also included. Table 38 gives an overview of these costs. Each of these costs; fixed, variable and financial input are discussed. To determine the influence of the financial parameters a sensitivity analysis on these values will be performed in section 7.3. This will shows the impact of the value and therefore the error marge if an assumption will deviate from the selected input value.

# 7 Results

In this section, the results of the base load analysis, the LCOE analysis, the sustainable impact and the sensitivity analysis of these values will be discussed.

## 7.1 Base load mismatch

To determine the costs involved in the system, an analysis on the base load and mismatch in power is required. In the first iteration, a base load requirement of 1.5 MW is assumed as the power output. This base load assumption is based on the input values of the first design iteration, as seen in appendix 34 and appendix 24. In the second iteration, optimized base loads will be selected as different scenarios, which will output the LCOE.

To determine the effectiveness of a hydrogen system, the security of supply, in percentages, is compared between a 4 MW wind turbine with and without a hydrogen system, as seen in figure 9. The security of supply is the amount of hours per year that the required base load can be provided divided by the total amount of hours in that year. This figure shows that a traditional wind turbine has a security of supply of 68%, whereby the addition of a hydrogen system the security of supply will increase to 86% (+18%) for a 1.5 MW base load. In this system, there are no outages due to maintenance calculated, because these values will be applicable for both systems. This makes the values in this figure comparable. An additional side note on these values is the influence of the step function on the power generation of the hydrogen system. The power generation is simulated in different steps, which change the security of supply for a 1.5 MW base load from a smooth power curve to a stepped function. This difference can be neglected because of the small deviation this step function has in the total system (losses, outage due to maintenance, etc.).

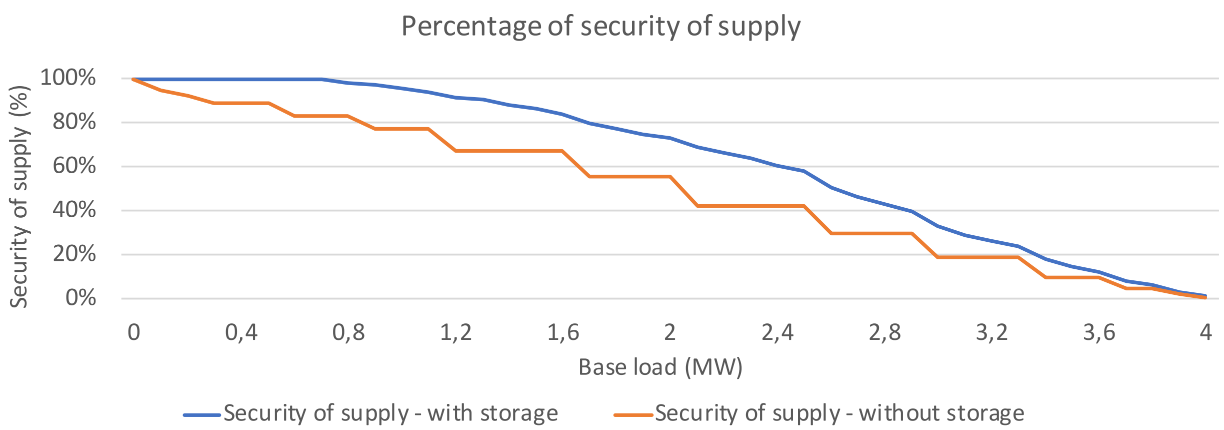



**Figure 9:** Percentage of security of supply.

To get insight into the moments of shortages figure 10 shows the status and shortages during the year for a base load of 1.5 MW. From this figure can be concluded that the supply and storage are not always sufficient for the base load requirement. This figure shows again that most of the outages are during the summer months. This can be explained by the decrease in wind speed during the summer months. To increase the total security of supply on the island this hydrogen wind turbine system can be complemented by, for example, solar energy, which has a reverse proportional power output during the year (higher energy production during the summer months). But this will be out of scope of this research. This figure also shows that the storage volume is not sufficient for the amount of energy which can be stored.

This is clearly visible at the flat peaks of the blue curve. During these moments, the storage is at the maximum storage capacity and will lose energy which otherwise would have been stored in the hydrogen storage tank.

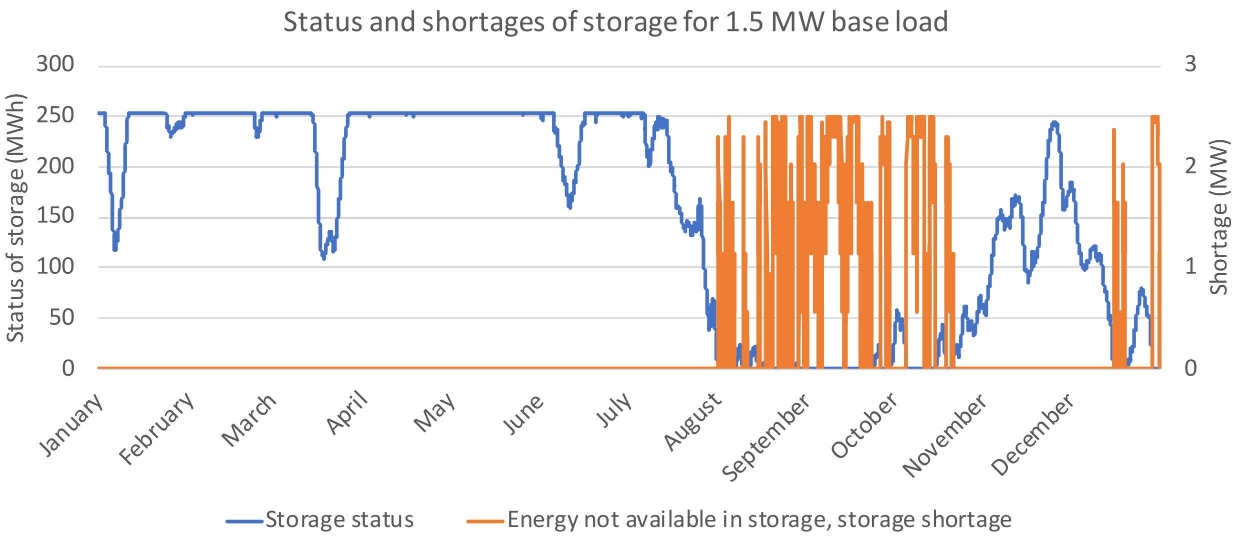



**Figure 10:** Status and shortages of storage for 1.5 MW baseload.

As discussed, the volume of the hydrogen storage will influence the security of supply of the total system. A large volume will provide a higher (full) start volume of energy and less energy loss due to an overfill of the storage. As discussed and seen in the figure, the storage volume starts full as a result of hydrogen production during testing of the WTG and hydrogen components, as discussed in section 3.2.2. Figure 11 gives the security of supply for 6 storage volumes: 50 MWh, 150 MWh, 254 MWh which is the selected storage volume, 1000 MWh, 2000 MWh and the maximum storage requirement of 3483 MWh, plotted against the base load. These plots show that the increase in volume and the relation to the security of supply are not linear. An increase for smaller storage volumes has a larger impact on the total security of supply compared to the larger volumes. This can be explained with figure 10; there will only be an impact on the security of supply if the storage volume is not sufficient to meet the base load requirement. In other words, if the storage is empty. Therefore, it is important that the wind turbine is able to fill the storage volume. Concluding regarding the storage volume, increasing the volume is only beneficial if there are moments of overproductions and increasing this volume will be increasingly expensive at larger storage volumes.

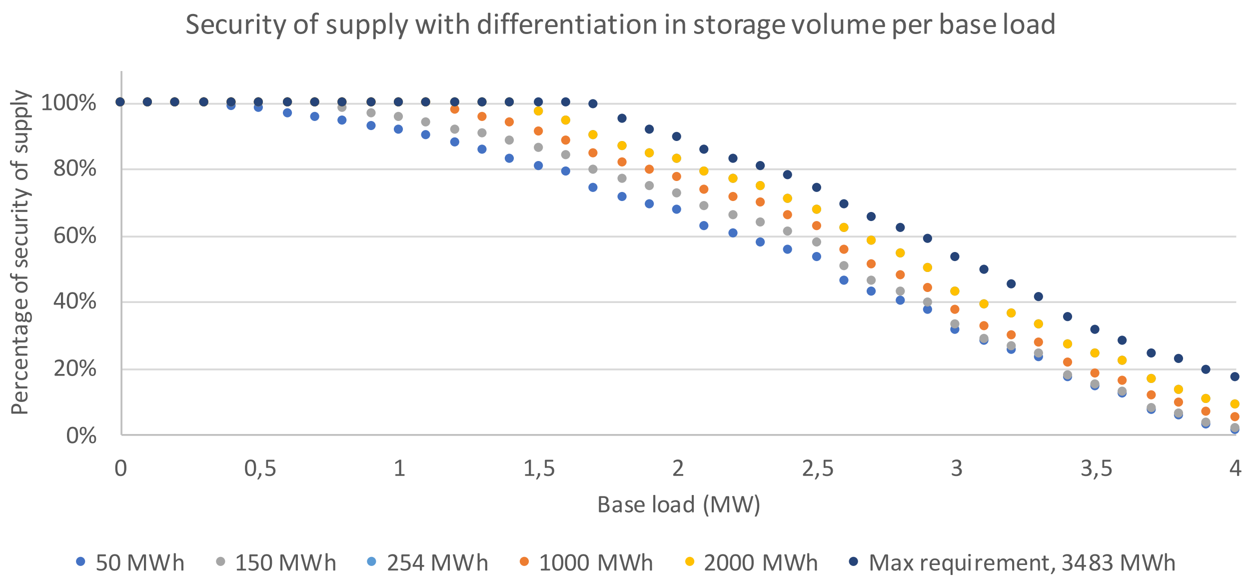



**Figure 11:** Security of supply with differentiation in storage volume.

There is a strong correlation between the security of supply, the base load and the overproduction (or wasted energy) in the system. Figure 12 gives a hypothetical schematic overview of this correlation and the influence of the increase of the storage capacity and the security of supply. In this overview the shortage of supply (the inverse of the security of supply), the storage capacity and the overproduction (wasted energy) are given. Depending on the demand side (TSO) of the location, the overproduction of the wind turbine system is wasted, whereby the wind turbine output is restricted (curtailed) or is provided as overproduction with a lower energy price, as discussed in section 3.2.1. In this overview, the base load will always shift with the storage capacity and will be visualised as an upper limit. In situation 1, there is a balance between these factors for a selected base load. In situation 2, a decrease in shortage of supply is required and therefore the storage capacity is increased. This will result in the same overproduction but also increase the costs of the hydrogen system and the need for a larger available space inside the monopile. To decrease these costs with the same low shortage of supply, the base load can be lowered, as seen in situation 3. This will reduce the costs, but on the other hand increases the overproduction or wasted energy.

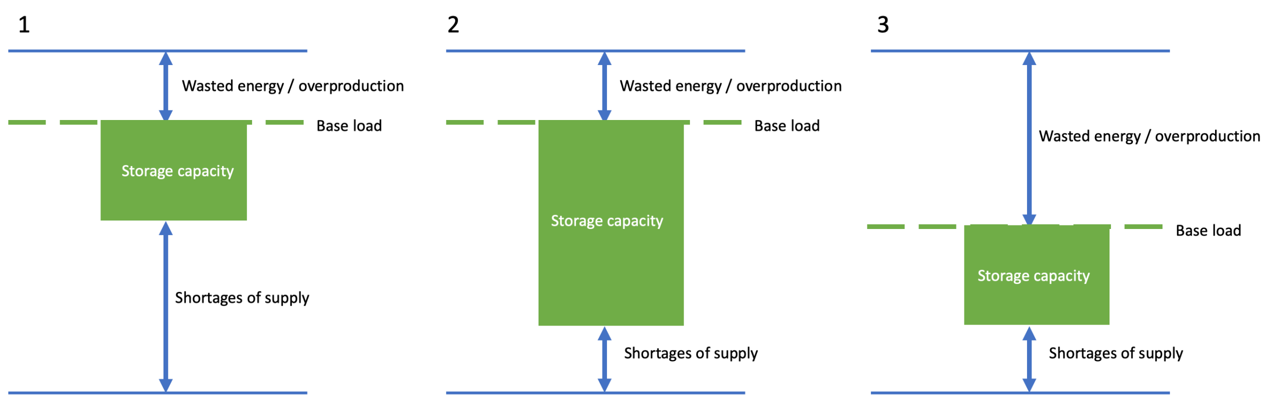



**Figure 12:** Correlation storage capacity, security of supply and overproduction. First an increase of storage then a decrease of storage with lowered base load.

As seen in this example, the shortage of supply, the hydrogen system and the wasted energy are connected. Decrease one of the values will result in altering the other variables. This correlation can also be analysed visually over the different base loads (0-4 MW). Figure 13 shows clearly that an decrease in wasted energy/overproduction, by increasing the base load requirement, will increase the shortage of supply. As discussed, an increased shortage of supply is the same as an decrease in security of supply.

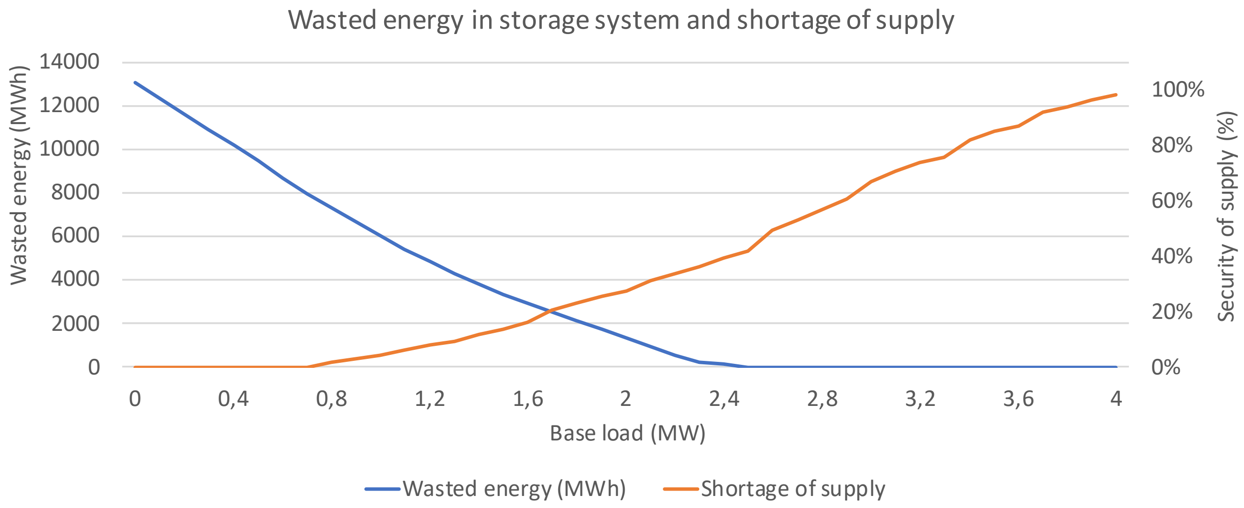



**Figure 13:** Wasted (overproduced) energy in the storage system (MWh) plotted against the shortage of supply.

The first iteration is based on a 1.5 MW assumption. Whereby, in the second iteration, an improved system is designed, based on the SoS requirements. For this analysis of this system, three values are important, as discussed in section 3.2.2:

- The maximum base load with which a security of supply of 100% can be provided, because this will make a 100% transition from diesel generated electricity to a wind generation system possible.
- The base load value which at least can provide a 80% security of supply. This value is determined in discussion with Van Oord as a respectable starting point for the security of supply for island with backup power
- The base load with the highest base load versus the security of supply.

Figure 56 gives an analysis of these three values, with the variables as discussed. For the first value, the maximum base load with 100% SoS (system of supply), the maximum base load is 0.6 MW. The second system requires a 80% or higher. Hereby, 1.6 MW will provide a Sos of 83.8%. The last researched scenario is the base load, whereby the combination between the security of supply and the generated base load are maximized. This is important because a high SoS will waste more electricity but a high base load will have a lower SoS and is therefore not suitable for a location where the overproduction can not be used or there is a lack of backup power. As seen in the figure below, the optimum SoS versus base load (%*MWh) is at a base load of 2.3 MW. This can also be seen as the realisation rate of the electricity output. Because the capability of using overproduction is beneficial for the LCOE and can be used at locations, other than the selected case, the overproduction is also compared in the following tables. However, the actual use of this energy is depending on the location.

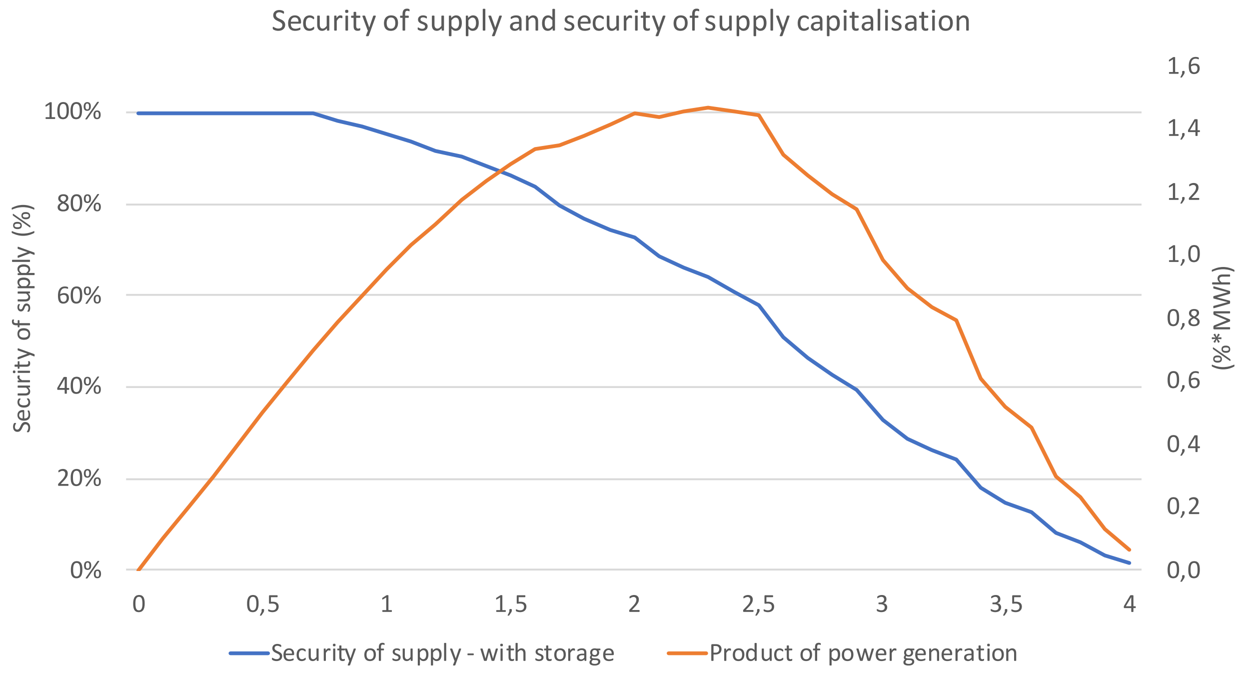



**Figure 14:** Security of supply and total energy generation with a storage volume of 314 $m^3$

Table 19 gives an overview of the energy output for the three base load scenarios, as selected in the previous paragraph. Appendix figure 56 gives an overview of the security of supply and total energy production per base load. The power outputs from the table are analysed for the use without overproduction, where the overproduction is wasted (curtailment) and for a situation in which the electricity can be used. This table shows that the storage capacity for the 100% SoS is too small; only a third of the electricity can be used, the rest is wasted. The annual power production of larger base loads is increasing. Lower base loads will convert more electricity into hydrogen and therefore induce more energy losses. Higher base loads will transport more electricity directly to shore, which will decrease these losses.

| Base load | Security of Supply | Annual power output | |
|---|---|---|---|
| | | Without overproduction | With overproduction |
| 0.6 MW | 100% | 5,270 MWh | 13,978 MWh |
| 1.6 MW | 83.8% | 12,419 MWh | 15,400 MWh |
| 2.3 MW | 64% | 15,781 MWh | 16,043 MWh |

**Table 19:** Security of supply and generated electricity, without and with overproduction, per base load scenario.

## 7.2 LCOE results

With the design parameters from the system optimization and input from experts, manufacturers and Van Oord, the LCOE output of the selected base load systems can be analysed. The scenarios which are tested in the following paragraphs are:

- A wind turbine farm, designed for Grenada, with a base load power output of 20 MW, the number of wind turbines will be adjusted to the selected 3 base loads (as listed below)
- A single wind turbine structure with hydrogen system, with the base load of 1.5 MW to analyse the selected components for a single structure
- As reference; a wind turbine farm, with the same input parameters, but without the hydrogen system

As discussed in the previous paragraphs, these scenarios will be tested with the following base load parameters:

- Base load of 0.6 MW for a 100% security of supply
- Base load of 1.6 MW for a minimal of 80% security of supply
- Base load of 2.3 MW for a maximized annual power output

### 7.2.1 Hydrogen wind turbine scenario for Grenada

First, the three Grenada scenarios will be analysed. The system is designed for Grenada's weather and locations conditions, however this system can be added to all the wind turbine designs. For this Grenada scenario the three base loads, as discussed in section 7.1 are analysed: 0.6, 1.6 and 2.3 MW. As discussed in section 5.6, Grenada does not has an extensive energy network or large industry which can profit from a large electricity supply. Therefore, the wasted energy, which is excess of the overproduction which is stored in the hydrogen tank, is not used. In practice the wind turbines are curtailed to prevent overproduction, excess to the storage capacity.

**LCOE results of the Grenada scenarios** Grenada has a base load requirement of 20 MW. Therefore, the total annual electricity output that the system will produce need to meet this base load requirement. Hereby, the number of wind turbines will be adjusted to this base load. Table 20 shows the number of turbines, SoS, electricity generation and LCOE of the three base load scenarios for Grenada. The LCOE is the energy price directly after the transportation to shore. Additional transportation losses, CAPEX and OPEX for the process between the cable that is connected to shore and the end-user (consumer) are not taken into account. From this table it can be concluded that the LCOE decreases when a higher base load is selected. This is a result of the low energy production (high amount of wasted energy) for smaller base loads, whereby the CAPEX is not decreased linear with the power output compared to higher base loads. Also the table shows that the total energy output does not meet the total annual electricity demand of Grenada (185.1 GWh). According to this table, a part of the wasted energy could be used. Because the price agreement is based on a base load output, the price will be different from the base load pricing. However, due to the start/stop costs for a wind turbine and hydrogen system it can be more cost effective to sell the "wasted" energy against a lower price than curtailing the system. For this optimization a more detailed research on the influence of curtailment and start-stop cycles of hydrogen system is required and therefore recommended for further research. For each combination of input parameters and selected base loads there is an minimum LCOE.

Important for the LCOE results is the variable hydrogen system layout for the different base load requirements. Whereby, at the single hydrogen wind turbine structure, the electrolyzer capacity is 3 MW, as discussed in section 4.3.3, are the components for this LCOE calculation scaled to the selected base load.

| Base load | WTG's required for 20 MW | Security of supply per WTG | Annual power output per WTG | Annual power output total | LCOE |
|---|---|---|---|---|---|
| 0.6 MW | 34 | 100% | 5,270 MWh | 179.2 GWh | €604.03/MWh |
| 1.6 MW | 13 | 83.8% | 12,419 MWh | 161.5 GWh | €289.52/MWh |
| 2.3 MW | 9 | 64% | 15,781 MWh | 142.0 GWh | €246.53/MWh |

**Table 20:** LCOE results of the Grenada wind turbine system scenarios, calculated with a required total base load of 20 MW.

**Cost distribution of Grenada scenarios** To determine the influence of the base load on the cost distribution the three scenarios are compared in the table below. For a visual representation of these values, see appendix figures 58, 59, 60 and 61 From this table the relation between the increase in base load requirement and cost distribution is shown. The following results can be drawn:

- The total CAPEX is decreasing if the number of WTG's is decreasing. The price per WTG is decreasing if there are more WTG's required. This is due to the economy of scale and the allocation of fixed costs over a larger number of wind turbines
- Despite the CAPEX is decreasing with a higher base load, the percentage of hydrogen component cost over the total CAPEX costs is increasing. This is a result of the larger fuel cell system required for the conversion of hydrogen to electricity, for larger base loads. Because fuel cells are more than 2 times (€1.2 versus €3/watt) as expensive than electrolyzers, the hydrogen/CAPEX ratio will be higher for larger base loads. On the other hand, a larger electrolyzer system is required for smaller base loads for the conversion of excess energy to hydrogen, which makes the system relatively cheaper.
- As a result of these higher hydrogen component costs the percentage of replacement costs, which are a part of the hydrogen component costs, are also higher for larger base load and therefore for more expensive hydrogen systems.
- The largest share of the OPEX costs are variable costs which are scaled with the number of WTG's. The economy of scale for larger wind farms is too small to see a percentual differences.
- The decommissioning costs, despite the adjustment for inflation with the use of the growth rate of 2%, are only a small part of the total costs. The hydrogen components increase the CAPEX, which result in a relatively low decommissioning percentage over the total costs compared to the system without hydrogen storage

| Base load | WTG's | CAPEX | $\frac{\text{Hydrogen costs}}{\text{CAPEX}}$ | Replacement costs | Total OPEX | Decommissioning |
|---|---|---|---|---|---|---|
| 0.6 MW | 34 | 60% | 28% | 31% | 8% | 1% |
| 1.6 MW | 13 | 57% | 32% | 34% | 8% | 1% |
| 2.3 MW | 9 | 55% | 34% | 36% | 8% | 1% |

**Table 21:** Cost distribution for the Grenada scenarios with the 3 base load variations.

**Combined LCOE with hydrogen wind turbines and diesel backup** As seen in table 20, a higher base load and lower security of supply will result in a lower LCOE. Because a lower security of supply needs to be supplemented with the current diesel generators. Therefore, the LCOE of the diesel generated electricity needs to be taken into account. As seen in the data from Grenlec, appendix 62, the average "overall" cost between 2013 and 2018 was €195/MWh. This energy price needs to be taken into consideration when comparing a power output which requires the back-up of a diesel generator. Table 22 gives the LCOE differences for the 3 selected base loads with this added diesel energy price in consideration. due to the lower LCOE of the diesel generator the LCOE is decreasing when there is more diesel energy required. In this overview, the overproduction of the hydrogen wind turbine system is not taken into account. Using this energy can increase the amount of electricity, but will not lower the LCOE below the level of diesel. Thus, a higher base load and therefore a higher amount of diesel generated energy will decrease the LCOE, but also increase the carbon emissions of the system. This will be analysed in more detail in section 7.4.

| Base load | Wind turbine generated | | Diesel generated | | Total LCOE |
|---|---|---|---|---|---|
| | Power output | LCOE | Power output | LCOE | |
| 0.6 MW | 5,270 MWh | €604.03/MWh | 0 MWh | - | €604.03/MWh |
| 1.6 MW | 12,419 MWh | €289.52/MWh | 2725.94 MWh | €195/MWh | €272.51/MWh |
| 2.3 MW | 15,781 MWh | €246.53/MWh | 7391.03 MWh | €195/MWh | €230.09/MWh |

**Table 22:** Total LCOE overview for different base loads with energy losses taken into account.

#### 7.2.2 Single wind turbine scenario

To analyse the influence of components in the system the first iteration of this design will be calculated. This design consists of a single wind turbine with the selected components as discussed in chapter 4 and a fixed electrolyzer system of 3 MW. The LCOE of this single wind turbine system including the hydrogen production, storage and reconversion system, suitable for a 1.5 MW, whereby the overproduction is wasted, is €501.32/MWh. If the wasted overproduction of this system is used at shore, the power output of this system will be higher, as seen in table below. This higher output will lower the LCOE to €390.46/MWh. This second result shows the importance of the total outputted electricity. For this single WTG, the LCOE is also calculated as electricity delivered to shore, including losses and without the profile costs of the TSO.

| Scenario | Base load | Annual power output | LCOE |
|---|---|---|---|
| Single wind turbine<br>without use of wasted energy | 1.5 MW | 11,862 MWh | €501.32/MWh |
| Single wind turbine<br>with use of wasted energy as output | 1.5 MW | 15,230 MWh | €390.46/MWh |

**Table 23:** LCOE results for a single wind turbine with hydrogen system.

The LCOE of a single wind turbine is relatively high. The fixed costs can not be allocated over multiple WTG's, whereby the development & project management, installation costs with travel expenses and the cables have a major impact on the LCOE. Therefore, a single wind turbine system, with or without a hydrogen system, is often not feasible in reality. Figure 61 gives a visual insight into the financial distribution of these costs. The difference between using and not using the wasted energy (22%) is directly converted into a decrease of also 22% in the LCOE.

#### 7.2.3 Comparison with the traditional wind turbine system

To analyse the influence of the hydrogen system on the LCOE, the LCOE of the wind turbine system is calculated without the addition of a hydrogen system and compared with the LCOE results from the previous paragraphs. Hereby, the location input parameters, such as the capacity factor as calculated in equation 6 and number of WTG's from the analysed scenarios will be used.

These input values give a LCOE between €125.10/MWh and €134.22/MWh according to the size of the wind turbine farm. Increasing the number of WTG's will decrease the LCOE because of the cost allocation over a larger number of wind turbines. The annual power output is calculated with the capacity factor of 0.45, number of hours in 2020 and the energy losses in the system. This gives a total annual electricity output of 15,021 MWh per WTG. As seen in the table below, with this output a minimum of 13 wind turbines needs to be installed to meet the 185.1 GWh total annual electricity requirement for Grenada. This will give a LCOE of €130.22/MWh. The reason for these lower LCOE, compared to the LCOE of the wind turbine with hydrogen system, consists of the following aspects: a lower CAPEX because there is no hydrogen system installed, a lower OPEX because there are no additional operating and maintenance costs for the hydrogen system, no hydrogen replacement costs and the decommissioning costs for a wind turbine without hydrogen system will be lower. Hereby, additional financial advantages, such as a lower discount rate because of the higher confidence in traditional technologies, are not taken into account.

| **Scenario** | **WTG's** | **Annual power output (including losses) per WTG** | **total** | **LCOE** |
|---|---|---|---|---|
| Traditional wind turbine | 34 | 15,021 MWh | 510.7 GWh | €125,10/MWh |
| Traditional wind turbine | 13 | 15,021 MWh | 195.3 GWh | €130,22/MWh |
| Traditional wind turbine | 9 | 15,021 MWh | 135.2 GWh | €134,22/MWh |

**Table 24:** LCOE of traditional wind turbine setups without hydrogen storage.

**Comparison of security of supply of traditional single wind turbine** Despite the higher LCOE for wind turbines with the addition of this hydrogen system, the higher security of supply is an advantage of this researched system. To analyse this advantage, the security of supply of the traditional wind turbine system, located at the selected business case Grenada, is added in the following table. In table 25, the same three base load requirements are used for a traditional wind turbine. The hours at which a traditional wind turbine is capable of producing the given base loads are given as a SoS value in the third column. This SoS is compared with the SoS of the wind turbine with hydrogen system at these base loads.

| **Traditional wind turbines** | | | |
|---|---|---|---|
| **Required power output** | **Hours capable of producing power requirement** | **Security of supply** | **Difference of SoS compared to wind turbine with hydrogen** |
| 0.6 MW | 7318 | 83% | -17% |
| 1.6 MW | 5932 | 68% | -15.8% |
| 2.3 MW | 3743 | 43% | - 21% |

**Table 25:** Security of supply for traditional wind turbines at Grenada over 2020, compared with the hydrogen wind turbine system.

This table shows clearly the increase in security of supply when adding the hydrogen system to a traditional wind turbine. The increase in security of supply for the three analysed scenarios is between 17% and 21%. This increase in SoS must justify the increase LCOE, as seen in the previous paragraphs.

## 7.3 Sensitivity analysis of the used input parameters

With the results from the last paragraphs, the question arises what the influence of each of the input parameters is on the LCOE. In this section, the following parameters will be analysed on their influence on the LCOE:

- The CAPEX of the hydrogen sytem
- The replacement costs of the hydrogen system
- The OPEX
- The discount rate

- The growth rate
- The total energy losses
- The base load

These values will be tested and the impact on the LCOE will be analysed. If possible, the single hydrogen wind turbine with a LCOE of €501.32/MWh is selected as reference. In this way, the economy of scale is tried to be eliminated.

#### 7.3.1 Influence of changes in the the CAPEX and OPEX on the LCOE results

Figure 15 gives an overview of the LCOE when the parameters; the initial investment of the hydrogen components, replacement costs and OPEX are varied. The percentage on the horizontal axis shows the percentage of change for the selected parameters. In this figure, there are 3 variations which visualise the sensitivity:

- The LCOE when only the initial hydrogen investment of the hydrogen components is increased. Hereby, the replacement costs are set to the same value as the current "single wind turbine" case and are not increased respectively. This is a scenario in which the hydrogen components are miscalculated, but due to development the replacement costs are in line with the used values for the "normal" case.
- The LCOE when the replacement costs are scaled with the increase in investment costs. In this scenario, the hydrogen components are miscalculated and there is not enough development of economy of scale to decrease the costs over the lifetime of the wind turbine.
- The third case is an analysis in which the sensitivity of the OPEX is analysed. Hereby, the initial investment, replacement costs and the discount rate are adjusted to the "normal" case values, as seen in appendix table 37. This case illustrates a scenario when the investment costs are calculated correctly, but the OPEX costs are higher than anticipated.

As seen in this figure, the influence of the hydrogen initial investment and OPEX are linear. The figure shows clearly that a percentual increase in the initial investment a larger influence has on the LCOE than the same percentage increase on the OPEX. This is partially due to the fact that the absolute value of the OPEX is much lower (roughly €0.6m versus €8.7m). On the other hand, the initial investment is a non-reoccurring investment, where the OPEX increase will have influence over the entire operating life time of 25 years. Adding the replacement costs in this percentual increase analysis will, of course, the LCOE even further. But interesting to see is that the replacement costs have a higher influence on the LCOE than the initial investment costs. The reason for this result is the relative high costs for the replacement of the hydrogen components and the fact that this is a reoccurring cost every 10 years. Therefore, the conclusion can be made that a miscalculation in the hydrogen component investment has less influence on the lCOE than miscalculations in reoccurring costs during the lifetime of the technology.

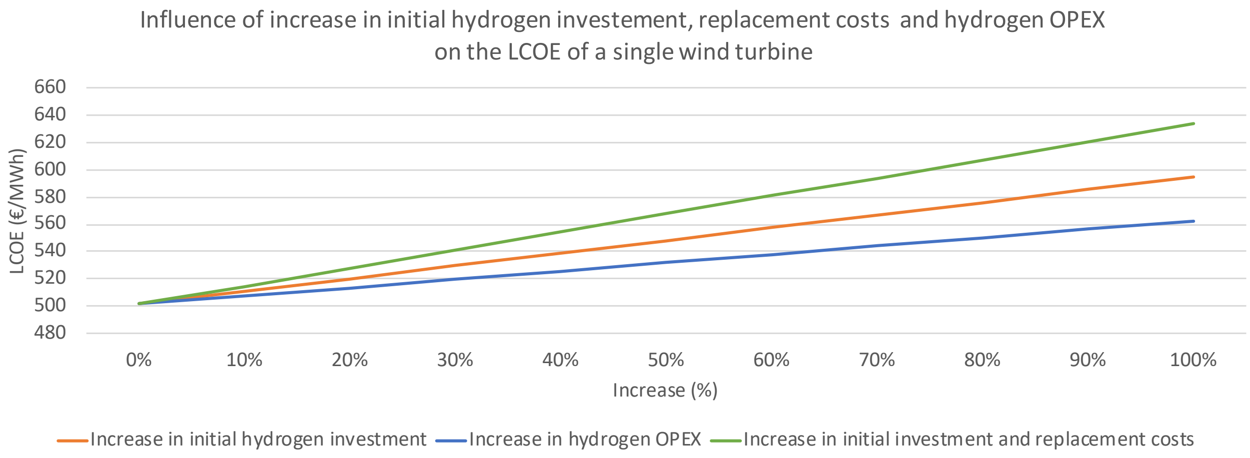



**Figure 15:** LCOE difference by increase of hydrogen CAPEX, replacement costs and total OPEX.

### 7.3.2 Influence of the discount rate on the LCOE results

One of the parameters which has a major impact on the LCOE is the discount rate. In section 3.3 and 6.4 the definition of the discount rate is discussed in more detail. As seen in figure 16, the LCOE does not increase linear when the discount rate is increased. This is a result of the fact that the discount rate is taken both over the costs to convert it to the NPV, as over the power output to create the NPE, as seen in equation 1. Figure 16 gives the LCOE values when the discount rate is increased from 0% to 20%. From this figure the conclusion can be drawn that decreasing the discount rate has a major impact on the LCOE. Therefore, a lower discount rate is preferred the market entry of a new technology. However, this creates a contradiction; a lower discount rate is the result of trust in a matured technology.

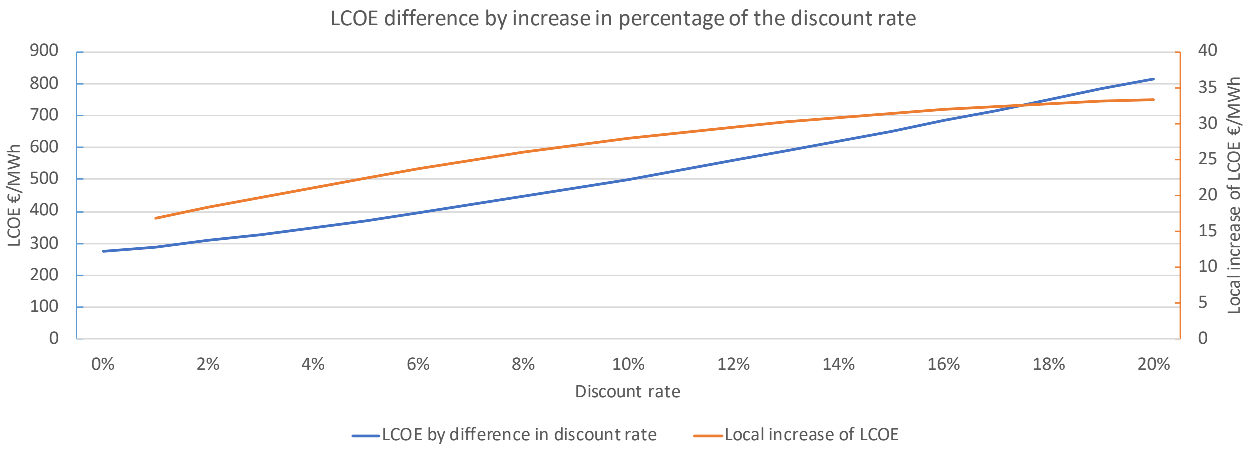



**Figure 16:** LCOE difference by increase in percentage of the discount rate.

### 7.3.3 Influence of the growth rate on the LCOE results

The annual growth rate is allocation of the interest rate over the costs. Figure 17 shows the LCOE, of a single wind turbine, when the growth rate is changed. As standard a growth rate of 2% is used in the LCOE model. This change in growth rate result in an increasing increase of the LCOE, due to the subsequently yearly increase of the interest rate. Therefore a change in growth rate will have a major effect on the LCOE. In this research the growth rate is assumed as stable during the operational years. Accounting for changes in the interest during the lifetime is out of the scope of this research, but needs to be taken into account if a ROI calculation is required.

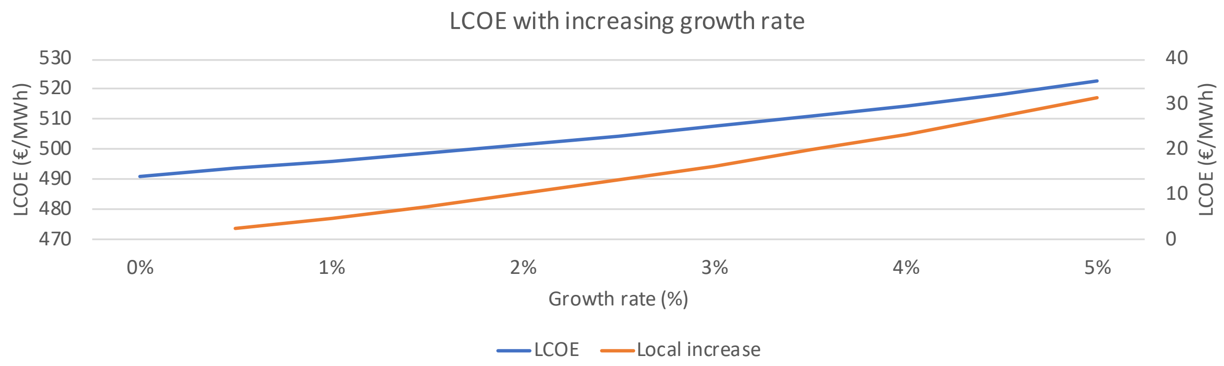



**Figure 17:** LCOE difference by increase in the growth rate percentage.

### 7.3.4 Influence of the total energy losses on the LCOE results

Most of the parameters of the system are changing the cost side of the LCOE calculation and therefore the numenator (NPV) of the LCOE equation. However, the energy losses are influencing the total energy output of the system. Because of the few parameters that influence the denominator (NPE) of the LCOE function a small change in losses will have a major impact on the total LCOE; high sensitivity. Figure 18 gives the LCOE values when the total energy losses of the system are changed, whereby the selected single wind turbine scenarios is calculated with a total energy loss of 5%. As discussed in section 6.4 the different energy losses which can occur in this wind turbine system are discussed.

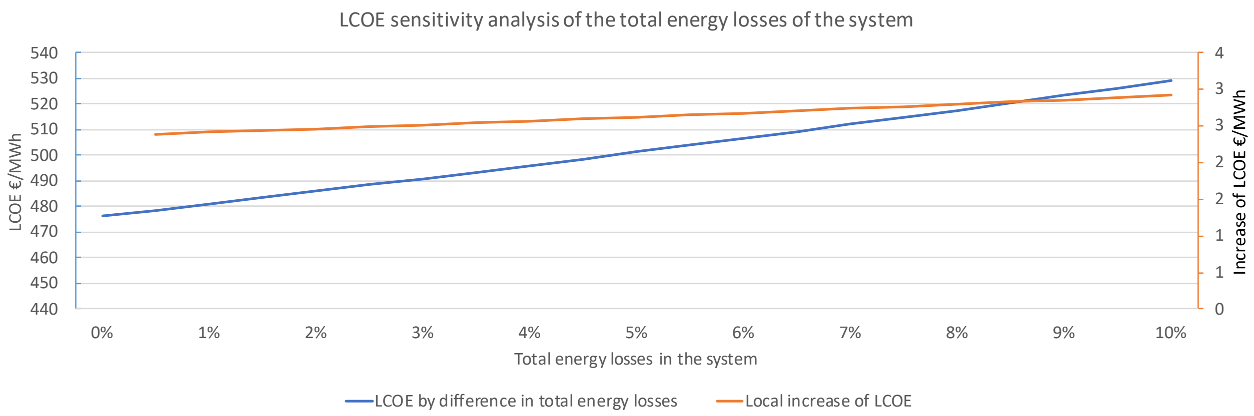



**Figure 18:** LCOE difference by increase in percentage of the energy losses in the system.

As seen in the figure the LCOE is increasing when the system losses are increasing. This can be explained by the fact that the output power is decreasing when the the total costs (investment, OPEX and decommissioning) do not change. Interesting is the local difference of the LCOE, which shows a small increase. This is a result of the power output, which becomes cumulatively smaller with every increase in energy loss.

### 7.3.5 Influence of the base load selection on the LCOE results

As seen in section 7.2, the LCOE is highly sensitive to the selected base load. In these LCOE results the system selection was changed and therefore the LCOE also changed due to a shift in cost distribution. To determine the influence of the base load, the 1.5 MW system is selected and the LCOE is calculated by only a change in base load, as seen in figure 19. This figure clearly shows that the LCOE exponential decreases when the base load is increased.

It also shows that there is a minimal LCOE; for this system at a base load of 2.9 MW, after which the LCOE is slowly increasing.

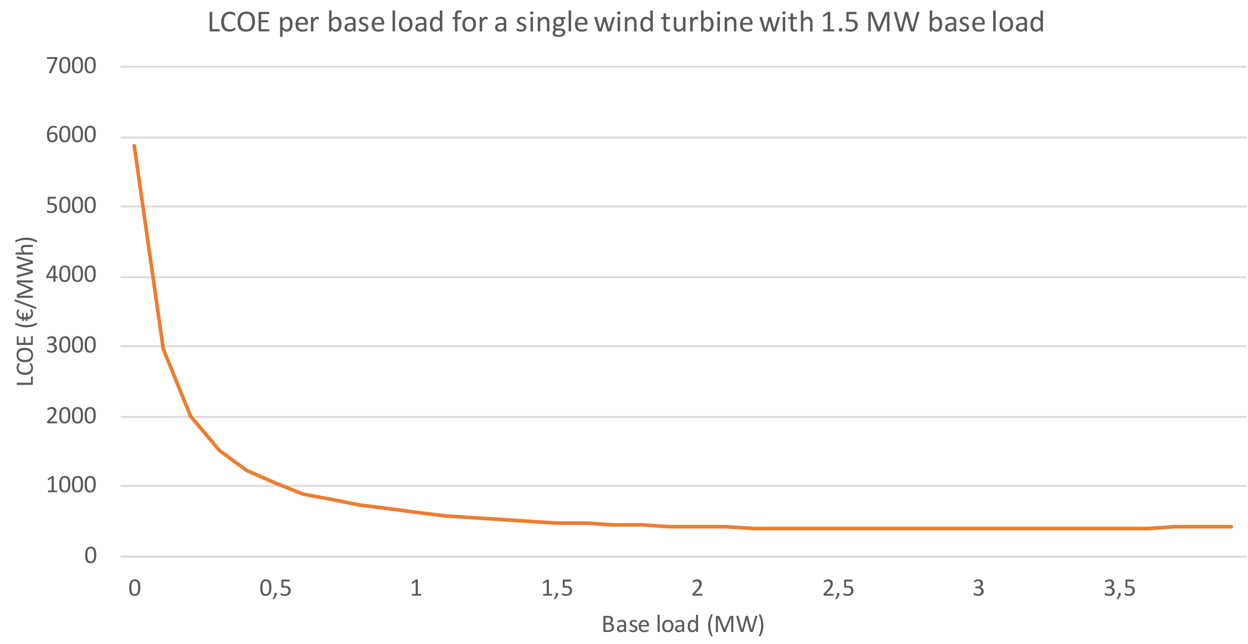



**Figure 19:** LCOE per base load for a single wind turbine, without the use of overproduction or system optimization.

### 7.3.6 Conclusion of the sensitivity analysis

As seen in the last sections, the LCOE is depending on multiple variables. Hereby, an increase in the base load, number of WTG's, power output and storage will decrease the LCOE. An increase in energy losses, discount rate, OPEX, CAPEX, decommissioning costs and growth will however increase the LCOE. There is also an interconnection between the variables, for example the base load, storage volume and CAPEX. These variables will limit the options for decreasing the LCOE. Figure 30 gives a structured overview of the influence on LCOE of all these parameters.

## 7.4 Sustainable impact of the system

As discussed in the section 3, the extended framework of a wind turbine with hydrogen system is analysed. The extension of this LCOE calculation is the renewable impact of the transition from diesel generated electricity to hydrogen producing offshore wind turbines. In the following section, the impact on the $CO_2$ production will be discussed and will therefore give answer to sub question 6; What is the sustainable impact of this technology. With the difference in $CO_2$ the hypothetical financial break-even point is calculated.

## 7.5 Carbon emission calculation

A litre of diesel weights 840 grams and contains 730 grams (87%) of pure carbon. Burning a litre of diesel fuel emits 2.68 kg of $CO_2$ (Hanania, Martin, Stenhouse & Donev, 2015). As seen in chapter 5, the total current annual electricity generation is 185.1 GWh and the energy density of diesel, combusted in a diesel generator, is around 10.62 kWh per liter of diesel. This result in a consumption of around 17.5 million liters of diesel per year at a 100% efficiency. However, large scale diesel generators have only a efficiency of around 30% at there optimal running load (65-70%). Which result in 3.19 kWh per liter of diesel. With the required annual electricity generation of 185.1 GWh, 58.12 million liters of diesel are required, only as fuel for the generators. Hereby 155,669 tonnes of $CO_2$ are emitted per year (Wheeler & Southward, 2017).

To compare these values the $CO_2$ is recalculated in kg of $CO_2$/kWh. As described above a liter diesel produces 2.68 kg of $CO_2$/10.617 kWh of energy (0,252 kg/kWh at $\eta = 100\%$). Wind turbine energy produces between 5 to 8.2 grams of $CO_2$/kWh output power and 6 grams for offshore wind turbines. When the diesel generator efficiency of 30% is used in the calculation, the electricity generated with diesel emits more than 100 times the amount of $CO_2$ compared to wind turbines. The reason for the large emission range (5-8.2 grams) for onshore wind turbines is a result of the larger number of wind turbine projects which are constructed and analysed (Wang & Sun, 2012). Offshore wind has a larger installation carbon footprint compared to onshore turbines, but this is compensated with the higher capacity factor and larger electricity production of an offshore wind turbine (Wang & Sun, 2012). A note on these values is that this are average values over larger wind turbine systems. Smaller systems will have relatively higher emissions: not scalable emissions can not be allocated over a large number of wind turbines or electricity outputs. An example of this is an installation vessel, which induces large emissions, per kWh of electricity, when it is only used for a single wind turbine. Table 26 gives an overview of the emission comparison between diesel and offshore wind turbines.

| | | **Diesel** | | **Wind turbine** | |
|---|---|---|---|---|---|
| | | **$\eta$=100%** | **$\eta$=30%** | **Onshore** | **Offshore** |
| **Emissions** | kg $CO_2$/kWh | 0.252 | 0.841 | 0.005 (cases up to 0.0082 kg) | 0.006 |

**Table 26:** Emission comparison between diesel and wind turbine generated electricity (Wang & Sun, 2012).

### 7.5.1 Impact of hydrogen wind turbines on the carbon emissions

Table 27 gives an overview of the $CO_2$ decrease per scenario. For this comparison, there are 5 scenarios compared to the current diesel generation scenario:

- The traditional wind turbine at 1.6 MW base load
- The Grenada scenarios (0.6, 1.6 and 2.3 MW base loads), supplemented with diesel generated energy
- A 100% hydrogen wind turbine generated energy

The first scenario is the traditional wind turbine, calculated as in 7.2.3. To make this scenario comparable, a 1.6 MW base load is selected, which gives a SoS of 68% for a traditional wind turbine without storage, the power output is scaled and the wasted energy is not taken into account as useful energy. The second comparison is with the three Grenada scenarios including hydrogen wind turbines, as discussed in section 7.2.3. These scenarios are also scaled to the base load requirement of 20 MW and therefore do not meet the total annual power requirement only with wind powered electricity. To meet this annual power and to be able to compare the $CO_2$ emissions, the power is supplemented with diesel generated power. The last scenario; 0.6 MW base load wind, 100% SoS, is the scenario in which the number of WTG's are matched with the required annual power consumption of Grenada (185.1 GWh), instead of scaled to the required base load. This results in the addition of 2 extra WTG's, a security of supply of 100% and a 100% renewable production of electricity. However, these characteristics result also in a relatively high LCOE of €600.01/MWh, due to the low base load system and high CAPEX for the electrolyzer system.

The first comparison with the traditional wind turbine clearly shows a significant decrease in the carbon footprint of 68%. However, due to the lower SoS the amount of supplemented energy by diesel generation will result in relatively high emissions, compared to the Grenada scenarios. Even if all wasted energy can be used, the power output will be 135 GWh, which will decrease the emissions further to 73%. Increasing the number of WTG's will be beneficial, but will also increase the costs of the project and more important, the maximum security of supply of a traditional wind turbine without storage will never be 100% due to fluctuations in wind speed. The second comparison are the Grenada scenarios. The table shows that a lower base load output, with more wasted energy is able to produce more renewable energy and has therefore lower emissions. But still, the 2.3 MW base load scenario has an emission decrease of 76% which is better than the traditional wind turbine system. The last comparison is the 100% wind and hydrogen generated electricity. This will have a major impact on the total emissions with a decrease of 99%. As discussed in the LCOE analysis, these emission decreases come at high energy costs and may not be financial feasible. Therefore, the carbon certificate costs are taken into account in the next section.

| | | **Current 100% diesel generated** | **Traditional wind turbine, 68% SoS** | **0.6 MW base load wind + diesel generator** | **1.6 MW base load wind + diesel generator** | **2.3 MW base load wind + diesel generator** | **0.6 MW base load wind, 100% SoS** |
|---|---|---|---|---|---|---|---|
| **Hydrogen system** | (-) | No | Yes | Yes | Yes | Yes | Yes |
| **Number of WTG's** | (-) | (-) | 9 | 34 | 13 | 9 | 36 |
| **Wind power per WTG** | MWh | (-) | 15,021 | 5,270 | 12,419 | 15,781 | 5,270 |
| **Total wind power output** | GWh | (-) | 126 (68%) | 179 | 161 | 142 | 185.1 |
| **CO2 emissions** | kg tonnes | (-) | 755 | 1,075 | 969 | 852 | 1,111 |
| **Diesel generated power** | GWh | 185.1 | 59.23 | 5.92 | 23.65 | 43.07 | (-) |
| **$CO_2$ emissions** | kg tonnes | 155,669 | 49,814 | 4,979 | 19,892 | 36,223 | (-) |
| **Total emissions** | kg tonnes | 155,669 | 50,569 | 6054 | 20,861 | 37,075 | 1,111 |
| **Change in emissions (Compared to current system)** | % | (-) | -68% | -96% | -87% | -76% | -99% |

**Table 27:** $CO_2$ impact of different scenarios at Grenada.

**Assumptions used in the carbon emissions comparison** To be able to analyse the renewable impact of the implementation of this technology, the following three assumptions and simplifications are made; the $CO_2$ emissions for the transportation of the diesel, the wasted energy (curtailment) could be used, the carbon footprint of the addition of a hydrogen system inside a wind turbine and $CO_2$ emissions for the O&M and replacement of the hydrogen system.

First, the $CO_2$ emitted to transport the diesel from shore to the island is not taken into account. In this calculation, only a fixed emission per outputted kWh is taken into account. According to the distance, type of vessel and the necessity of the vessel, the allocation of these emissions can vary. For example, Grenada needs to be supplied with goods and materials that are not available on the island This will combine the need for a cargo ship which also carries diesel fuel for the generators. An analysis on the diesel transport required for these diesel generators is out of the scope of this research, but is recommended for future research to get a more detailed overview of the sustainable impact of this transition.

Secondly, in these scenarios the wasted energy; energy which can not be stored in the system, is seen as wasted energy whereby the wind turbine will be turned off; curtailment. This energy can also be used to supplement the base load power whereby less diesel generated energy needs to be used. This will lower the carbon footprint of the hydrogen wind turbine system even further.

Thirdly, the carbon footprint of the hydrogen system is not taken into account, but only the carbon footprint of the wind turbine. This is because of the fact that, according to the interviews with hydrogen component manufacturers, the carbon footprint of the manufacturing and operating processes of these components are low. Most of the production of hydrogen components (fuel cell, electrolyzer, etc) are only labor intensive and does not require heavy industry or energy intensive manufacturing methods. Most of the companies in this sector are interested in their own sustainable footprint and therefore try to use only sustainable generated electricity. For example, they use blue or green hydrogen as an energy resource to minimize their carbon footprint. However, due to the development stage of these companies, they do not have the resources for a detailed carbon footprint analysis of their supply chain yet. This detailed sustainable impact analysis is recommended for future research on internal hydrogen for offshore wind turbines (IRENA, 2020b). Also, the manufacturing, operating & maintenance, decommissioning and breakdown of the components need to be taken into account in this future research to analyse the supply on its sustainability. The opportunities for reusing materials or components will have a major impact on the sustainable impact of this system (Valente, Iribarren & Dufour, 2020). Thus, to determine the exact carbon footprint of the O&M and replacement of components is an interesting area for future scientific research.

### 7.5.2 Financial break-even point with carbon certificates

The production of $CO_2$ is not taken into account when comparing the energy prices. Due to harmful effects of emissions, with especially $CO_2$, these need to be discouraged with the addition of financial structures. Several of these structures are discussed in chapter 2, with carbon certificates as one of the currently used solutions. These certifications need to be bought to produce $CO_2$. The addition of these certificates must be taken into account when comparing LCOE's. To analyse the financial feasibility of each scenario the theoretical price of a carbon certificate for a financial break-even point with the current diesel generated system will be calculated.

Table 28 gives an overview of the different scenarios and their outputted power for wind energy and the supplemented diesel power. This table shows the price of the carbon certificates (per 1000 kg of $CO_2$) at which the technology has a financial break-even point with the current diesel generated energy. Whereby the total energy costs are divided over the difference in carbon emissions. The same assumptions as in the carbon emission comparison are applicable for this calculation. For the three Grenada scenarios the price of the additional certificates must be between €42 and €489 per kg tonnes of $CO_2$. To set these values in context, a current estimation on carbon certifications shows that the current social costs of a ton of $CO_2$ is around $50 (€40) (EDF, 2017). This makes the 2.3 MW scenario, besides the argumentation for an independent power generation, also financially interesting. However, the lower base load scenarios will probably not be financial feasible with only carbon certificates or subsidies, despite their lower carbon footprint, if the current estimation of €40 is used.

Compared to the traditional wind turbine, the financial break-even point is relatively high. The lower LCOE of traditional wind electricity, combined with the lower emissions creates a negative certificate price. In other words, traditional wind turbines are already competitive with the current diesel system, also without financial structures. This result is mainly due to the zero fuel costs of wind energy and the maturity of the technology.

| | | **Current 100% diesel generated** | **Traditional wind turbine, 68% SoS** | **0.6 MW base load wind + diesel generator** | **1.6 MW base load wind+ diesel generator** | **2.3 MW base load wind + diesel generator** | **0.6 MW base load wind, 100% SoS** |
|---|---|---|---|---|---|---|---|
| **Power requirement (GWh)** | Wind | 0 | 125.9 | 179.2 | 161.4 | 142.0 | 185.1 |
| | Diesel | 185.1 | 59.2 | 5.9 | 23.7 | 43.1 | 0 |
| **LCOE (€/MWh)** | Wind | (-) | 134.22 | 604.03 | 272.51 | 230.09 | 600.01 |
| | Diesel | 195 | 195 | 195 | 195 | 195 | 195 |
| | Total | 195 | 153.67 | 590.95 | 262.60 | 221.93 | 600.01 |
| **Total energy costs** | (-) | €36m | €28m | €109m | €49m | €41m | €111m |
| **Emissions** | kg tonnes of $CO_2$ | 155,669 | 50,569 | 6,054 | 20,861 | 37,075 | 1,111 |
| **$CO_2$ certificate for break-even point with diesel as comparison** | | (-) | €-72.79 | €489.86 | €92.82 | €42.03 | €485.04 |

**Table 28:** Comparison for different scenarios on their $CO_2$ certificate price for a break-even LCOE.

# 8 Conclusion

This research has focused on the extended LCOE calculation for an internal hydrogen production, storage and reconversion system for remote locations, whereby the extension consists of a carbon emission comparison between the current diesel system and this technology. First, the technical design and costs, based on Grenada as the selected location, are analysed. The technical design and the financial parameters are the input for the LCOE calculation. To validate the input variables of the LCOE, they are tested with a sensitivity analysis. The extended part of this research is the sustainable impact analysis for the transition from diesel to wind energy supplemented with hydrogen.

The traditional wind turbine depends on the wind energy for the production of electricity. When the wind speed is too low or too high, the wind turbine does not produce enough electricity. A wind turbine with hydrogen storage system is able to reconvert stored hydrogen into electricity. Therefore, the wind turbine system will still produce electricity during these instances of shortage. To fill this hydrogen storage, the overproduced electricity, electricity production higher than the required power output, is used for the production of hydrogen. To produce, store and reconvert hydrogen, several components need to be added to the system. First, an electrolyzer is required to convert the overproduced electricity of the wind turbine into hydrogen. For this process, the electrolyzer requires fresh water and therefore, a desalinator needs to be added. This hydrogen is pressurized with a compressor and stored in a storage tank. Pressurizing the hydrogen will increase the amount of stored energy. This stored hydrogen is reconverted with a fuel cell into electricity. With the use of this storage system, a base load can be outputted, instead of the fluctuating electricity output of a traditional wind turbine. Base load is the minimum power output which a system can generate at any given time. The advantage of reconverting hydrogen back into electricity is that there is only an electricity cable as connection to shore, instead of the addition of a pipeline for the transportation of hydrogen. Besides the connection, there is no need for a hydrogen infrastructure or conversion components on the remote location. Disadvantages of this system are the energy losses during the conversion and the higher costs for investment and operation & maintenance.

To test the feasibility of the hydrogen wind turbine system, the technology is tested with Grenada, one of the small island developing states (SIDS), as test location. Grenada is selected because of its suitable conditions and the opportunities which can be enabled by this technology. The disadvantageous characteristics of SIDS can also be beneficial for the roll-out of the technology:

- The island is remote, which makes electricity supply, by cable, from outside the island not feasible. Therefore, the location needs to have a self-sufficient electricity generation with a high security of supply
- The location conditions are favourable for wind energy; high average wind speed and wind capacity, water depths suitable for fixed bottom wind turbines and currently a small share of sustainable produced electricity
- The current energy is generated with diesel generators, whereby the diesel is transported from shore. Consequently, the electricity is relatively expensive. This makes renewable energies competitive in an early stage of development, because the high installation costs, a result of the remote location of SIDS, will be offset with this high electricity price
- Besides the high energy price, the use of diesel as fuel creates emissions and pollution. Due to the current energy goals, the interest in sustainable energies is growing. This creates opportunities for this technology, because it can heavily reduce the sustainable

impact by decreasing the carbon emissions from energy generation

- The supply of imported fuel creates political sensitivity. Elimination of the need for fuel decreases the political leverage of countries on Grenada
- The system has many social economic advantages related to the total energy production which enables electricity supply for the total population, creates opportunities for decreasing the monopoly position of an electricity supplier and will lower externalities, which are globally beneficial due to the wide impact of climate change

These remote located islands also have some challenges regarding the development and roll-out of this technology. Examples are the high import costs for goods such as diesel, scarcity of land for electricity production and the fragile economic and ecological system. These opportunities and challenging conditions are not only applicable for Grenada, but also applicable for several other islands in the Caribbean and remote locations around the world. This makes the hydrogen technology scalable and will lower the LCOE over time.

To calculate the extended LCOE two models are used. First, the base load calculation model, which uses the hourly wind speed to determine the electricity generation, overproduction, status of the hydrogen storage and the conversion of hydrogen into electricity. With the output data of the base load model, the hydrogen components are selected and sized. These components are the input for the LCOE calculation, which converts the costs (CAPEX, OPEX, decommissioning, etc) with the use of financial parameters into the net present value and with the electricity output into the LCOE value. With these models, the LCOE of three scenarios are calculated. The scenarios used in the LCOE analysis are based on the security of supply, which is the percentage of time, over a year, in which the selected base load can be outputted. The security of supply is important if a location, without additional electricity generation supply, is completely switched to this sustainable technology. Otherwise, power outages will occur due to a lack of backup power. For the LCOE analysis, the following scenarios are analysed:

- 0.6 MW base load scenario which is the highest base load with a 100% security of supply
- 1.6 MW base load scenario, which is the highest base load which will provide a minimum of 80% security of supply
- 2.3 MW base load scenario, which is selected because of the optimum balance between base load output and security of supply

## 8.1 Levelized cost of energy results

These three scenarios are compared with the current diesel electricity generation system and a traditional wind turbine without hydrogen system with a security of supply for a 1.6 MW base load. With this comparison, the impact of this transition and the competitiveness, with an existing alternative, can be analysed. All the scenarios are scaled to output the 20 MW base load requirement of Grenada. This gives the following LCOE values per scenario, as seen in the table 29.

| Scenarios | WTG's required for 20 MW | Security of supply per WTG | LCOE |
|---|---|---|---|
| **Hydogen wind turbine** | | | |
| 0.6 MW base load | 34 | 100% | €604.03/MWh |
| 1.6 MW base load | 13 | 83.8% | €289.52/MWh |
| 2.3 MW base load | 9 | 64% | €246.53/MWh |
| | | | |
| **Comparison scenarios** | | | |
| Current 100% diesel generated | (-) | 100% | €195/MWh |
| Traditional wind turbine at 1.6 MW | 9 | 68% | €134.22/MWh |

**Table 29:** LCOE results for the Grenada scenario wind turbine system and 2 comparison scenarios. All with a required total base load of 20 MW.

With the LCOE results and a sensitivity analysis of the used parameters, conclusions can be made. These conclusions are divided into four categories: base load requirement, number of WTG's, security of supply and financial parameters. For each of these conclusions, the argumentation and influence of the parameters are discussed.

The main constrain in the ability to balance the electricity fluctuations is the requirement of a base load output. As seen in the table, an increase in base load will decrease the LCOE, because a higher base load will allow for more electricity transported directly to shore, whereby less energy is converted into hydrogen or wasted if the storage is full. Both processes decrease the total output which increases the LCOE: conversion to hydrogen introduces large efficiency losses and a curtailment (turn off) of the wind turbine at full storage.

Because of the 20 MW base load requirement for Grenada, the number of WTG's depends on the selected base load. The number of wind turbines increases with a lower base load. Despite the hydrogen component costs decreases with a lower base load, the lower total electricity output results in a higher LCOE. With the same base load, a higher number of WTG's will decrease the LCOE by allocating the fixed costs over more WTG's. An other technical parameter that can be changed to decrease the LCOE is: increasing the power output by decreasing the system losses. In all these cases, the costs are allocated over a higher quantity of electricity. According to the sensitivity analysis, an increase in the selected base load will exponentially decrease the LCOE. For each combination of input parameters and selected base loads, there is a minimum LCOE. To give a structured overview of these variables, table 30 shows the different parameters and their influence on the LCOE.

The security of supply is increased with the addition of the internal hydrogen production, storage and reconversion system. The hydrogen system will secure the power output during instances of low wind speeds and therefore low wind power output. A lower base load will create more overproduction, energy above the selected base load. With the use of the hydrogen system, the security of supply can be increased up to 32%, with a 15,8% for the 1.6 MW base load. However, this increased security increases the LCOE by €155,33/MWh. According to table 29 the 2.3 MW option appears to be a less competitive decision compared to traditional wind turbines: a lower security of supply at a higher energy price. Improvement of the security of supply requires a larger storage system, which is even more expensive. However, in this conclusion there are no financial structures included which stimulate the sustainable impact.

The financial input parameters have a major influence on the LCOE. Increasing the discount rate, which accounts for the value of money over time, and growth rate, which accounts for the interest rate over time, will both increase the LCOE of the technology. Hereby, the discount rate is applicable for both the costs and the electricity output and the growth rate adjusts the costs for the annual interest. Trying to decrease the financial input parameters will increase the opportunities for the technology. Possible examples are mitigation of investment risks or increasing the percentage of own equity. Lastly, increasing only the CAPEX or OPEX, if the power output is constant, will increase the LCOE.

| Increase in | Influence on LCOE | Details |
|---|---|---|
| Base load | Decrease | Decreasing exponential, with a minimum |
| Number of WTG's | Decrease | Decreasing exponential |
| Power output | Decrease | Major influence on the LCOE |
| Storage volume | Decrease | If the system and power output are scaled |
| | | |
| Energy losses in the system | Increase | Decreasing increase |
| Discount rate | Increase | Decreasing increase |
| OPEX | Increase | Linear increase |
| CAPEX | Increase | Linear (larger influence than the OPEX) |
| Decommissioning costs | Increase | Linear increase |
| Growth rate | Increase | Increasing increase |

**Table 30:** Influence of input parameters on the LCOE of an internal hydrogen system for offshore wind turbines.

As seen in the table, the LCOE of this technology range between €246 and €604 per MWh, depending on the base load and security of supply. To determine the significance of these LCOE values, they must be compared with the LCOE values from scientific research. According to this research, the nonrenewable technologies have a LCOE between €45 and €146 per MWh for regular locations. For disadvantageous locations, such as the SIDS, the LCOE of nonrenewables is at least €195/MWh, which is high but still lower than the LCOE of this system. This makes the hydrogen wind turbine technology more expensive than the current diesel system. However, looking only at the sustainable technologies, their LCOE's range between €36-277/MWh, whereby comparable sustainable technologies for remote islands have a LCOE between €232-349/MWh, which is more in line with the LCOE values of this research. Depending on the scenario, the LCOE of this technology will lay within the field of existing sustainable technologies for remote locations and even shore locations. However, the feasibility of the technology also depends on the constrains and requirements of the location. One of these examples is the willingness to pay (more) for a higher security of supply.

The second comparison which is made is between the added costs of a hydrogen system to a wind turbine, compared to a traditional wind turbine. This comparison shows the influence of the added hydrogen system to an offshore wind turbine. According to scientific research, the additional costs of the hydrogen system added to a wind turbine are between €38-78/MWh. If the traditional wind turbine and wind turbine with hydrogen system are compared, when using the same number of WTG's, there is a major increase in LCOE of €112-479/MWh. This is partially due to the short lifetime and therefore high replacement costs of the hydrogen components. An increase in lifetime, to more than 10 years, would decrease the LCOE, but must be validated in future research.

Despite the higher LCOE, there are two reasons, from the social economic side, which counteract these results. The first are the profile costs of the TSO. By adding a storage system and therefore providing base load, the costs for the TSO to counterbalance the electricity supply (profile costs) are much lower. This shift in cost allocation, from TSO to wind turbine

CAPEX, makes the technology more interesting and will increase the potential roll-out. An indication for the additional profile costs and TSO profits is given by the difference between the locations current electricity price of €330/MWh and the overall cost for electricity of €195/MWh, which results in €135/MWh. This gives a financial margin to partially justify a higher LCOE for this technology. The second advantage of this system, compared to the current electricity generation is the sustainable impact. One of the shortcomings of the LCOE is the allocation of emissions, pollution and externalities. Financial structures, for the encouragement of sustainable energy, can shift the competitiveness of the LCOE for this technology.

## 8.2 Carbon emission comparison

For this reason, the LCOE calculation is extended with a carbon emission comparison between the current diesel generated electricity and this new technology. Hereby, the emission reduction and the influence of carbon certificates on the financial feasibility have been calculated, as seen in the table 31. The financial break-even point is calculated with the price of the added carbon certificate at which the scenario will have the same LCOE as the current diesel generation system. When more $CO_2$ emitted, more carbon certificates must be bought, which will drive the LCOE of non-sustainable electricity generation. These financial structures, in the form of added costs when producing $CO_2$ or by subsidising renewable energies, try to discourage the production of emissions. In this comparison, multiple factors are not taken into account: the carbon footprint for the transportation of diesel, the added carbon emissions for the manufacturing of the hydrogen components and overproduced energy, which can not be stored, is considered as wasted energy. However, this excess electricity can often be used to lower the need for diesel generated backup. These simplifications are made because of a lack of available knowledge or the possible allocation of these emissions among other goods, for example, transportation emissions can also be allocated for other products from shore to Grenada. These simplifications are assumed to counteract each other or have only a small influence on the total emissions.

| **Scenario** | **Change in $CO_2$ emissions** | **$CO_2$ certificates for financial break-even point** |
|---|---|---|
| | % | €/tonnes of kg $CO_2$ |
| **Hydrogen wind turbine + diesel** | | |
| 0.6 MW base load hydrogen wind + diesel generator | -96% | €489.86 |
| 1.6 MW base load hydrogen wind + diesel generator | -87% | €92.82 |
| 2.3 MW base load hydrogen wind + diesel generator | -76% | €42.03 |
| | | |
| **Comparison scenarios** | | |
| Current 100% diesel generated | (-) | (-) |
| Traditional wind turbine, 68% SoS + diesel | -68% | €-72.79 |
| 0.6 MW base load only hydrogen wind, 100% SoS | -99% | €485.04 |

**Table 31:** $CO_2$ impact and financial break-even point of different scenarios compared to current energy generation.

As seen in the table, the $CO_2$ emissions can be reduced for the three scenarios by respectively 78%, 87% and 96%, with the highest sustainable impact for the lowest base load. This is an even higher impact than the traditional wind turbine, with a sustainable impact change of 'just' 68%. An even higher sustainable impact, up to 99%, is possible by increasing the number of WTG's and therefore mitigating the need for backup power, as seen in the third comparison scenario. According to the financial results of this table, a higher base load requires a lower carbon certificate price for a break-even point with the current electricity generation. These certificate prices range between €42 and €489 per kg tonnes of carbon emission. This wide range is a result of the large differences in LCOE between the three scenarios. Interesting is the negative price for traditional wind turbines, which is a result of lower investment costs and lower carbon emissions. However, this technology is not able to supply a constant base load and therefore only has a 68% decrease in carbon emissions. To set these carbon certificate prices in context, the current estimation of a certificate is around €40 per kg tonnes of $CO_2$. This makes the hydrogen system with 2.3 MW, even in the current environment competitive, despite the earlier conclusions on its financial comparison. Looking at the added comparison scenarios with only hydrogen wind turbines compared to the 0.6 MW base load scenario; a setup with a high sustainable impact can be financially more interesting compared to the same system with backup diesel.

## 8.3 Added value and implications of this technology

With these conclusions, the added value for scientific literature can be evaluated. As seen in the literature research, the missing link is the use of hydrogen storage for short-term balancing of offshore wind turbines at remote locations. These remote locations create constrains wherefore many currently available sustainable technologies are not suitable. Examples of these constrains are the scarcity of land area and the less matured energy grid, which makes the security of supply important. In this research, not only the LCOE and carbon comparison for the selected remote location, Grenada, are analysed, but also the interdependency between these constrains and the use of a new sustainable technology. This knowledge can be used for the optimization of short-term balancing for remote locations, but also have given insights into the social aspects of a sustainable technology at a remote island. With this knowledge improved technological solutions can be designed to counteract climate change.

This will raise the question if this technology should be built. This question can be answered for different stakeholders and perspectives; whereby this research will focus on the social economic perspective of Grenada and Van Oord, as the two stakeholders. First, the economic perspective question can be answered with input from the characteristics of the SIDS. As seen, the LCOE of this technology will be at least €51.53/MWh higher than the current LCOE. Although, this will be counteracted by the positive sustainable impact and independence the island obtains. If these sustainable factors are taken into account, this technology will be even financially competitive for higher base loads. As discussed, these higher electricity costs will also be counterbalanced which will diminish the difference even further. Therefore, the conclusion is drawn that this technology is interesting for Grenada to built and will have several positive social economic side effects. However, with the results the conclusion can also be drawn that a 100% security of supply is relatively expensive, as seen in the literature research comparison between the LCOE's of alternative technologies. Therefore, combining this technology with different electricity generation technologies, such as solar, will probably improve the electricity price and is recommended.

The second analysed stakeholder is Van Oord. Van Oord's main focus in the wind energy industry is the installation of monopiles. Despite the interesting technological and financial opportunities, the conclusion that can be drawn is that this technology does not have enough directly related corporate benefits to be justified for Van Oord, if the assumption is made that their profit is the same for the traditional wind turbine and this technology. The added project costs are delivered by third party suppliers and therefore, do not create added value for Van Oord. Although, two factors can still justify the installation of this technology for

Van Oord. First, if the requirements of the location demand a 100% security of supply or base load energy from wind energy, this technology will be preferred over a traditional wind turbine. Secondly, if Van Oord has a long-term interest in hydrogen and storage systems, this will be an interesting opportunity to gain knowledge and experience. These factors can make this technology still interesting from Van Oord's corporate standpoint, however they can also be achieved via other means.

## 8.4 Answers to the research questions

The main research question is divided in several sub-questions, which reflect the sections in this research report. First, the sub-questions will be answered with which the main research question can be answered.

### 8.4.1 Sub research questions

**1. What is the added value of an internal hydrogen production, storage and reconversion system for offshore wind turbines?**
Current offshore wind turbine systems provide an excellent sustainable solution for electricity generation. However, this electricity supply is fluctuating with the changes in wind speed, while the electricity demand is also fluctuating at a different rate. This results in a mismatch in electricity supply and demand. Locations with a large electricity network, multiple electricity providers and the possibility for storage can balance these fluctuations. However, locations, such as remote islands, do not have an extensive electricity grid, land area for large storage facilities or sustainable backup systems which can balance this mismatch.

The decision to select hydrogen as storage medium also has future benefits. As seen in the literature research, the interest in hydrogen is increasing. If the hydrogen economy is expanded, with more hydrogen fuelled products, the location can easily shift to this new energy economy by adding pipelines from the wind turbines to shore. This has a higher total process efficiency as added advantage; there are no reconversion losses in the energy grid if the hydrogen is used directly.

**2. What is the most suitable technological setup, created with the current knowledge and state of technology, for internal hydrogen production, storage and reconversion for offshore wind turbines?**
The current setup for an internal hydrogen system is a design whereby the hydrogen components are located inside the transition piece and the storage tank inside the monopile. Within this setup, a desalination system provides fresh water for the electrolyzer, which produces hydrogen. This hydrogen is pressurized with a compressor and stored in a storage tank. If the electricity supply of the wind turbine needs to be supplemented, the stored hydrogen is reconverted into electricity with the use of the fuel cells. The internal placement of these components will prevent damage during installation & operation and will make maintenance and replacement possible during its lifetime. According to interviews with hydrogen component manufacturers, the technology is already suitable for the use in an offshore environment, whereby the challenge lays in the scalability and adaptation of the technology. The design of chapter 4 is a suitable technical scenario for Grenada, however design optimization and standardization are key elements in a successful roll-out of this development stage technology. Therefore, there is not a general optimal scenario because of the inter dependency of the variables and constrains of the locations.

**3. Which financial method will be used and which parameters are required in this cost analysis of internal hydrogen for offshore wind turbines?**
For the financial analysis of this technology, the levelized cost of energy (LCOE) calculation is used. The output of a levelized cost of energy is a price per unit of electricity, such as €/MWh. This calculation uses financial parameters, discount rate and growth rate, electricity output and costs as input for the calculation of the LCOE. The discount rate accounts for the change in the value of money over time. The growth rate accounts for the allocation of interest over the costs. With these parameters, the costs are converted into the net present value (NPV). These costs consist of capital investment (CAPEX), operational and maintenance costs (OPEX) and decommissioning costs. The electricity output is combined with the system losses and converted into the net present value of energy. Dividing the NPV of the costs by the NPV of the electricity gives the LCOE value.

However, the LCOE calculation is a simple and widely used method, it also has many disadvantages: the daily variations in demand and supply, integration costs for new technologies and the integration of externalities, such as carbon emissions, are not taken into account. To take into consideration the change in carbon emissions in this energy transition comparison, the LCOE calculation will be combined with a carbon emission calculation, which is called the extended LCOE.

**4. What is the business case for small-scale internal hydrogen systems for offshore wind turbines?**
The business case for this internal hydrogen system for offshore wind turbines is complex. Offshore wind turbines have scaled exponentially in size and number over the last 20 years. However, wind turbines are still depend on the fluctuating wind speed and therefore their output fluctuates. This creates opportunities for sustainable electricity generation with integrated storage systems. They can provide a base load energy, which mitigates the problem of electricity fluctuations. However, these systems increase the costs of electricity and therefore require a shift in the business model whereby also the disadvantageous characteristics of remote locations, such as SIDS, can be used as an advantage:

- A remote location with only a few options for energy generation. This makes it not possible to buy energy for a competitive price from outside the selected location or creates large opportunities for different technologies
- A high energy price. Renewable energies, especially technologies which are in the development phase, do not have the advantages of economies of scale or optimized designs, which will result in higher LCOE's. These technologies are only suitable if the location already has relatively high energy prices
- Currently a minimal share of sustainable electricity generation. However, these locations need to have an interest or necessity to change to a more renewable energy generation. Besides the high energy prices, the LCOE will probably still be high compared to the current situation. Other incentives, such as regulations for emissions or the interest to be more independent from other energy resources, will increase the need to change to renewable energies
- Resources must be transported to the remote location. This supply of imported goods, such as fuel, creates political sensitivity. Eliminating the need for fuel decreases the political leverage
- The wind speed needs to cause small durations of shortage of supply, which will create a need for the hydrogen storage. If the wind speed is too stable, there is enough wind energy available to create a base load and therefore there will be no need for an additional storage system. The wind speed needs to be high enough that the wind turbine

produces an excess of electricity (overproduction), which will fill the storage tank, but not too much wind that the wind turbine needs to be curtailed to prevent damage
- Besides the wind speed characteristics the location needs to be suitable for bottom fixed wind turbines; not too deep and available space without hindering marine traffic

**5. What are the scenarios that need to be analysed for this technology?**
To minimize the combinations of design scenarios, three scenarios have been selected based on a specific base load and security of supply. The scenarios are compared with each other and with the current electricity generation. The first scenario is the hydrogen wind turbine with a 100% security of supply. This scenario simulates a case in which the location wants to transition to a 100% sustainable electricity generation. Increasing the number of traditional wind turbines does not increase the security of supply. Only a system with added storage can meet this demand, although this will increase the cost and therefore the LCOE. The second scenario is a scenario with a minimal security of supply of 80%. This will give a combination of relatively high SoS with an interesting electricity price. A less than 100% SoS will also provide room in the electricity grid for a mixed electricity generation; for example the addition of solar panels. The third scenario is based on the best combination of security of supply and base load. According to the output values of the system, the specific base load and security of supply of this scenario is selected: 2.3 MW with a SoS of 64%.

**6. What is the sustainable impact of the transition from the current energy generation to an internal hydrogen production wind turbine?**
The extension of the LCOE calculation of this research is the carbon emission comparison between the current electricity generation system and the hydrogen storage wind turbine technology. These technologies and the required amount of fuel are scaled to the total annual electricity demand of Grenada, 185.1 GWh. The carbon emission comparison takes into account the direct emissions from the combustion of diesel, including components, and the embodied emissions from the wind turbine components into account. However, in this comparison, multiple factors are not taken into account: the carbon footprint for the transportation of diesel, the added carbon emissions for the manufacturing of hydrogen components and overproduced energy, which not can be stored, is considered as wasted energy, although this electricity can often be used to lower the need for diesel generated backup. These simplifications are made because of a lack of available knowledge or the possible allocation of these emissions among other goods.

According to these calculations, the emission decrease with the hydrogen wind turbine system is heavily depending on the security of supply. A higher security of supply (SoS) results in less diesel backup power and therefore an improved sustainable impact. The decrease in carbon emissions for the three scenarios are 76%, 87% and 96%. The lowest base load, 0.6 MW, with the higher SoS of 100%, will have the highest impact. Compared to a traditional wind turbine, the change in emissions is only 68%, due to the lower security of supply and more wasted energy over the years.

### 8.4.2 Main research question

The main research question of this report is:

***What is the extended LCOE of a combined offshore wind, hydrogen production, storage and reconversion energy system in integrated single structures for remote locations?***

The extended LCOE for an internal hydrogen production and storage system depends on many variables; location, component selection and decisions on the security of supply and base load. Therefore, the LCOE of three scenarios is calculated with base loads of 0.6, 1.6 and 2.3 MW. The LCOE's of the Grenada scenarios range between €604.03-246.53/MWh, with the highest LCOE for the lowest base load. If electricity is supplemented with diesel generated power, at the current electricity price, the LCOE can drop to €230.09/MWh. To improve the LCOE, the following changes can be made on the variables: increasing base load, increase the number of WTG's, increase the annual electricity output and increase the the storage volume, decrease the costs (CAPEX, OPEX, etc) or decrease the financial parameters (discount rate and growth rate).

The extended analysis of this LCOE calculation is the sustainable impact of the technology. According to the sustainable impact, the assumed carbon footprint can be reduced up to 96% for a wind turbine system supplemented with diesel energy and up to 99% if the energy production is only generated with wind turbines. If these emissions are taken into account as costs for externalities, the financial break-even point will shift with the use of financial structures, such as $CO_2$ certificates or subsidies. For the Grenada scenarios, these financial structures range between €42.03/kg tonnes of $CO_2$ up to €489.86, depending on the selected base load and configuration.

With these extended LCOE values and the LCOE of alternative sustainable technologies for remote locations, it can be concluded that the technology can be financially interesting. According to the selected scenario, the technology is competitive, especially when the added benefits are taken into account: major decrease in carbon emissions, increase in security of supply compared to traditional wind turbines, social economic benefits, a decrease in the balancing cost for a TSO, all with a future oriented technology.

# 9 Discussion and recommendations

In this section, the analysis are discussed and recommendations for further research are given. In the following paragraphs, the simplifications, assumptions and the future approach to improve these assumptions are discussed. These recommendations are divided in four parts: technological, financial, location recommendations and stakeholder implications.

## 9.1 Technological discussion and recommendations

In this research, the technical analysis was focused on the hydrogen system. Therefore, the wind turbine and foundation parameters have been taken as a constant input in this LCOE calculation: wind turbine, foundation and storage volume. Analysing different wind turbines would change the power output, available volume due to a change in monopile/TP size, cable sizing and cable layout. Due to this complexity, the WTG is held as a constant factor during this research, but it may lower the LCOE of the technology. The wind turbine foundation is assumed to be suitable for a heavier monopile and transition piece. In future research, the foundation needs to be analysed in more detail, which can have an influence on the available volume inside the monopile or will be affected by the maximum capacity of the installation vessel. This detailed design can have a positive or negative effect on the storage volume and LCOE, depending on the relationship between possible added steel, components and the increase in power output. Besides the foundation, the design of the hydrogen system in combination with the TP is assumed to be feasible. In this detailed hydrogen and TP design, additional supports for the hydrogen components and separate compartments need to be designed. Again, adding these components in the design, the maximum lifting capacity of the installation vessel needs to be taken into account.

The hydrogen flows, inside the system, are assumed to have a constant temperature and no losses. It is recommended to analyse these losses and calculate the influence of a non-constant environmental temperature. This temperature change will also affect the energy density of the storage and will change the base load calculations. Therefore, cooling or heating can be required, which can have a major impact on the technical and financial feasibility and lifetime of the components.

The components in chapter 4 are selected with publicly available information. By connecting with hydrogen manufacturers, knowledge about improved technologies can probably be gained and make tailor made designs possible. This development of the technology will impact the LCOE, sustainable impact and feasibility of the technology. An example are the current designs for the fuel cell, desalination system, compressor and electrolyzer. The specifications in the design phase are scaled linearly, which results in a larger or smaller system than will be used in the final design. This difference in volume, weight, etc is a result of adding components (piping, cables, etc) or removing the casing from a single unit. By designing a specific system for the required power supply of the WTG and base load, major financial improvements can be made.

In this research, only hydrogen as a storage medium is analysed. As discussed, there are many alternatives for energy storage with each their own advantages and disadvantages. Because of the simplicity, maturity of technology, volume or additional (harmful) materials, the compressed hydrogen storage is selected. It is recommended to analyse the opportunities for these technologies within this system and to stay on top of the developments. Major improvements in the system can be made if new storage technologies can be implemented.

Besides the storage medium, the storage system is assumed to be full at the first operating year. During the tests of the wind turbine and hydrogen system, the tank is filled. Due to the zero base load during testing, the storage can be filled at maximum rate. To maintain this storage level, the system needs to be filled at the end of the year. However, the storage status difference at the end of the year is not taken into account, which is in line with the yearly energy date recommendation. Therefore, a detailed multi-year analysis on the storage system and during maintenance is recommended to determine the SoS for long-term use. In reality, the storage tank will be filled with the overproduced electricity which is not used in this research or can be refilled during outages and maintenance. This will mitigate the effects of this assumption slightly.

The advantage of this technology, compared to a traditional wind turbine, is the ability to increase the security of supply. However, this security of supply depends on the reliability of the components. To determine the sensitivity, a separate multivariate reliability analysis on the security of supply during outages is recommended. This analysis will calculate, according to the Monte Carlo analysis, the SoS, whereby the SoS depends on the failure of different components and the status of the storage.

The degradation and replacement of the components is an important factor in this LCOE analysis. In this research, a set lifetime of 10 years has been used for the hydrogen production and conversion components. It is recommended to analyse this lifetime and the degradation of the components when using them with different base loads. For example, the curtailment of wind turbines and the correlated start-stop cycles will have an influence on the efficiency and lifetime of the technology. Over-designing the system and increasing the lifetime or vice versa can have a positive effect on the feasibility of the technology.

The scope of this research was an internal hydrogen production and storage system inside the monopile/TP. As discussed in the current design, the available volume restricts the opportunities for an optimized system design and therefore, energy is wasted or components overdimensioned. In future research, the opportunities for an offshore centralised substation for hydrogen conversion/reconversion must be explored. The advantages of hydrogen on larger scale can be studied, whereby instead of a single smaller-scale system, the overproduction of electricity is transported to a dedicated hydrogen substation. Depending on the scale and wind turbine layout, the wind turbine foundations can be used for hydrogen storage. This will probably shift the design restriction and can improve the LCOE of the system. Besides the financial opportunities, this design will also ease the process of carrying out maintenance and replacing components. In this layout, hydrogen can be transported to shore by pipeline. This may decrease the transportation costs and will be interesting for locations with an onshore hydrogen demand. The different types of transportation are in line with the decision to use a decentralised system. For this research, only electricity is transported to shore. However, the use of pipelines instead of electricity cables can induce costs and energy loss reductions. Therefore, research into the opportunities for different types of transportation and centralisation of components is recommended for future research.

As seen in figure 7, the wind speed is lower during the summer months. This result is in line with the expectation and what can be counteracted by combining sustainable technologies. To increase the security of supply, the storage system of the hydrogen storage technology needs to be overdesigned to account for these months. The combination of technology can eliminate this overdesigning. An example of a supplementing technology is solar energy. This supplementary solar energy is out of the scope of this research, but will be interesting for future research.

In this report, the safety regulations for hydrogen are not taken into account, mainly because no specific regulations and standardization exist for this technology. However, hydrogen in combination with high voltage gearing inside a confined space, which is enclosed from the salty environment, can induce major safety hazards. This safety issue needs to be addressed in the design phase and can be solved by adding separate compartments for the current wind turbine components and the hydrogen system. These safety issues will also receive attention when the certification of wind turbines with hydrogen system is devised.

## 9.2 Financial, sustainable and LCOE model recommendations

The costs (CAPEX and OPEX) for the hydrogen components are an estimation based on scientific research on these components. To validate these values, hydrogen companies have reviewed the input values in the LCOE model. However, economy of scale, collaboration of manufacturers and development of technology will decrease these costs. Only prognoses on the decrease of costs and increase of efficiency are made, but will have a major effect on the feasibility of this technology. Therefore, collaboration between all stakeholders (manufacturers, investors and installation companies) is highly recommended for a successful roll-out of the technology. In line with this collaboration, small-scale pilots will be required for offshore testing and development. The first design iterations will probably not be financial interesting, but an increased interest in the technology will improve the opportunities for future projects and ultimately will induce large decreases in the carbon footprint of remote locations.

For the sustainable comparison between the current diesel generated system and the hydrogen wind turbine, many assumptions and simplifications have been made. These consist of:

- The carbon footprint of the transportation of diesel, the added carbon footprint of the hydrogen components and overproduced energy which can not be stored is considered to be wasted energy.
- The transportation of diesel is not taken into account, because the cargo vessels which transport the diesel can also transport other goods, which are used on the island. Therefore, the carbon footprint of the transportation is partly from the goods.
- The carbon footprint of the hydrogen components is not taken into account because the sustainability of the hydrogen manufacturers their supply chain is not yet analysed because of their phase of company development.
- The wind turbines will create overproduction which is wasted. However, to meet the annual electricity demand, the wind turbine electricity is supplemented with diesel generated electricity, which could also be (partially) derived from this wasted electricity. This will lower the carbon footprint even further.

As seen, many assumptions have been made, but these can also counteract each other, which makes the comparison still interesting. However, a detailed research is recommended, especially to justify the higher LCOE for a hydrogen system compared to a traditional wind turbine.

The overproduced electricity which can not be stored in the hydrogen tank is seen as wasted. However, it might be financially more interesting to sell this wasted electricity at a low electricity price than curtailing the wind turbine. Curtailment can introduce higher O&M costs due to start-stop cycles, create latency due to the ramp-up/down times and introduce the need for supplemented electricity, as discussed above.

For the LCOE calculation, the financial growth is used to account for the interest rate over the lifetime of the technology, whereby the growth rate is a constant. In reality, the interest rate is not constant and should be accounted for in a cost analysis. Therefore, it is recommended to analyse the interest prognosis and recalculate the LCOE results. However, due to the changes and uncertainties in the financial performance of a location, this is not taken into account in this research.

In the LCOE, the financial investment structure is not taken into account. The financing is assumed as 100% own equity without debts and repayments. This decision is made to analyse the influence of the hydrogen system instead of the financing costs on a LCOE. In reality, this 100% own equity financing structure will not be feasible, especially for larger wind farms with high initial investment costs. The investment opportunities and financial structures are recommended for future assessments. One of these structures are subsidies on renewable energies or carbon certificates, as discussed in section 7.5.2. However, investors need to be willing to invest in this technology, which will probably add some health, safety & environmental (HSE) controls to the feasibility analysis.

## 9.3 Location specific recommendations

For this research, only the hourly wind data set of 2020 of Grenade is used for the hydrogen system design. For a more detailed LCOE analysis, more data needs to be incorporated into the models: a multiple year wind data set, long-term electricity price prognoses and competitiveness prognosis for different technologies. With this data, the security of supply per hour and long-term competitiveness can be validated, whereby an optimization for the design can be made. All these factors can have a significant impact on the performance of this technology.

In this research, the base load output is used for the energy production, but a supply and demand management system may decrease the installed capacity or will lower the LCOE by decreasing the wasted energy. Connecting with the energy production company, Grenlec for Grenada, is recommended to optimize the design and lower the costs.

For the Grenada scenario, the overproduced energy, which is excess of the storage volume, is assumed to be "wasted" energy. However, there are instances when a higher base load can be supplied to the island. A detailed analysis of these instances and the corresponding pricing of this extra electricity is recommended. A higher energy output will lower the LCOE, even when this is sold at a lower price.

Besides the technological location constrains (power requirement, water depth and wind speeds), no location variables are taken into account. Examples of these variables are nearby mountains which can have an impact on the wind speed and direction or the layout of the wind turbines, which will have an impact due to the blockage effect or will impact the cable length. These constrains will probably shift the point of optimization by changing the BoP and CAPEX values. Therefore, they are recommended for future research.

The hydrogen components are assumed as non-usable after their 10-year lifetime. However, a future research on the decommissioning cost is recommended. The re-usability of hydrogen components and materials can decrease these costs, which will have a positive effect on the LCOE of the system.

## 9.4 Implications for stakeholders

For the roll-out of a technology, many stakeholders must be in line with each other. For this technology, the following stakeholders are important: the electricity provider, electricity consumers, government, investors and secondary stakeholders.

Electricity generator and provider company Grenlec is one of the major stakeholders in the roll-out. In this research, the assumption is made that the electricity provider is willing to change to a new sustainable technology. Arguments for these assumptions are the decrease in profile cost and less dependency on imported fuel. In addition, the consumer's role is important. What are they willing to pay for the electricity and which security of supply is required? This needs to be researched in more detail to determine the detailed feasibility of the technology.

The government of Grenada is assumed to be interested in the transition to sustainable energies. This assumption is based on their energy goals and their SIDS alliance. However, they have not determined their concrete implementation of these renewable goals. Because of the environmental characteristics, wind energy would be a viable option, but as seen in figure 6 solar and geothermal are also major contenders. Besides the government, there are numerous other stakeholders which have influence in this selection: local population, marine industry and environmentalists, such as local ecologists. Each of these stakeholders should collaborate for a successful roll-out.

A new technology can also attract new stakeholders, new opportunities or create beneficial byproducts. Examples for this technology are fresh water, salt and heat. For the production of hydrogen, fresh water is required. Wind turbines can also be used to produce fresh water as output. This is a product which can be scarce at remote locations. The second byproduct which can be used is salt. The desalinator will output salt to produce this fresh water. This can be stored and used for other purposes. The last option is to use the heat, from the fuel cell, in a heat recovery system. All these technological options and stakeholders are recommended topics for future research, because they may increase the opportunities of this technology or social economic benefits.

# References

Abb. (2010). XLPE Submarine Cable Systems Attachment to XLPE Land Cable Systems - User ´ s Guide. *User's Guide*. Retrieved from http://www04.abb.com/global/seitp/seitp202.nsf/0/badf833d6cb8d46dc1257c0b002b3702/$file/XLPE+Submarine+Cable+Systems+2GM5007+.pdf

ABB. (2020). *ABB scales up fuel cells for shipping's greener future.* Retrieved 2021-05-04, from https://new.abb.com/news/detail/60295/abb-scales-up-fuel-cells-for-shippings-greener-future

Abdusamad, K. (2018). Wind Energy Reliability Analysis based on Monte Carlo Simulation Method. , *2*, 734–745. doi: 10.21467/proceedings.4.41

ABN AMRO. (2021). *Confidential information.*

Adedipe, T. & Shafiee, M. (2021, feb). An economic assessment framework for decommissioning of offshore wind farms using a cost breakdown structure. *International Journal of Life Cycle Assessment*, *26*(2), 344–370. Retrieved from https://link.springer.com/article/10.1007/s11367-020-01793-x doi: 10.1007/s11367-020-01793-x

AGI. (2019). *What are the advantages and disadvantages of offshore wind farms? — American Geosciences Institute.* Retrieved 2021-06-24, from https://www.americangeosciences.org/critical-issues/faq/what-are-advantages-and-disadvantages-offshore-wind-farms

Agora Energiewende, Couture, T. D., Jacobs, D. & Appleman, N. (2018). A word on Low Cost Renewables. *Report*, 1–9.

Akinyele, D., Olabode, E. & Amole, A. (2020). Review of fuel cell technologies and applications for sustainable microgrid systems. *Inventions*, *5*(3), 1–35. doi: 10.3390/inventions5030042

Aldersey-Williams, J. & Rubert, T. (2019). Levelised cost of energy – A theoretical justification and critical assessment. *Energy Policy*, *124*(September 2018), 169–179. Retrieved from https://doi.org/10.1016/j.enpol.2018.10.004 doi: 10.1016/j.enpol.2018.10.004

A.M. Othman, H. G. (2017). *Energy Storage Technology - an overview — ScienceDirect Topics.* Retrieved 2021-05-03, from https://www.sciencedirect.com/topics/engineering/energy-storage-technology

Andersson, J. & Grönkvist, S. (2019, may). *Large-scale storage of hydrogen* (Vol. 44) (No. 23). Elsevier Ltd. doi: 10.1016/j.ijhydene.2019.03.063

Awalom, M. T., Tesfa, A. F., Kidane, M. E., Ghebremedhin, M. R. & Teklesenbet, A. H. (2015). Eritrean pharmacists' job satisfaction and their attitude to re-professionalize pharmacy in to pharmaceutical care. *International Journal of Clinical Pharmacy*, *37*(2), 335–341. Retrieved from https://www.energy.gov/sites/prod/files/2015/08/f25/LCOE.pdf%0Ahttps://energy.gov/sites/prod/files/2015/08/f25/LCOE.pdf doi: 10.1007/s11096-015-0064-9

Badouard, T., Moreira de Oliveira, D., Yearwood, J., Torres, P. & Altmann, M. (2020). *Final Report Cost of Energy ( LCOE ) : Energy costs, taxes and the impact of government interventions on investments.*

Barney, A., Polatidis, H., Jelić, M., Tomasević, N., Pillai, G. & Haralambopoulos, D. (2021, oct). Transition towards decarbonisation for islands: Development of an integrated energy planning platform and application. *Sustainable Energy Technologies and Assessments*, *47*. Retrieved from http://creativecommons.org/licenses/by/4.0/ doi: 10.1016/J.SETA.2021.101501

BEIS. (2016). BEIS Electricity Generation Costs. (November), 85. Retrieved from https://www.gov.uk/government/publications/beis-electricity-generation-costs-november-2016

Beiter, P. (2019). LCOE Alternatives: System Value and Other Profitability Metrics. Retrieved from https://api.misoenergy.org/MISORTWD/lmpcontourmap.html

Beiter, P., Musial, W., Duffy, P., Cooperman, A., Shields, M., Heimiller, D. & Optis, M. (2020). The Cost of Floating Offshore Wind Energy in California Between 2019 and 2032. (November). Retrieved from www.nrel.gov/publications.

Blix Consultancy. (2020). Determination of the cost levels of wind farms (and their grid connections) in new offshore wind energy search areas.

Bloomberg NEF. (2019). *Hydrogen: The economics of production from renewables - costs to plummet.* Bloomberg NEF. Retrieved from https://about.bnef.com/blog/booming-lng-faces-big-swings-supply-demand-balance/?utm_medium=Newsletter&utm_campaign=BNEF&utm_source=Email&utm_content=wirmay14&mpam=21051&bbgsum=DM-EM-05-19-M21051

Bulbaai, R. (2019). *Toward 100structural decrease in energy demand: Curaçao, as a case study of small island developing states* (Doctoral dissertation, University of Twente, Netherlands). doi: 10.3990/1.9789402817218

center for energy policy, K. (2020). *Innovation in Isolation: Islands and the Energy Transition.* Retrieved 2021-11-08, from https://kleinmanenergy.upenn.edu/research/publications/innovation-in-isolation-islands-and-the-energy-transition/

Cheboxarov, V. V., Yakimovich, B. A., Abd Ali, L. M. & Al-Rufee, F. M. (2019). An Offshore Wind-Power-Based Water Desalination Complex as a Response to an Emergency in Water Supply to Northern Crimea. *Applied Solar Energy (English translation of Geliotekhnika)*, *55*(4), 260–264. doi: 10.3103/S0003701X19040030

Climate Change Laws of the World. (2021). *Grenada Vision 2030.* Retrieved 2021-06-14, from https://climate-laws.org/geographies/grenada/policies/grenada-vision-2030

Climatechangenews. (2021). *Why Grenada had to nationalise its electricity for $60m to pursue renewables.* Retrieved 2021-06-03, from https://www.climatechangenews.com/2021/02/05/grenada-nationalise-electricity-60m-pursue-renewables/

Compressors, M. (2018). *Which are Better: Rotary Vane or Reciprocating Compressors?* Retrieved 2021-11-06, from http://compressors.matteicomp.com/blog/which-are-better-rotary-vane-or-reciprocating-compressors

Costoya, X., DeCastro, M., Santos, F., Sousa, M. C. & Gómez-Gesteira, M. (2019, jul). Projections of wind energy resources in the Caribbean for the 21st century. *Energy*, *178*, 356–367. doi: 10.1016/j.energy.2019.04.121

Crivellari, A. & Cozzani, V. (2020, jan). Offshore renewable energy exploitation strategies in remote areas by power-to-gas and power-to-liquid conversion. *International Journal of Hydrogen Energy*, *45*(4), 2936–2953. doi: 10.1016/j.ijhydene.2019.11.215

Curto, D., Franzitta, V. & Guercio, A. (2021). A review of the water desalination technologies. *Applied Sciences (Switzerland)*, *11*(2), 1–36. doi: 10.3390/app11020670

D'Amore-Domenech, R., Santiago, Ó. & Leo, T. J. (2020). Multicriteria analysis of seawater electrolysis technologies for green hydrogen production at sea. *Renewable and Sustainable Energy Reviews*, *133*(August). doi: 10.1016/j.rser.2020.110166

Demirel, Y. (2015). Technoeconomics and Sustainability of Renewable Methanol and Ammonia Productions Using Wind Power-based Hydrogen. *Journal of Advanced Chemical Engineering*, *5*(3). doi: 10.4172/2090-4568.1000128

Dincer, I., Alzahrani, A. A. & Systems, E. (2018). Electrolyzer Technology PEM Electrolyzers and PEM Regenera- tive Fuel Cells Industrial View.

Dinh, V. N., Leahy, P., McKeogh, E., Murphy, J. & Cummins, V. (2020). Development of a viability assessment model for hydrogen production from dedicated offshore wind farms. *International Journal of Hydrogen Energy*(xxxx). Retrieved from https://doi.org/10.1016/j.ijhydene.2020.04.232 doi: 10.1016/j.ijhydene.2020.04.232

Dolphyn. (2019). Dolphyn Hydrogen Phase 1 - Final Report. *Low Carbon Hydrogen Supply Programme*(October). Retrieved from https://www.gov.uk/government/publications/hydrogen-supply-competition

Dols, F. L. (2019). The Impact of Desalination and Climate Change on Salinity in the Arabian Gulf.

Dranka, G. G., Ferreira, P. & Vaz, A. I. F. (2021, oct). Integrating supply and demand-side management in renewable-based energy systems. *Energy*, *232*, 120978. doi: 10.1016/j.energy.2021.120978

Dupont, E., Koppelaar, R. & Jeanmart, H. (2018). Global available wind energy with physical and energy return on investment constraints. *Applied Energy*, *209*(October), 322–338. doi: 10.1016/j.apenergy.2017.09.085

EC. (2016). *Emissions cap and allowances.* Retrieved 2021-11-19, from https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets/emissions-cap-and-allowances_en

EDF. (2017). *The true cost of carbon pollution — Environmental Defense Fund.* Retrieved 2021-09-29, from https://www.edf.org/true-cost-carbon-pollution

EH Group. (2021). EH Fuel Cell Stack Technology. , 1–3.

Energy Efficiency & Renewable Energy. (2017). *Advantages and Challenges of Wind Energy — Department of Energy.* Retrieved 2021-03-29, from https://www.energy.gov/eere/wind/advantages-and-challenges-wind-energy

Energy Information Administration [EIA]. (2021). Levelized Cost of New Generation Resources in the Annual Energy Outlook 2021. *US Energy Information Administration*(January), 1–25. Retrieved from https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf

Energy Transition Initiative. (2015). Island Energy Snapshot - Grenada (Fact Sheet).

Espinasa, R., Humpert, M., Gischler, C. & Janson, N. (2015). *Challenges and Opportunities for the energy sector in the Eastern Caribbean: Antigua and Barbuda Energy Dossier* (No. December). Retrieved 2021-05-18, from https://publications.iadb.org/publications/english/document/Challenges-and-Opportunities-for-the-Energy-Sector-in-the-Eastern-Caribbean-Grenada-Energy-Dossier.pdf

Europa.eu. (2018). 2017 Energy Report Card – Trinidad and Tobago. *Caricom*(December). Retrieved from https://energy.caricom.org/reports-2/

Fernández-Guillamón, A., Das, K., Cutululis, N. A. & Molina-García, Á. (2019, nov). Offshore wind power integration into future power systems: Overview and trends. *Journal of Marine Science and Engineering*, *7*(11), 399. Retrieved from https://www.mdpi.com/2077-1312/7/11/399/htmhttps://www.mdpi.com/2077-1312/7/11/399 doi: 10.3390/jmse7110399

Frames Group. (2020). *Frames group - Hydrogen electrolyzers.* Retrieved 17-05-2021, from https://www.frames-group.com/getmedia/727ab9e3-bd08-410e-b9b9-d6d006bd4ba9/Frames-Electrolyzer-System.pdf.aspx?ext=.pdf

Frames Group. (2021). *Interview Frames - Suerd Polderdijk.*

Franco, B. A., Baptista, P., Neto, R. C. & Ganilha, S. (2021, mar). Assessment of offloading pathways for wind-powered offshore hydrogen production: Energy and economic analysis. *Applied Energy*, *286*, 116553. doi: 10.1016/j.apenergy.2021.116553

Gao, L., Yoshikawa, S., Iseri, Y., Fujimori, S. & Kanae, S. (2017). An economic assessment of the global potential for seawater desalination to 2050. *Water (Switzerland)*, *9*(10), 1–19. doi: 10.3390/w9100763

Garzon, F. H., Rockward, T., Mukundan, R., Kienitz, B., Chlistunoff, J., Brosha, E. L., … Garland, N. (2007). Effects of Fuel and Air Impurities on PEM Fuel Cell Performance, DOE Hydrogen Program FY 2010 Annual Progress Report. , 722–726. Retrieved from https://www.hydrogen.energy.gov/pdfs/progress10/v_c_1_garzon.pdf

Gazey, R., Salman, S. K. & Aklil-D'Halluin, D. D. (2006, jul). A field application experience of integrating hydrogen technology with wind power in a remote island location. *Journal of Power Sources*, *157*(2), 841–847. doi: 10.1016/j.jpowsour.2005.11.084

Gemini. (2021). *Details TPs.* Retrieved 2021-04-29, from https://www.geminiwindpark.nl/details-tps.html#d1

Gencell. (2018). *Comparing Fuel Cell Technologies - GenCell - Fuel Cell Generators.* Retrieved 2021-11-06, from https://www.gencellenergy.com/news/comparing-fuel-cell-technologies/

Ghasemian, S., Faridzad, A., Abbaszadeh, P., Taklif, A., Ghasemi, A. & Hafezi, R. (2020). An overview of global energy scenarios by 2040: identifying the driving forces using cross-impact analysis method. *International Journal of Environmental Science and Technology*(0123456789). Retrieved from https://doi.org/10.1007/s13762-020-02738-5 doi: 10.1007/s13762-020-02738-5

Giraldo, J., Cardenas, A. & Quijano, N. (2014, 10). Attenuating the impact of integrity attacks on real-time pricing in smart grids. *arXiv*.

Global wind atlas. (2018). *Global Wind Atlas of Grenada.* Retrieved 2021-05-25, from https://globalwindatlas.info/

Google. (2021). *Google Maps - Grenada.* Retrieved 2021-06-14, from https://www.google.com/maps/place/Grenada/@13.058774,-70.0077714,5.59z/data=!4m5!3m4!1s0x8c381789f4877bd1:0x36d8c7015a1f4f8e!8m2!3d12.1165!4d-61.679

Gosselin, D. (2014). A Stack Cost Comparison of 100 kW Combined Heat and Power Fuel Cell Systems. , 100.

Government of Grenada - National Plan Secretariat. (2019). National Sustainable Development Plan Grenada 2020-2035. , *255*(22), 71–89. Retrieved from https://observatorioplanificacion.cepal.org/sites/default/files/plan/files/GRANADA-NSDP20202035.pdf

Grenlec. (2019). Grenlec - Annual report 2019. , 77.

H2-view. (2021). *EH Group: Redesigning fuel cell technology.* Retrieved 2021-06-29, from https://www.h2-view.com/story/eh-group-redesigning-fuel-cell-technology/

Hanania, J., Martin, J., Stenhouse, K. & Donev, J. (2015). *Diesel generator - Energy Education.* Retrieved 2021-08-20, from https://energyeducation.ca/encyclopedia/Diesel_generator

He, X., Li, C. & Gu, W. (2010). Research on an innovative large-scale offshore wind power seawater desalination system. *Proceedings of 2010 World Non-Grid-Connected Wind Power and Energy Conference, WNWEC 2010*, 237–240. doi: 10.1109/WNWEC.2010.5673305

Heather, C., Peter H, G. & Gary, W. (2006). *Desalination, with a grain of salt. A California Perspective* (Vol. 35; Tech. Rep. No. June). Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Desalination,+With+A+Grain+of+Salt+-+a+california+perspective#0

Hirth, L., Ueckerdt, F. & Edenhofer, O. (2015). Integration costs revisited - An economic framework for wind and solar variability. *Renewable Energy*, *74*, 925–939. Retrieved from http://dx.doi.org/10.1016/j.renene.2014.08.065 doi: 10.1016/j.renene.2014.08.065

Hooper, T., Armstrong, A. & Vlaswinkel, B. (2021, may). Environmental impacts and benefits of marine floating solar. *Solar Energy*, *219*, 11–14. doi: 10.1016/j.solener.2020.10.010

Hormerenergy. (2016). *Hydrogen Tank.* Retrieved 2021-07-31, from https://www.alibaba.com/showroom/hydrogen-storage-tank.html

Hou, P., Enevoldsen, P., Eichman, J., Hu, W., Jacobson, M. Z. & Chen, Z. (2017). Optimizing investments in coupled offshore wind -electrolytic hydrogen storage systems in

Denmark. *Journal of Power Sources*, *359*, 186–197. Retrieved from http://dx.doi.org/10.1016/j.jpowsour.2017.05.048 doi: 10.1016/j.jpowsour.2017.05.048

Hua, T. Q., Ahluwalia, R. K., Peng, J. K., Kromer, M., Lasher, S., McKenney, K., … Sinha, J. (2011). Technical assessment of compressed hydrogen storage tank systems for automotive applications. *International Journal of Hydrogen Energy*, *36*(4), 3037–3049. Retrieved from www.anl.gov. doi: 10.1016/j.ijhydene.2010.11.090

HY-GRO. (2019). *DUWAAL: waterstof uit wind in Noord Holland.* Retrieved 2021-03-24, from https://hy-gro.net/nl/duwaal

IDB. (2016). *The Promise of Renewables in Grenada - Caribbean Development Trends.* Retrieved 2021-06-10, from https://blogs.iadb.org/caribbean-dev-trends/en/the-promise-of-renewables-in-grenada/

IEA. (2021). *Projected Costs of Generating Electricity 2020 – Analysis - IEA.* Retrieved 2021-11-09, from https://www.iea.org/reports/projected-costs-of-generating-electricity-2020

Initiative Energy Transition. (2020). Grenada Snapshot.

Investopedia. (2013). *Discount Rate Definition.* Retrieved 2021-06-23, from http://www.investopedia.com/terms/d/discountrate.asp

IRENA. (2012). Renewable Energy Technologies: Cost Analysis Series. *Green Energy and Technology*, *1*(4/5), 52. Retrieved from www.irena.org/Publications

IRENA. (2018). *Renewable Power Generations Costs.*

IRENA. (2020a). Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 C Climate Goal. */publications/2020/Dec/Green-hydrogen-cost-reduction*, 105. Retrieved from /publications/2020/Dec/Green-hydrogen-cost-reduction%0Ahttps://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

IRENA. (2020b). Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 C Climate Goal. */publications/2020/Dec/Green-hydrogen-cost-reduction*, 105. Retrieved from /publications/2020/Dec/Green-hydrogen-cost-reduction%0Ahttps://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

IRENA. (2021). SIDS Lighthouses Initiative Progress and way forward. (January). Retrieved from https://islands.irena.org/-/media/Files/IRENA/Sids/IRENA_SIDS_Brochure_2019.ashx

ITM-power. (2020). *ITM Power and Ørsted: Wind Turbine Electrolyser Integration.* Retrieved 2021-03-24, from https://www.itm-power.com/news/wind-turbine-electrolyser-integraion?cid=Jzy84bswKBGQE_1j8x9B6-JQ-xMxWUYtDtT9GtPDCeNtgUMmylcrQ7oPSkk715_Nyz-LCip72tVZVMrkCGLT_Q..

Jaax, A. (2016, 01). Skill relatedness and economic restructuring: The case of bremerhaven. *Regional Studies, Regional Science*, *3*, 58-66. doi: 10.1080/21681376.2015.1116958

Jepma, C., Kok, G.-j., Renz, M., Schot, M. V. & Wouters, K. (2018). Towards sustainable energy production on the North Sea - Green hydrogen production and CO 2 storage : onshore or offshore ? *North Sea Energy*, *D3.6*, 1–79.

Jung, W., Jeong, J., Kim, J. & Chang, D. (2020, mar). Optimization of hybrid off-grid system consisting of renewables and Li-ion batteries. *Journal of Power Sources*, *451*, 227754. doi: 10.1016/j.jpowsour.2020.227754

Kelsey, E. C., Felis, J. J., Czapanskiy, M., Pereksta, D. M. & Adams, J. (2018, dec). Collision and displacement vulnerability to offshore wind energy infrastructure among marine birds of the Pacific Outer Continental Shelf. *Journal of Environmental Management*, *227*, 229–247. doi: 10.1016/j.jenvman.2018.08.051

Khawaji, A. D., Kutubkhanah, I. K. & Wie, J. M. (2013). Advances in seawater desalination technologies. *Desalination*, *221*(1-3), 47–69. doi: 10.1016/j.desal.2007.01.067

Kim, B., Kwak, R., Kwon, H. J., Pham, V. S., Kim, M., Al-Anzi, B., ... Han, J. (2016, aug). Purification of high salinity brine by multi-stage ion concentration polarization desalination. *Scientific Reports*, *6*(1), 1–12. Retrieved from www.nature.com/scientificreports doi: 10.1038/srep31850

Lamine, M. & Agbossou, K. (2009, dec). Photovoltaic/Wind Energy System with Hydrogen Storage. *Renewable Energy*. doi: 10.5772/7367

Lazarou, S. & Makridis, S. (2017, jun). Hydrogen Storage Technologies for Smart Grid Applications. *Challenges*, *8*(1), 13. Retrieved from www.mdpi.com/journal/challenges doi: 10.3390/challe8010013

Lee, A. (2019). *Floating wind-to-hydrogen plan to heat millions of UK homes.* Retrieved 2021-03-24, from https://www.rechargenews.com/wind/floating-wind-to-hydrogen-plan-to-heat-millions-of-uk-homes/2-1-670960

Lee, A. (2020). *World's largest offshore wind farm to power green hydrogen under UK plan.* Retrieved 2021-03-24, from https://www.rechargenews.com/transition/worlds-largest-offshore-wind-farm-to-power-green-hydrogen-under-uk-plan/2-1-757976

Lenntech. (2021). *Seawater Reverse Osmosis Plant.* Retrieved 2021-11-02, from https://www.lenntech.com/systems/reverse-osmosis/ro/rosmosis.htm

Linde. (2014). Hydrogen technologies. The Ionic Compressor 90 MPa - IC90. , 2.

Lindtvedt, K. (2019). Deep Purple. *MarkenR*, *20*(11-12), 546–553. doi: 10.1515/markenr-2018-2011-1208

Linnenschmidt, J.-N. (2021). Cost comparison between bottom-fixed and floating offshore wind turbines Calculating LCOE based on full hours of utilization and corresponding break-even points. Retrieved from https://doi.org/10.25974/ren_rev_2021_02 doi: 10.25974/ren_rev_2021_02

Matek, B. & Gawell, K. (2015, mar). The benefits of baseload renewables: A misunderstood energy technology. *Electricity Journal*, *28*(2), 101–112. doi: 10.1016/j.tej.2015.02.001

Mavroyeoryos, K., Engonopoulos, I., Tyralis, H., Dimitriadis, P. & Koutsoyiannis, D. (2017). Simulation of electricity demand in a remote island for optimal planning of a hybrid renewable energy system. *Energy Procedia*, *125*, 435–442. Retrieved from https://www.sciencedirect.com/science/article/pii/S1876610217335786 doi: 10.1016/j.egypro.2017.08.095

McDonagh, S., Ahmed, S., Desmond, C. & Murphy, J. D. (2020). Hydrogen from offshore wind: Investor perspective on the profitability of a hybrid system including for curtailment. *Applied Energy*, *265*(September 2019), 114732. Retrieved from https://doi.org/10.1016/j.apenergy.2020.114732 doi: 10.1016/j.apenergy.2020.114732

Meteoblue. (2021). *Climate St. George's.* Retrieved 2021-05-24, from https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/st.-george%27s_grenada_3579925

Meza, C. G., Zuluaga Rodríguez, C., D'Aquino, C. A., Amado, N. B., Rodrigues, A. & Sauer, I. L. (2019). Toward a 100Ometepe's energy mix. *Renewable Energy*, *132*, 628–648. Retrieved from https://www.scopus.com/record/display.uri?eid=2-s2.0-85051683566&origin=resultslist&sort=plf-f&src=s&nlo=&nlr=&nls=&sid=174e7d179205d60b5cb3037bbb199b89&sot=b&sdt=sisr&sl=19&s=TITLE-ABS-KEY%28LCOE%29&ref=%28%28%28remote%29%29+AND+%28offshore%29%29+AND+%28hydrogen%29&relpos=12&citeCnt=19&searchTerm= doi: 10.1016/j.renene.2018.07.124

Mokhi, C. E. & Addaim, A. (2020). Optimization of wind turbine interconnections in an offshore wind farm using metaheuristic algorithms. *Sustainability (Switzerland)*, *12*(14), 1–24. doi: 10.3390/su12145761

Mongird, K., Viswanathan, V., Alam, J., Vartanian, C., Sprenkle, V. & Baxter, R. (2020).

2020 Grid Energy Storage Technology Cost and Performance Assessment. (December), 117. Retrieved from https://www.pnnl.gov/sites/default/files/media/file/Final-ESGCCostPerformanceReport12-11-2020.pdf

Myers, S. C. & Ridge, B. (2008). CORPORATE.

Myhr, A., Bjerkseter, C., Ågotnes, A. & Nygaard, T. A. (2014). Levelised cost of energy for offshore floating wind turbines in a lifecycle perspective. *Renewable Energy*, *66*, 714–728. Retrieved from http://dx.doi.org/10.1016/j.renene.2014.01.017 doi: 10.1016/j.renene.2014.01.017

Native. (2017). *Differences between carbon offsets & carbon allowances nativeenergy.* Retrieved from https://native.eco/2017/12/carbon-offset-vs-carbon-credit/

Nedstack. (2021). *Confidential information.*

Nordhaus, W. (2009, jul). Economics of Climate Change. *EPA*, *317*(5835), 201–202. Retrieved from https://www.epa.gov/environmental-economics/economics-climate-change doi: 10.1126/SCIENCE.1137316

Offshore-mag. (2021). *TechnipFMC leading hydrogen subsea storage project.* Retrieved 2021-08-24, from https://www.offshore-mag.com/renewable-energy/article/14198977/technipfmc-leading-hydrogen-subsea-storage-project

OffshoreWind.biz. (2020). *Ørsted and ITM Power Explore Different Approach to Integrating Offshore Wind and Hydrogen — Offshore Wind.* Retrieved 2021-03-24, from https://www.offshorewind.biz/2020/04/13/orsted-and-itm-power-explore-different-approach-to-integrating-offshore-wind-and-hydrogen/?utm_source=offshorewind

of Regions, E. C. (2021). *Glasgow chronicles: Eu and the us announce a global pledge to slash methane.* Retrieved from https://cor.europa.eu/en/news/Pages/Glasgow-Chronicles-EU-and-the-US-announce-a-global-pledge-to-slash-methane.aspx

Ortt, J. R. & Schoormans, J. P. (2004, 12). The pattern of development and diffusion of breakthrough communication technologies. *European Journal of Innovation Management*, *7*, 292-302. doi: 10.1108/14601060410565047

Painuly, J. P. & Wohlgemuth, N. (2021). *Renewable energy technologies: barriers and policy implications.* Retrieved 2021-10-25, from https://reader.elsevier.com/reader/sd/pii/B9780128205396000182?token=8825F4183A4D0A0A0C6E67C97C1EBCBC77229FAFD005D7A8B5D574ADA647F0D9CA2A1B3BF363C1A1802
eu-west-1&originCreation=20211025101452 doi: 10.1016/b978-0-12-820539-6.00018-2

Perdan, S. & Azapagic, A. (2011, oct). Carbon trading: Current schemes and future developments. *Energy Policy*, *39*(10), 6040–6054. doi: 10.1016/j.enpol.2011.07.003

Pitschak, B. & Mergel, J. (2016, 1). Electrolytic processes. *Hydrogen and Fuel Cell: Technologies and Market Perspectives*, 187-207. Retrieved from https://link.springer.com/chapter/10.1007/978-3-662-44972-1_11 doi: 10.1007/978-3-662-44972-1_11

Prochazka, T. (2012). Framework for Developing Innovation Systems in Small Island Developing States: Roadmap for turning Curacao into the OTEC Centre of Excellence. (August).

Pure Energy Centre. (2021). *Hydrogen compressor.* Retrieved 2021-07-29, from https://pureenergycentre.com/hydrogen-compressor/

Rahman, M. L., Oka, S. & Shirai, Y. (2010). Hybrid power generation system using offshore-wind turbine and tidal turbine for power fluctuation compensation (HOT-PC). *IEEE Transactions on Sustainable Energy*, *1*(2), 92–98. doi: 10.1109/TSTE.2010.2050347

Raikar, S. & Adamson, S. (2020, jan). Renewable energy finance in the international context. *Renewable Energy Finance*, 185–220. doi: 10.1016/b978-0-12-816441-9.00013-1

Renewable, I. & Agency, E. (2016). A Path to Prosperity : Renewable energy for islandS Third Edition. (November), 7–18.

Richardson, I. A., Fisher, J. T., Frome, P. E. & Smith, B. O. (2015). Low-cost , Transportable Hydrogen Fueling Station for Early FCEV Adoption. *Elsevier*. Retrieved from https://digitalcommons.unomaha.edu/econrealestatefacpub/15

Ritchie, H. & Roser, M. (2020). Energy. *Our World in Data*. (https://ourworldindata.org/energy)

Rivard, E., Trudeau, M. & Zaghib, K. (2019). Hydrogen storage for mobility: A review. *Materials*, *12*(12). doi: 10.3390/ma12121973

Schachner, J. (2004). Power Connections for Offshore Wind Farms. , 78.

Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J. & Few, S. (2017, dec). Future cost and performance of water electrolysis: An expert elicitation study. *International Journal of Hydrogen Energy*, *42*(52), 30470–30492. doi: 10.1016/j.ijhydene.2017.10.045

Sdanghi, G., Maranzana, G., Celzard, A. & Fierro, V. (2019, mar). Review of the current technologies and performances of hydrogen compression for stationary and automotive applications. *Renewable and Sustainable Energy Reviews*, *102*, 150–170. doi: 10.1016/j.rser.2018.11.028

Semeraro, M. A. (2021, may). Renewable energy transport via hydrogen pipelines and HVDC transmission lines. *Energy Strategy Reviews*, *35*, 100658. doi: 10.1016/j.esr.2021.100658

Serna, Á. & Tadeo, F. (2014, jan). Offshore hydrogen production from wave energy. *International Journal of Hydrogen Energy*, *39*(3), 1549–1557. doi: 10.1016/j.ijhydene.2013.04.113

Shahzad, M. W., Burhan, M., Ybyraiymkul, D. & Ng, K. C. (2019). Desalination processes' efficiency and future roadmap. *Entropy*, *21*(1). doi: 10.3390/e21010084

Shatnawi, M., Qaydi, N. A., Aljaberi, N. & Aljaberi, M. (2018). Hydrogen-Based Energy Storage Systems: A Review. *7th International IEEE Conference on Renewable Energy Research and Applications, ICRERA 2018*, *2*(1), 697–700. doi: 10.1109/ICRERA.2018.8566903

Shiva Kumar, S. & Himabindu, V. (2019, dec). Hydrogen production by PEM water electrolysis – A review. *Materials Science for Energy Technologies*, *2*(3), 442–454. doi: 10.1016/j.mset.2019.03.002

Shorman, M. & Alshorman, A. (2016, 10). Parametric investigation of wind energy for jordanian metrological conditions. *Australian Journal of Basic and Applied Sciences*, 26-36.

Simpson, J. G., Hanrahan, G., Loth, E., Koenig, G. M. & Sadoway, e. a., D. R. (2021, oct). Liquid metal battery storage in an offshore wind turbine: Concept and economic analysis. *Renewable and Sustainable Energy Reviews*, *149*, 111387. doi: 10.1016/j.rser.2021.111387

Singlitico, A., Ostergaard, J. & Chatzivasileiadis, S. (2021). Onshore, offshore or in-turbine electrolysis? Techno-economic overview of alternative integration designs for green hydrogen production into Offshore Wind Power Hubs. *Renewable and Sustainable Energy Transition*, *1*(May), 100005. Retrieved from https://doi.org/10.1016/j.rset.2021.100005 doi: 10.1016/j.rset.2021.100005

Sklar-Chik, M. D., Brent, A. C. & de Kock, I. H. (2016). Critical review of the levelised cost of energy metric. *South African Journal of Industrial Engineering*, *27*(4), 124–133. Retrieved from http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S2224-78902016000400011&lng=en&nrm=iso&tlng=enhttp://www.scielo.org.za/scielo.php?script=sci_abstract&pid=S2224-78902016000400011&lng=en&nrm=iso&tlng=en doi: 10.7166/27-4-1496

StatiolHydro. (2009). Experiences from the wind-hydrogen plant at Utsira.

Statista. (2021). *Electricity prices by country 2020.* Retrieved 2021-05-10, from https://www.statista.com/statistics/263492/electricity-prices-in-selected-countries/

Steilen, M. & Jörissen, L. (2015, jan). Hydrogen Conversion into Electricity and Thermal

Energy by Fuel Cells: Use of H2-Systems and Batteries. In *Electrochemical energy storage for renewable sources and grid balancing* (pp. 143–158). Elsevier Inc. doi: 10.1016/B978-0-444-62616-5.00010-3

Stenhouse, K., Hanania, J. & Donev, J. (2018). *Access to electricity - Energy Education.* Retrieved 2021-06-24, from https://energyeducation.ca/encyclopedia/Access_to_electricity

Steward, D., Saur, G., Penev, M. & Ramsden, T. (2011). Lifecycle cost analysis of hydrogen versus other technologies for electrical energy storage. *Energy Storage: Issues and Applications*, 59–120. Retrieved from http://www.osti.gov/bridge

Stram, B. N. (2016, sep). Key challenges to expanding renewable energy. *Energy Policy*, *96*, 728–734. Retrieved from http://dx.doi.org/10.1016/j.enpol.2016.05.034 doi: 10.1016/j.enpol.2016.05.034

Sun, Q., Ye, Z. S. & Zhu, X. (2020, jul). Managing component degradation in series systems for balancing degradation through reallocation and maintenance. *IISE Transactions*, *52*(7), 797–810. Retrieved from https://www.tandfonline.com/doi/abs/10.1080/24725854.2019.1672908 doi: 10.1080/24725854.2019.1672908

The Titus Company. (2021). *Differences Between Rotary Vane & Rotary Screw Compressors.* Retrieved 2021-11-06, from https://www.titusco.com/the-difference-between-rotary-vane-and-rotary-screw-compressors/

TNO. (2019). *World first: an offshore pilot plant for green hydrogen.* Retrieved 2021-03-24, from https://www.tno.nl/en/focus-areas/ecn-part-of-tno/roadmaps/towards-co2-neutral-fuels-and-feedstock/hydrogen-for-a-sustainable-energy-supply/world-first-an-offshore-pilot-plant-for-green-hydrogen/

Tomlinson, C. (2012). E-on - Rampion Offshore Wind Farm. (2). Retrieved from http://www.sussexwindenergy.org.uk/

Tougaard, J., Hermannsen, L. & Madsen, P. T. (2020, nov). How loud is the underwater noise from operating offshore wind turbines? *The Journal of the Acoustical Society of America*, *148*(5), 2885–2893. Retrieved from https://doi.org/10.1121/10.0002453 doi: 10.1121/10.0002453

Tu, Q., Liu, Z., Li, B. & Mo, J. (2021). Achieving grid parity of offshore wind power in China–A comparative analysis among different provinces. *Computers and Industrial Engineering*, *162*. doi: 10.1016/j.cie.2021.107715

UNFCCC. (2019). *The Paris agreement.* Retrieved 2021-10-28, from https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement doi: 10.4324/9781351270090-20

United Nations. (2021). *About Small Island Developing States — Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States.* Retrieved 2021-11-16, from https://www.un.org/ohrlls/content/about-small-island-developing-states

United Nations Framework Convention on Climate Change. (2015). *Grenada.* Retrieved 2021-06-14, from https://www.ctc-n.org/sites/www.ctc-n.org/files/UNFCCC_docs/grenada_indc.pdf

US EIA. (2013). Assessing the Economic Value of New Utility-Scale Electricity Generation Projects. (July), 1–15. Retrieved from http://www.eia.gov/forecasts/aeo/er/electricity_generation.cfm.

Valente, A., Iribarren, D. & Dufour, J. (2020). Prospective carbon footprint comparison of hydrogen options. *Science of the Total Environment*, *728*, 138212. Retrieved from https://doi.org/10.1016/j.scitotenv.2020.138212 doi: 10.1016/j.scitotenv.2020.138212

Van Eldik, G. (2015). *Introducing energy performance indicators for the residential sector in Curacao* (Tech. Rep.).

Van Oord. (2021). *Confidential information.*

Van Poeck, K., Östman, L. & Block, T. (2020, mar). Opening up the black box of learning-by-doing in sustainability transitions. *Environmental Innovation and Societal Transitions*, *34*, 298–310. doi: 10.1016/j.eist.2018.12.006

Vestas. (2017). Are you looking for the maximum return on your investment in wind energy?

vestas. (2021). *Confidential information.*

Wang, Y. & Sun, T. (2012, jul). Life cycle assessment of CO 2 emissions from wind power plants: Methodology and case studies. *Renewable Energy*, *43*, 30–36. doi: 10.1016/j.renene.2011.12.017

Wheeler, K. R. & Southward, S. C. (2017). Efficient Operation of Diesel Generator Sets in Remote Environments. *Virginia Polytechnic Institute and State University*. Retrieved from https://vtechworks.lib.vt.edu/handle/10919/78374

Wolf, E. (2015). *Large-Scale Hydrogen Energy Storage*. Elsevier B.V. Retrieved from http://dx.doi.org/10.1016/B978-0-444-62616-5.00009-7 doi: 10.1016/B978-0-444-62616-5.00009-7

Worlddata.info. (2021). *Grenada: country data and statistics.* Retrieved 2021-06-07, from https://www.worlddata.info/america/grenada/index.php

Xiang, X., Merlin, M. M. & Green, T. C. (2016). Cost analysis and comparison of HVAC, LFAC and HVDC for offshore wind power connection. *IET Conference Publications*, *2016*(CP696). doi: 10.1049/CP.2016.0386

Xiao, P., Hu, W., Xu, X., Liu, W., Huang, Q. & Chen, Z. (2020, sep). Optimal operation of a wind-electrolytic hydrogen storage system in the electricity/hydrogen markets. *International Journal of Hydrogen Energy*, *45*(46), 24412–24423. doi: 10.1016/j.ijhydene.2020.06.302

Yang, W. J. & Aydin, O. (2001, apr). Wind energy-hydrogen storage hybrid power generation. *International Journal of Energy Research*, *25*(5), 449–463. doi: 10.1002/er.696

Youssef, P. G., Al-Dadah, R. K. & Mahmoud, S. M. (2014). Comparative analysis of desalination technologies. *Energy Procedia*, *61*, 2604–2607. Retrieved from http://dx.doi.org/10.1016/j.egypro.2014.12.258 doi: 10.1016/j.egypro.2014.12.258

Zappa, W. & van den Broek, M. (2018, oct). Analysing the potential of integrating wind and solar power in Europe using spatial optimisation under various scenarios. *Renewable and Sustainable Energy Reviews*, *94*, 1192–1216. doi: 10.1016/j.rser.2018.05.071

Zero Emission Fuels. (2020). *Methanol from sunlight and air.* Retrieved 2021-03-24, from https://zeroemissionfuels.com/

Zhou, Y. & Gu, A. (2019). Learning curve analysis of wind power and photovoltaics technology in US: Cost reduction and the importance of research, development and demonstration. *Sustainability (Switzerland)*, *11*(8). doi: 10.3390/su11082310