A Standardised Comparison Model for Offshore Wind to Hydrogen Concepts

Through Industry Validation and Promotion of Widespread Adoption Towards Improved Stakeholder Cooperation in the Energy Transition

W.J.F. Van den Haak

TU Delft

A Standardised Comparison Model for Offshore Wind to Hydrogen Concepts

Through Industry Validation and Promotion of Widespread Adoption Towards Improved Stakeholder Cooperation in the Energy Transition

by

W.J.F. Van den Haak

to obtain the degree of Master of Science in Hydraulic Engineering
at the Delft University of Technology,
to be defended publicly on May 25, 2023 at 16:00.

Student number:	4479378	
Project duration:	September 12, 2022 – May 25, 2023	
Thesis committee:	Prof. dr. ir. M. van Koningsveld,	TU Delft, supervisor
	Dr. P. Taneja,	TU Delft
	Dr. G. Lavidas,	TU Delft
	W. Sieval,	Van Oord
	A. de Gruijter	MTBS

An electronic version of this thesis is available at http://repository.tudelft.nl/.

TU Delft

Preface

This report marks the end of my studies in Delft. Upon completion of my graduation thesis, I will obtain my Master's degree in Hydraulic Engineering from TU Delft. As I reflect on the past few months, I am pleased to have had the opportunity to delve into such a timely topic. My research has ignited my passion for the energy transition and revealed where I would like to apply my acquired knowledge at the start of my career. The enthusiasm I have gained is due in part to the infectious energy of everyone involved in this project, including my committee and all those interviewed. I am grateful for their contributions and would like to thank several individuals in particular.

First and foremost, I would like to express my gratitude to my supervisors from TU Delft. Mark van Koningsveld, the chairman of my committee, provided me with invaluable help, motivation, and energy throughout my thesis. From our weekly Monday-morning meetings to working together in the Van Oord canteen on a Python model, I am appreciative of his dedicated time. Although I was not initially a fan of Python, I am grateful he persevered in using this method as I have gained a new and exciting skill.

Secondly, I want to thank Poonam Taneja for her support and guidance, especially during more challenging times. Her confidence in my approach, positive attitude, and critical questions were invaluable during this process. I would also like to express my gratitude to George Lavidas for sharing his knowledge about renewable energy. Our discussions have been incredibly helpful, and his expertise and confidence have enabled me to take my research to the next level.

Thirdly, I would like to acknowledge Walter Sieval for his assistance and supervision on behalf of Van Oord. His contagious enthusiasm for renewable energy, particularly hydrogen, was truly motivating. Our meetings helped me to better understand the current offshore wind and hydrogen market, and without his network, I would not have been able to establish all the contacts required for my interviews.

Finally, I would like to thank Adriaan de Gruijter and his colleagues from MTBS. Thanks to their help and expertise, I was able to develop a complete financial model from scratch, something I had not done before and had no prior knowledge of. It was wonderful to have an office where I could brainstorm the financial perspective of my thesis and also have a good laugh.

I am aware that the size of my committee was above average, and I am therefore grateful that five people were enthusiastic enough to find the time to supervise me. Their knowledge and energy have helped shape me into a graduated Hydraulic Engineer with a strong passion for renewable energy.

W.J.F. Van den Haak
Amsterdam, May 2023

Summary

The global response to climate change requires renewable energy sources like wind and solar. Onshore wind turbines present visual pollution and land use issues, which has led to the increasing importance of offshore wind energy. However, the cables used to transport electricity to the grid can be costly and result in power loss over long distances. Additionally, the fluctuating nature of wind energy creates a potential imbalance between supply and demand. As more renewable electricity is generated in the future, grid capacity constraints will arise, meaning that not all generated electricity can be used and may be lost. One possible solution is the use of electricity storage options like hydrogen, particularly ”green hydrogen” produced through electrolysis using renewable electricity. Hydrogen is a valuable addition to the energy system since it can be used directly as gas or converted back into electricity. The Dutch government plans to produce hydrogen on a large scale on the North Sea (e.g. offshore energy hubs) to integrate fluctuating offshore wind energy into the energy system.

To facilitate the energy transition, effective collaboration among all stakeholders is necessary. However, there is currently a lack of understanding regarding the impact of different components in the value chain on the energy system's overall structure and the final energy price. This knowledge gap poses a significant obstacle to cooperation and progress in the energy transition. It creates the risk that effort goes into developing certain partial solutions when they may not be feasible from a larger system perspective. For instance, an electrolyser manufacturer may prioritise improving the efficiency and capacity of its machines, without considering the cost and feasibility of producing the required renewable energy to power them. By focusing on their own component, stakeholders do not fully take into account the needs and interests of others involved. As the development of green hydrogen projects is in its early stages, it is important to think in terms of systems. Stakeholders should establish an ecosystem where players operating in different parts of the value chain are collaborating together. This helps to de-risk projects, share lessons and promote the development of innovative, first-mover initiatives.

This study aims to develop a standardised method to evaluate offshore wind to hydrogen concepts through a techno-economic analysis. This analysis method combines technical analysis with economic evaluation of projects and concepts to determine the potential economic outcomes and impacts of implementing a particular technology or project. One commonly used metric for techno-economic analyses in the hydrogen sector is the Levelised Cost of Hydrogen (LCOH). However, despite its widespread use for comparing different hydrogen concepts, discrepancies in research papers often arise due to varying assumptions.

To date, it seems that no research has been done to standardise a method that allows for transparent and equal comparisons of every possible wind-hydrogen concept. Additionally, understanding the technical and financial assumptions made by researchers when interpreting results can be challenging. A standardised method should also address this problem, for example in the form of a standard notation system. This approach would serve as a tool to facilitate a discussion between parties working on the energy transition. This method will be implemented in the form of a comparison model using software tools such as Excel and Python. Therefore, the adoption of the model by key stakeholders is also being considered. The objective is to create a trusted model that can be used by different stakeholders in the industry. The model will focus on the pre-feasibility stage of a project, and its functionality will be tested using some basic offshore wind to hydrogen concepts.

Through stakeholder interviews, the study found that stakeholders in the offshore wind and hydrogen market have distinct objectives and concerns. In total, 13 interviews were conducted out of which 13 statements were formulated. 10 stakeholder categories were defined, but for some categories, multiple parties were interviewed. 100% of these formulated statements were shared with the interviewees and 100% was validated. Key factors influencing their willingness to contribute include confidentiality, competition, and reputation. Stakeholders expressed reluctance to share their prices and assump-

tions, as they perceive such sharing as too risky in the rapidly evolving market. Others mentioned they would only be willing to share specific cost data in an anonymised industry consortium. As they do not know the exact values yet, they are afraid of negative reputational implications regarding their assumptions. To overcome potential barriers, stakeholders could verify price ranges instead of disclosing exact values. Moreover, relying on transparent and publicly researched assumed prices for various supply chains would allow stakeholders to adjust prices for their respective segments, leading to cost reductions from the initial point. This approach would enhance the trust and validation of the model among users. The study recommends prioritising the industry-wide adoption of the developed model instead of only the industry-wide contribution to the model. The stakeholders need a clear overview comparing different concepts in terms of costs, efficiency, and feasibility. This overview ensures that attention is appropriately allocated to influential parts of the supply chain, avoiding disproportionate focus on elements with minimal impact on final feasibility.

The current financial feasibility assessment method was examined for offshore energy constructions to identify limitations and develop a more comprehensive analysis. The stakeholder analysis highlighted the importance of transparency for industry-wide adoption of the cost model, as well as the desire to assess environmental impact using diverse data sources. An Excel-based financial model used in the study was found to be complex, hindering user comprehension of assumptions and calculations. While Excel is widely used in the industry, its limitations make it challenging to meet the stakeholder's desires. Python seems to be a suitable alternative for this, although coding can be complex and may not be easily understood by everyone. Nonetheless, when people understand coding, the written code is clear and transparent.
The Python model was iteratively developed and compared with the Excel model, revealing discrepancies attributed to small errors in the latter. This underscores the need for a more robust and error-resistant modelling approach, which Python provides. The improved model allows analysis of complex supply chains and efficient handling of large data sets and calculations. Monte Carlo simulations were performed to generate ranges and probabilities for LCOH, enhancing feasibility analyses.

Based on the stakeholder input, the model should prioritise transparency and ease of result sharing. Suggestions include explicitly stating model assumptions, costs considered, financial methodology, and project characteristics. Presenting a standard notation alongside the comparison model results would aid in the understanding of underlying assumptions. This research offers a developed standard notation system proposal.

A case study was conducted to demonstrate the capability of the improved model, which involved calculating the efficiency, LCOH, LCOE, and NPV for four different supply chain scenarios of offshore (energy island) and onshore electrolysis. It was found that onshore electrolysis had a lower LCOH and was financially more feasible for all cases compared to offshore electrolysis. The onshore electrolysis supply chain was also more efficient than the one with an energy island. However, the study highlights that onshore space in ports is expected to become scarce, which would increase the costs of acquiring or renting properties for onshore electrolysis. Although it is uncertain whether this increase will make offshore electrolysis more feasible in the future, follow-up research could explore the financial feasibility of other offshore electrolysis options, such as caissons, platforms, and in-turbine electrolysis. Additionally, a planned 5-year investment delay for a second wind park caused a higher LCOH and LCOE, and lower final year NPV for all cases as less energy was generated over the project's lifetime. The study determined that the financially most feasible option were the cases where 30% of the wind energy was used for hydrogen and 70% for electricity, as opposed to the cases where the majority (70%) of the energy was used for hydrogen production.

The improved model presented in this study has the potential to make a significant impact on the green hydrogen industry. By addressing current challenges hindering cooperation between parties working on the energy transition, the model could be established as a reliable and widely accepted tool for decision-making. Through industry validation and refinement based on stakeholder feedback, the model could help advance the industry towards a sustainable future. This research provides an essential first step towards that goal, demonstrating how the use of Python in cost modelling can improve transparency, flexibility, and analytical capability.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
LCOH	Levelised Cost of Hydrogen
LCOE	Levelised Cost of Electricity
NPV	Net Present Value
Capex	Capital Expenditures
Opex	Operational Expenditures
IRR	Internal Rate of Return
WACC	Weighted Average Cost of Capital

1
Introduction

1.1. Background

1.1.1. Offshore Wind and Hydrogen

In 2015, the Paris Agreement was reached with the aim of ensuring that the global response to the threat of climate change is strengthened (UNFCC, 2022). To achieve this goal, greenhouse gas emissions must be at least 55% below 1990 levels by 2030 (European Commission, 2020b). This means that more and more of the electricity will be generated by renewable energy sources such as wind and solar. The disadvantage of these renewable energy sources is that they have a fluctuating character, i.e. electricity is only produced when there is sun and/or wind (Impram et al., 2020). This is disadvantageous because the demand and supply may not be in balance.

In order to ensure that this fluctuating power generation can be accommodated in the energy system, electricity storage options are needed (Beaudin et al., 2010). This allows electricity to be stored when more is produced than is required so that it can be used when less is produced than is demanded. Various technologies have been proposed as potential solutions to address the energy storage challenge, including but not limited to pumped hydro, compressed air energy storage (CAES), lithium-ion batteries, and hydrogen (Barton & Infield, 2004; Gür, 2018). Hydrogen is an attractive option for energy storage due to its relatively high *gravimetric* energy density (the amount of energy per unit weight) and potential for large-scale grid storage, especially when used in conjunction with fuel cells for backup power generation (Tashie-Lewis & Nnabuife, 2021). However, it should be noted that all options have their pros and cons, but in this paper, the focus lies on hydrogen.

When hydrogen is produced by renewable electricity it is called 'green hydrogen' (IEA, 2019). Wind-generated energy, for example, is then used to set electrolysis in motion. It is a technology that produces hydrogen and oxygen by dissociating water with a direct electric current (Ursua et al., 2012). Hydrogen can be converted back into electricity, but it can also be used directly as a gas in, for example, industrial processes where currently natural gas is used (Neuwirth et al., 2022). In contrast to electricity, hydrogen can be transported across great distances and stored for long periods of time. As a result, the energy system is less susceptible to interruptions in the energy supply (IEA, 2019). To transport or store hydrogen, it must be compressed, liquefied or attached to a carrier due to safety (relatively low inflammation point), and cost-effectiveness (its low *volumetric* energy density in the gaseous state requires more space) (Tashie-Lewis & Nnabuife, 2021).

For the longest time, onshore wind turbines have been dominant in the wind power harvesting process. However, the lack of affordable land near major population centres and the visual pollution of large wind turbines limit the growth potential. When compared to onshore wind power, offshore winds typically flow faster than onshore winds, allowing turbines to generate more electricity offshore (Bilgili et al., 2011).

At present, offshore wind energy is produced in a wind turbine at sea where the electricity is brought ashore via cables and fed into the grid (Srinil, 2016). A disadvantage of this system is that the cables are expensive and lose power over the distance (Jin et al., 2019). This means that if a wind farm is built further from the coast, it will have a major impact on the cost price of the delivered electricity. In addition, the electricity is fed directly into the power system without a (long-term) storage option. This could lead to capacity constraint issues. Due to the greater transport distances, different ways of getting the energy to the coast must be considered (as electrons, as hydrogen, or in different configurations).

Due to the ever-increasing demand for renewable energy, offshore wind and other energy sources need to be scaled up. This has been accelerated by the European Commission's REPowerEU plan. This was presented in 2022 in order to reduce the EU's dependence on Russian fossil fuels and fast forward the green transition. The Commission proposes to increase the percentage of renewable energy in the total energy from 40% to 45%. In order to reach this, it among others sets a target of 10 million tonnes of domestic (EU) green hydrogen production by 2030, to replace natural gas, coal, and oil (European Commission, 2022). In addition, the Dutch government is planning for large-scale hydrogen production in the North Sea. This will allow a good part of the industry to switch from gas to green hydrogen. From 2030, offshore wind energy will come mainly from more distant areas of the North Sea, 60-100 kilometres from the coast (Figure 1.1) (RVO, 2021). With distances probably increasing further in the future. The government wants to realise large-scale offshore energy hubs in these distant areas (Guidehouse, 2022).

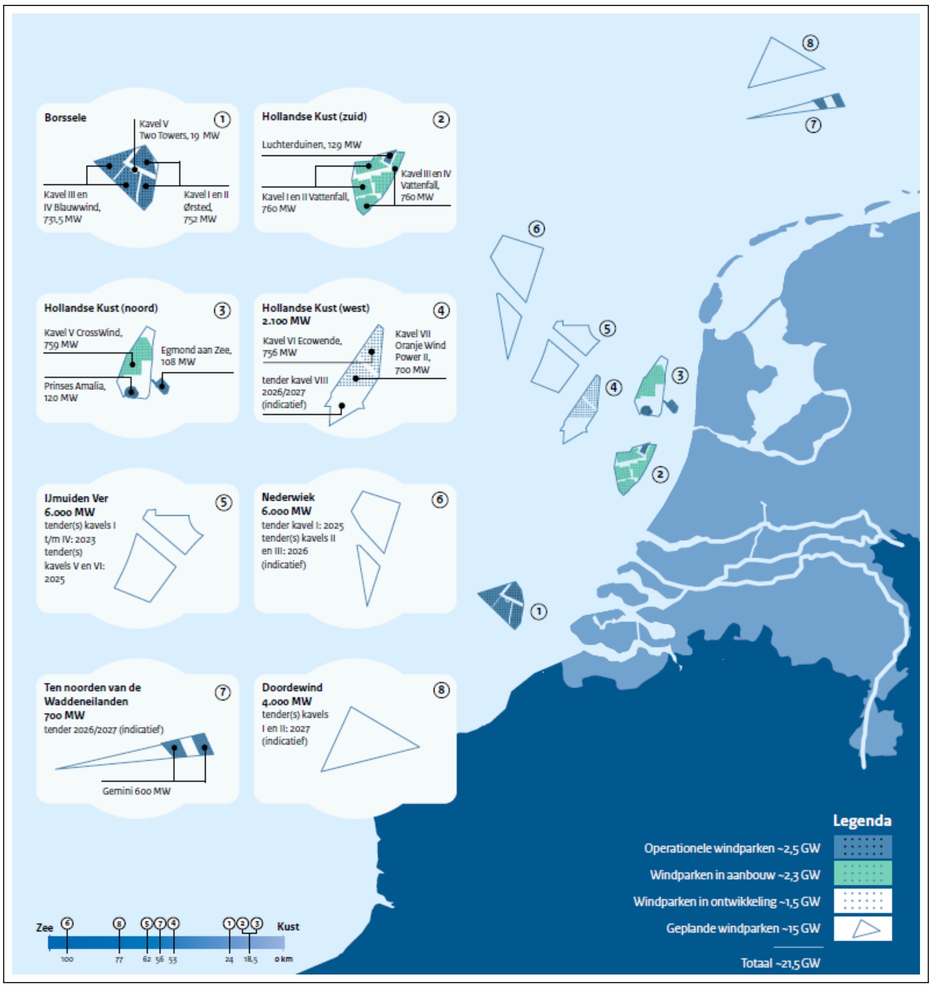

Figure 1.1: Future tender locations for offshore wind parks, proposed by the Dutch government (RVO, 2021)

In addition, as discussed above, there is a need for ways to better integrate this fluctuating energy from the offshore wind into the energy system. When thinking of new ways to transport offshore energy onshore, it is difficult to properly value developments in components (e.g. wind turbines, electrolysers, pipelines), and translate them into total system costs or an energy price. This is because these components are often developed independently and evaluated in isolation. Thus without considering the wider energy system.

For example, offshore wind farm developers may focus on optimising the performance and costs of their turbines. But, it is important to also consider the impact of the farm's output on the overall grid and whether it is possible to integrate that amount of energy into the system. It is known that manufacturers may be hesitant to reveal performance metrics or design details due to competition (Kusiak, 2016). Similarly, an electrolyser manufacturer may focus on improving the efficiency and capacity of its machines. But less knowledge might be present on the cost and feasibility of producing the necessary renewable energy to power it.

This siloed approach risks that a lot of effort goes into developing certain partial solutions when they may not be feasible from a larger system perspective. For instance, an offshore island or platform may be developed to provide a hub for offshore wind farms to connect to the grid. But, proper consideration of the overall energy system is necessary. The hub capacity should be based on the planned wind farm energy output. But also should be thought of the different options to transport the energy onshore (e.g. hydrogen, electricity). Other factors to consider are the transportation capacity and the cost and feasibility of building new infrastructure. And the potential impact on energy prices. By not looking at the overall system, the energy island may not be as effective as originally intended.

By focusing on their own component, stakeholders such as the wind farm developer and the government do not fully take into account the needs and interests of others involved. As the development of green hydrogen projects is in the early stage, it is important to think in terms of systems. Stakeholders should establish an ecosystem where players operating in different parts of the value chain collaborate together. This helps to de-risk projects, share lessons and promote the development of innovative, first-mover initiatives.

1.1.2. Stakeholders

It is important to understand what other parties are involved in the North Sea offshore wind market and in the future (offshore) hydrogen production. As this research is done in cooperation with Van Oord, their expertise is used to get a clear overview of the different stakeholder categories. According to them, the Dutch offshore wind to hydrogen market can be split up into ten different categories. These categories are based on future concepts, which would allow the generation of green hydrogen

1. *Energy infrastructure*
2. *Energy supplier*
3. *Offshore dredging company*
4. *Offshore project developer*
5. *Governmental organisation*
6. *Research institute*
7. *Electrolyser manufacturer*
8. *Wind turbine manufacturer*
9. *Engineering consultant*
10. *Port*

A future offshore hydrogen integration problem is to coordinate decision-making among the participating parties. For example, when an offshore project developer wants to integrate an electrolysis plant into their system to produce green hydrogen. This would involve coordination with several stakeholders. The electrolyser manufacturers would need to provide the technology and expertise for hydrogen production. The wind turbine manufacturer would need to ensure that the wind turbines can provide enough power to the electrolysers. But without compromising the overall performance of the wind farm.

The energy infrastructure would need to ensure that the energy generated is transported to the electrolysis plant and onshore. But without too many losses or disruptions. And the governmental organisation must provide the required subsidy to finance the project.

These stakeholders would need to work together to ensure the right integration of the electrolysis plant into the offshore wind farm. Such that it is technically feasible, cost-effective and sustainable. There are several investments and actions involved at every step of the value chain, and various parties will bear responsibility for them. The development of these comprehensive value chains depends on the cooperation of all different stakeholders involved in such a value chain.

One way to evaluate an overall energy value chain's cost-efficiency is the Levelised Cost of Electricity and Levelised Cost of Hydrogen (Hansen, 2019). It allows investors, project developers, policymakers, and other stakeholders to compare the cost of producing energy from different offshore wind (to hydrogen) concepts. Furthermore, it allows them to compare the cost with the cost of producing energy from fossil fuels. The formulas behind the LCOE and the LCOH are explained in the next paragraph.

1.1.3. Levelised Cost of Hydrogen & Levelised Cost of Electricity

Two important metrics in renewable energy decision-making are the LCOH and LCOE. They are determined by comparing the discounted present value of produced and transported energy to that of costs. It can also be viewed as the energy rate that allows investors to break even by covering capital returns and expenses incurred over a technology's lifespan (Q. V. Dinh et al., 2023; Lorenczik et al., 2020).

As the LCOH and LCOE depend on the produced energy that is transported onshore, supply chain efficiency has a large influence on these two metrics. Therefore, losses over the supply chain should be carefully considered. Furthermore, the supply chain efficiency on itself is an important metric to compare energy projects. This will be further elaborated on in section 4.1.

When determining the LCOH and LCOE using annual discounting, Equation 1.1 is utilised to compare the current value of discounted incomes with the current value of discounted expenses. The left side represents the discounted profits, while the right side represents the discounted expenses (Lorenczik et al., 2020).

$$\sum P * E * (1+r)^{-t} = \sum (Capex_t + Opex_t) * (1+r)^{-t} \tag{1.1}$$

Here, P is the energy price, E the amount of energy produced annually, $(1+r)^{-t}$ the real discount rate corresponding to the cost of capital, $Capex_t$ the total capital expenditures in year t, and $Opex_t$ the total operational expenditures in year t.
When we assume the energy price P to be constant over time, it can be brought out of the summation and Equation 1.1 can be transformed into the following two formulas:

$$LCOH = P_{H_2} = \frac{\sum_{i=1}^{n} \frac{\text{Capex + Opex (related to H2 production and transport)}}{(1+\text{Discount rate})^i}}{\sum_{i=1}^{n} \frac{\text{Produced H2 transported onshore in year i}}{(1+\text{Discount rate})^i}} = [\frac{€}{kg}] \tag{1.2}$$

$$LCOE = P_E = \frac{\sum_{i=1}^{n} \frac{\text{Capex + Opex (related to electricity production and transport)}}{(1+\text{Discount rate})^i}}{\sum_{i=1}^{n} \frac{\text{Produced electricity transported onshore in year i}}{(1+\text{Discount rate})^i}} = [\frac{€}{kWh}] \tag{1.3}$$

There could be some confusion when looking at Equation 1.2 and Equation 1.3 without seeing Equation 1.1. The equation seems to suggest that energy is being discounted. However, P is a constant value that can be removed from the overall summation of revenues earned by the power plant over its lifetime. Both sides of Equation 1.1 can be divided by this summation. It is important to note that it is not the energy (in kg or kWh) itself that is discounted, but rather the revenue earned from those kgs or kWh. Investors, owners, and operators place more value on revenue earned today compared to revenue earned in the future. The discounted value is not based on output alone, but rather on the economic value of that output. This is a standard practice in cost-benefit accounting (Lorenczik et al., 2020).

1.2. Research Problem

The question now remains for the government on how offshore wind to hydrogen facilities should be optimally integrated. This knowledge must be present, to determine what initiatives should be focused on and what concepts are eligible for future tenders on the North Sea.
Further, most applications for green hydrogen are not cost-competitive without direct government support. It is therefore important for players active in the offshore and/or hydrogen industry to convince the government of the feasibility of their ideas (IEA, 2019).

To accelerate the energy transition, it is important that all relevant stakeholders work together. Currently, there is an insufficient understanding of the influence of the different elements of a supply chain on the larger energy system (structure of the supply chain) and the final energy price (LCOH & LCOE). These are critical aspects, which hinder cooperation and progress in the energy transition. For example, the government might promote the realisation of offshore electrolysis. However, electrolysers' technology might not be ready for that yet. And furthermore, it might not even be clear what the effect on the final energy price would be if hydrogen was produced offshore instead of onshore. For better cooperation, more insight into the offshore wind to hydrogen supply chain is required. Without cooperation, there is a risk of misusing significant financial resources on inappropriate infrastructure in unsuitable locations. This would also result in the wasteful utilisation of an even scarcer resource: time.

To determine what could be the best offshore wind to hydrogen concept on the North Sea, different parties involved should have a transparent discussion. A standardised method to compare alternative concepts could be helpful in this discussion. There are two challenges here. Firstly, a standardised method does not seem to be available yet. Secondly, the offshore hydrogen market will be a competitive market where parties involved will be hesitant in sharing their data. This will not contribute to an open discussion.

Therefore, more research needs to be carried out on currently known methods for comparing alternative offshore wind to hydrogen concepts.

1.3. Research Gap

In this section, the research gap is defined by reviewing relevant literature for this study. First, studies with similar topics are analysed and the current present knowledge is described. Next, the actual research gap drawn from this literature review is discussed. As offshore wind to hydrogen is a fairly new concept which is still under development, it was decided to only consider papers which were published post-2017.

Research has been carried out on various offshore wind to hydrogen concepts and their economic feasibility. Analysing the economic performance of technical processes or concepts is called a techno-economic analysis (Chai et al., 2022). Research is conducted to determine the most economical method of connecting offshore wind farms and hydrogen production facilities (Jang et al., 2022). The economic feasibility was compared using the Levelised Cost of Hydrogen (LCOH), Net Present Value (NPV), sensitivity analysis, and Monte Carlo simulation. The NPV and LCOH were assessed based on the cash flow, which can be calculated from estimated revenue and expenditure items. In that study, a sensitivity analysis was done to find out how different factors would affect the price of producing hydrogen. Sensitivity analysis (SA) is frequently used in engineering because it highlights the significance of each input variable and aids in the identification of the crucial variables that influence the results. The results showed that the capacity factor is most dominant, followed by the tax rate. The capacity factor compares the utilisation (in hours) of a facility to its maximum amount of possible operational hours (Jang et al., 2022).

A similar study was performed, in which a techno-economic assessment of the different production and exportation pathways of offshore hydrogen was done (Franco et al., 2021). In this analysis, the determination of their LCOH, NPV and energy expenditure was included. According to the research, the LCOE was found to be the largest contributor to the LCOH, because the production of hydrogen requires a lot of electricity (Franco et al., 2021).

Another study uses both the LCOH and LCOE to compare alternative integration designs for green hydrogen production (onshore, offshore, or in-turbine electrolysis) (Singlitico et al., 2021). Here, again, a sensitivity analysis was performed to determine the influence of different parameters on the LCOH. It was found that the cost of the wind turbines has the biggest impact, regardless of the electrolysis placement and operation mode (Singlitico et al., 2021).

Finally, one study considered the investor perspective on the profitability of wind to hydrogen configurations (McDonagh et al., 2020). This research also used an LCOH model to determine future viability. Through sensitivity analysis, it was found that the wind turbine Capex, the hydrogen Capex (electrolysis, compression, and balance of plant) and the discount rate were the three most dominant parameters for both the LCOH and NPV (McDonagh et al., 2020). More studies have been done into the economic feasibility of green hydrogen concepts, both qualitative (Tashie-Lewis & Nnabuife, 2021) and quantitative (Groenemans et al., 2022). In addition, all literature focuses on one or more specific concepts. An example is a study by (Di Lullo et al., 2022), who does a techno-economic analysis of just hydrogen pipelines.

What comes forward from this literature review is that the most common method to compare hydrogen concepts is by considering the LCOH. However, when comparing the results of these studies, significant discrepancies in the LCOH are observed. These differences can be attributed to the various assumptions made by the authors when computing the LCOH. Table 1.1 displays recent literature, its system focus, whether efficiency is considered, whether costs are defined, and how discounting is taken into account. These factors all affect the LCOH. Other parameters that also varied, but are not displayed in the table, were the discount rate, the project lifetime, the inflation rate, the consideration of tax, and the distance from the shore. Notably, this study solely focuses on the LCOH for green hydrogen, and thus research or findings related to fossil-based hydrogen are not included. The values identified in the literature range from a minimum of €1.27 / kg hydrogen to a maximum of €57.61 / kg hydrogen.

Based on the analysed research, it can be found that the techno-economic evaluation of offshore wind to hydrogen concepts is a complex process. This includes the calculation of hydrogen production, wind power generation, and electrolysis plant scale, and assessment of the project cash flow using multiple inputs of data (V. N. Dinh et al., 2021; Yan et al., 2021). For these inputs, assumptions must be made as future concepts are investigated that have never been realised yet. In response, research has been done into the establishment of a new and comprehensive techno-economic assessment model to assess the technical and economic feasibility of a project by calculating the NPV and LCOH or LCOE (V. N. Dinh et al., 2021; Yan et al., 2021). In 2021, researchers tried developing a model for viability assessment of offshore wind to hydrogen production, in which parameters (wind power output, electrolysis plant size, and hydrogen production) are determined using the input time-varying wind speed (V. N. Dinh et al., 2021). There, both NPV and the Discounted Payback (DPB), which take into account the value of capital over time by discounting net cash flows of each period, are used to forecast the costs to a specific time. Another study only used the NPV but did not use the DPB (Yan et al., 2021). However, neither of these papers seem to have considered the adoption and contribution by stakeholders of the method.

Author	Focus	Efficiency	Costs defined	Discounting	LCOH [EUR / kg]
Roos, 2021	Electrolysis and Transport	Yes	Yes	Capex and Energy, not Opex	2.50
Groenemans et al., 2022	Electrolysis	No	Yes	None	1.89 - 3.49
Yan et al., 2021	Offshore Electrolysis using Offshore Wind Energy	Yes	Yes	Opex and Energy, not Capex	3.08
ISPT, 2023	Onshore Electrolysis	Yes	Yes	Capex and Opex, not Energy	N/A
Singlitico et al., 2021	Onshore, Offshore and In-Turbine Electrolysis using Offshore Wind Energy	Yes	Yes	Capex, Opex, and Energy	2.40
Lazard, 2021	Onshore Electrolysis	Yes	Yes	No formula provided	1.27 - 2.67
BEIS, 2021	Onshore Electrolysis	No	No	Capex, Opex, and Energy	N/A
Lucas et al., 2022	Offshore Electrolysis and Storage using Offshore Wind Energy	Yes	Yes	Capex, Opex, and Energy	4.25 - 8.47
McDonagh et al., 2020	Onshore Electrolysis and Storage using Offshore Wind Energy	Yes	Yes	Capex, Opex, and Energy	3.77 - 4.50
Breunis, 2021	Onshore and Offshore Electrolysis using Offshore Wind Energy	Yes	Yes	Capex, Opex, and Energy	N/A
V. N. Dinh et al., 2021	Developing a Viability Model for Offshore Electrolysis using Offshore Wind Energy	Yes	Yes	No LCOH	N/A
Franco et al., 2021	Offshore Electrolysis and Transport using Offshore Wind Energy	Yes	Yes	Capex, Opex, and Energy	5.35
Povacz and Bhandari, 2023	Onshore Electrolysis using Onshore Wind/Solar Energy	Yes	Yes	Opex and Energy, not Capex	3.08 - 13.12
Q. V. Dinh et al., 2023	Onshore and Offshore Electrolysis using Offshore Wind Energy	Yes	Yes	None	3.04 - 3.40
Jang et al., 2022	Onshore, Offshore and In-Turbine Electrolysis using Offshore Wind Energy	Yes	Yes	Opex and Energy, not Capex	12.50 - 13.20
Benalcazar and Komorowska, 2022	Onshore Electrolysis using Onshore Wind/Solar Energy	Yes	No	None	2.33 - 13.48
Di Lullo et al., 2022	Hydrogen Pipelines	Yes	Yes	No formula provided	0.60
Tang et al., 2022	Onshore Electrolysis using Onshore Wind/Solar Energy	No	Yes	Capex, Opex, and Energy	7 - 15.08
Bhandari and Shah, 2021	Onshore Electrolysis using Onshore Solar Energy	Yes	Yes	Opex and Energy, not Capex	57.61

Table 1.1: Comparison of previous research in the field of LCOH using renewable energy

It seems that no research has yet been done to standardise a method whereby every possible wind-hydrogen concept can be compared in a transparent and equal way. It is clear, though, that all studied papers focus on a techno-economic analysis. Therefore, in this research, the choice will be made to investigate the set-up of a standardised comparison model which allows its users to perform a techno-economic analysis. This method should allow users to compare projects based on their costs, supply chain efficiency, and energy production. These numbers can then be used to calculate comparison metrics, such as LCOH, LCOE, and NPV.

From the analysed research in Table 1.1, it came forward that it is often difficult to understand what technical and financial assumptions are done by the author. Especially when interpreting results, there was a lack of transparency. If a standardised method were to be developed, this problem should also be addressed.

Further, in a competitive market like the offshore wind-hydrogen market, it is important that all stakeholders trust the model. Therefore, to make the model even more reliable and accurate, it may be valuable to gather input data from the same stakeholders. It seems that no research has yet been done on how to create an industry-wide accepted method and model to compare alternative offshore wind to hydrogen concepts. For this, we need to explore how to keep such a model transparent, while still making each stakeholder feel comfortable sharing their data to make the model more accurate. Or at least, make them comfortable enough to be willing to use the model. The aim of this research is to address these knowledge gaps.

1.4. Objective and Scope

1.4.1. Objective

This research aims at developing a standardised techno-economic method to compare alternative offshore wind to hydrogen concepts, which will be used and trusted by various stakeholders in the industry. The method would establish the guidelines and principles for conducting the analysis. This method will be implemented in the form of a model using software tools (Python and Excel). The goal of such a model would be to improve cooperation between parties working on the energy transition. By systematically and transparently quantifying various offshore wind to hydrogen concepts and the influence of the components on the final energy price more insight could be provided, which currently seems to be lacking.

The first step is to study the components of an offshore wind to hydrogen supply chain. The next step is to further analyse the Dutch wind and hydrogen playing field. The key categories have been stated in subsection 1.1.2, but more research should be done on their incentives, objectives, and views. This is to gain a better understanding of the desired functionalities of a comparison model. Then, the current common method for conducting techno-economic analyses should be determined. By identifying the limitations of this method, an improved method can be developed and implemented that could become an acceptable and adopted industry standard.

1.4.2. Scope

This research will focus on establishing a model that can be used to compare greenfield offshore wind to hydrogen concepts that are feasible on the North Sea. Therefore, for the stakeholder analysis, only parties involved in the Dutch wind and hydrogen playing field will be considered. Greenfield means that nothing has been built yet. The fact that only greenfield concepts will be considered, means that no existing constructions (e.g. platforms) and transport connections (e.g. pipelines) can be used.

The research will focus on the pre-feasibility stage of the project, which is part of the concept development phase. Taking into consideration the available time, a certain level of detail should be determined for the work breakdown and cost breakdown. This will be done in agreement with MTBS' and Van Oord's expertise in combination with information gathered from stakeholders.

As the focus of this research is to establish a standardised model, some basic offshore wind to hydrogen concepts will be considered to test the functionality of the model. These will be base cases of which all parameters and input data are publicly available.

Finally, the tools that will be considered for the setup of the model will be Excel and Python.

1.5. Research Question

Now that the research problem is defined, the research gap is explained and the objectives and scope are determined, the research question is formulated. It is defined as follows:

How can you develop a standardised comparison model to compare alternative offshore wind to hydrogen concepts to improve cooperation between parties working on the energy transition? And what is required to obtain industry validation and promote widespread adoption of the model among key stakeholders?

In order to answer these main research questions the study addresses various sub-questions.

Understanding Desired Functionalities of Comparison Model

1. *What critical aspects do stakeholders involved in the energy transition believe a comparison model could help to better understand, and how can the development of such a model facilitate discussions among these stakeholders towards identifying the most feasible solutions?*
    - Goal: understand the desired functionalities of the comparison model.

Incentivising Stakeholder Use and Contribution

2. *How can the model be developed in a way that incentivises stakeholders to both use and contribute to the model? What are the key factors that influence stakeholder willingness to contribute, and what measures can be taken to address potential barriers to contribution?*
    - Goal: understand how to obtain industry validation and promote widespread adoption of the model among key stakeholders.

Developing the Comparison Model

3. *What is the current method for assessing the financial feasibility of offshore energy supply chain elements, and how can these separate elements be effectively integrated into a cohesive system view?*
    - Goal: understand how to set up the comparison model.

Improving the Current Method

4. *What are the limitations of the current method in answering the questions of parties involved in the energy transition, and how can the method be extended to address these limitations and provide a more comprehensive analysis?*
    - Goal: understand how the current method can be improved to further obtain industry validation and promote adoption of the model among key stakeholders.
5. *In what respect has extending the method improved our ability to better understand the financial feasibility of various offshore wind to hydrogen chains?*
    - Goal: prove the added value of enhancing the current method.

Enhancing the Comparison Model and Facilitating Greater Cooperation

6. *How can we further enhance the comparison model and facilitate greater cooperation between stakeholders within the offshore wind and hydrogen industry?*
    - Goal: understand how to further develop the comparison model in the future.

1.6. Methodology

The aim of the research is to develop a standardised comparison method, which should improve cooperation between parties working on the energy transition. The method will be implemented in the form of a model using a software tool (Python and Excel). It is important that this model will be validated and adopted by the industry.
The defined sub-questions will help meet this objective. In this chapter, the suggested methodology to answer every sub-question will be defined.

1. *What critical aspects do stakeholders involved in the energy transition believe a comparison method could help to better understand, and how can the development of such a model facilitate discussions among these stakeholders towards identifying the most feasible solutions?*

   To answer this question, first, a literature review should be done on the Dutch wind and hydrogen playing field. Stakeholders from the following categories will be analysed: energy infrastructure, energy supplier, offshore dredging company, offshore project developer, policy maker, research institute, electrolyser manufacturer, wind turbine manufacturer, engineering consultant, and port. Additionally, interviews will be conducted with these stakeholders to learn more about their incentives, objectives, and views. Analysing these results will help gain a better understanding of the desired functionalities of a comparison method.

2. *How can the model be developed in a way that incentivises stakeholders to both use and contribute to the model? What are the key factors that influence stakeholder willingness to contribute, and what measures can be taken to address potential barriers to contribution?*

   The analysis of the stakeholder interviews can be used here to understand what the industry would need to be willing to both use and contribute to the model. Furthermore, as a standardised supply chain breakdown could contribute to industry-wide adoption, research needs to be done on the different elements offshore wind to hydrogen supply chains. Van Oord's expertise will be helpful here.

3. *What is the current method for assessing the financial feasibility of offshore energy constructions, and how can these separate constructions be effectively integrated into a cohesive system view?*

   To answer this question, MTBS' industry expertise will be valuable. A clear understanding is needed of various financial concepts, such as Discounted Cash Flow, Capex, Opex and Net Present Value. Furthermore, because of their expertise, MTBS' methodology will be considered as the current and common one. After studying this method with them, it will be implemented in Excel.

4. *What are the limitations of the current method in answering the questions of parties involved in the energy transition, and how can the method be extended to address these limitations and provide a more comprehensive analysis?*

   Through previous research questions, the target users and their specific needs and preferences should be identified. Next, various techniques for improving the usability of the model could be explored, such as incorporating interactive visualisation tools. Additionally, clear and concise explanations of the assumptions and calculations underlying the model can be developed, using plain language and visual aids to ensure users' comprehension. The goal will be to implement the extension of the current method in Python. It is important to define a clear methodology on how to develop this improved comparison model in an iterative way using both Excel and Python. This to ensure correct calculations and financial methodology.

   If an improved model will be realised, the functionality of it could be demonstrated and validated by analysing the cost structure of some basic offshore wind to hydrogen supply chains.

5. *In what respect has extending the method improved our ability to better understand the financial feasibility of various offshore wind to hydrogen chains?*

   To prove the added value of the new comparison model, the next step will be to recreate a more complex case, such as an offshore energy island. Data for this could be retrieved both through literature research and stakeholders (e.g. Van Oord). Furthermore, sensitivity analyses can be conducted to identify the critical factors that have the greatest impact on the model's outcomes. This information can then be used to make recommendations for optimising the financial feasibility of energy islands as an offshore wind to hydrogen concept.

6. *How can we further enhance the comparison model and facilitate greater cooperation between stakeholders within the offshore wind and hydrogen industry?*

   Answering this research question will serve as a recommendation for future improvement of the model. Here, it will be useful to analyse the stakeholder interviews again to determine what desired functionalities have not been implemented.

1.7. Report Outline

This research consists of seven chapters. Before diving into the research questions, it is useful to gain a better understanding of the components of an offshore wind to hydrogen supply chain. It forms the basis of the standardised method. This will be explained in Chapter 2. In Chapter 3, a stakeholder analysis of the Dutch wind/hydrogen playing field is done through desk research and interviews. It also discusses how the model should be developed to incentivise stakeholders to both use and contribute to the model. Chapter 4 discusses the current method for assessing the financial feasibility of offshore energy constructions using Excel and the limitations of this method. With these limitations known, an improved model will be developed and implemented in Python. Chapter 5 demonstrates the capability of the improved model by recreating a more complex case and analysing the financial feasibility of this. Also, the added value is demonstrated through an uncertainty analysis. Chapter 6 discusses the results of the previous chapter and addresses the limitations of the interviews and model. In Chapter 7, the conclusions are drawn by answering the research questions.

2 Breakdown of an Offshore Wind to Hydrogen Supply Chain

As we are striving for a standardised comparison method for offshore wind to hydrogen supply chains, it is important to be clear about the used terminology in these concepts. The generation of electricity and the production of hydrogen through electrolysis using offshore wind energy involves a complex supply chain. To better understand this process, it is helpful to break it down into five defined sub-systems: Wind energy source, AC substation, Converter, Electrolysis & Electricity, and Import into grid (Singlitico et al., 2021). Every sub-system also has a transport element. It should be noted that there are many different options to convert offshore wind energy to hydrogen. In light of the scope of this research, three supply chain variants will be considered for this chapter. These can be seen in Figure 2.1. The chain is split up into five *sub-systems*, which we call a 'Level 1' breakdown. An example of a sub-system is 'Wind energy source & Transport'. The five sub-systems each consist of their own *elements* or *compononents* - we call this a 'Level 2' breakdown. An example of a component or element is 'Turbine'. All elements of the supply chains displayed in Figure 2.1 will be discussed in detail in the next paragraph. The naming of these sub-systems, and elements/components will be used throughout this research. This can be considered as a standardised naming.

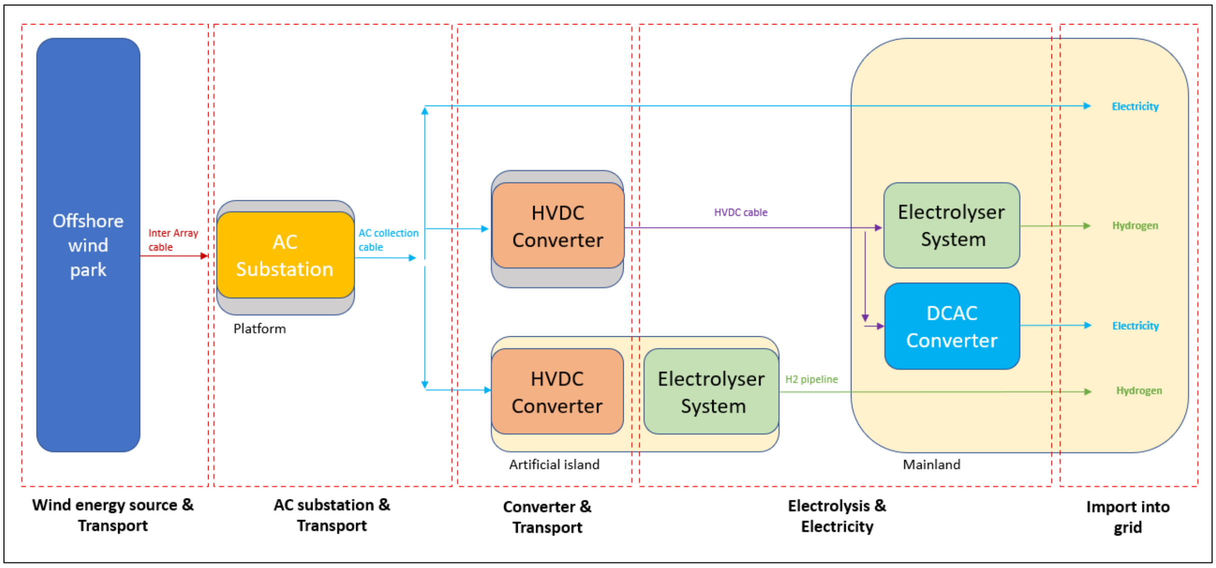

Figure 2.1: Three different offshore wind to hydrogen/electricity supply chains split up in five defined sub-systems

2.1. Wind Energy Source & Transport (Sub-system)

The wind energy source in this research is an offshore wind park. An offshore wind park is a collection of wind turbines which are located in the ocean, typically several kilometres off the coast. These wind turbines are connected to one another and to a substation through a network of underground and underwater cables. The electricity generated by these wind parks can be used to power the electrolysis process to produce hydrogen. Before this can be done, the wind energy is sent to a substation and a converter (RVO, 2022a).
Currently, the average operational Dutch wind park on the North Sea has a 700 MW capacity. Future wind parks that should be operational by 2030 are planned to have a 2000 to 6000 MW capacity (RVO, 2022b).

2.1.1. Turbine (Element)

Offshore wind turbines are the key component of offshore wind parks, designed to harness the power of the wind and convert it into electrical energy. These turbines are typically larger and more complex than their onshore counterparts, due to the harsher environmental conditions they must withstand. The turbine components include the rotor blades, rotor hub, nacelle, and tower. The rotor blades are designed to be aerodynamically efficient and are typically made of fibreglass or other composite materials. The nacelle houses the generator and other electrical components. The tower provides support and elevation to the entire structure (Letcher, 2017).

Offshore wind turbines can generate large amounts of electricity, with some of the largest turbines having a capacity of up to 15 MW (Vestas, 2023). The amount of power generated by an offshore wind turbine depends on several factors, including the wind speed, the size of the rotor, and the efficiency of the turbine. Offshore wind turbines require regular maintenance and repair to ensure they continue to operate safely and efficiently. This can be challenging in offshore environments, as turbines may be located in remote locations that are difficult to access (Letcher, 2017).

2.1.2. Foundation & Cables (Element)

Foundations are a critical component of offshore wind parks, as they provide a stable base for the turbines to stand on in the often harsh and unpredictable conditions of the open sea. There are several types of foundations used in offshore wind parks, including mono-piles, jackets, tripods, and floating platforms (Wu et al., 2019).

Mono-piles are the most commonly used foundation type for offshore wind turbines. They consist of a single steel pile driven into the seabed and attached to the turbine tower. Mono-piles are typically used in water depths up to around 30 meters (Wu et al., 2019).

Jackets, on the other hand, are typically used in deeper waters and are more complex than mono-piles. They consist of a lattice structure of steel pipes that are anchored to the seabed and provide a stable base for the turbine tower. Jackets can be designed to withstand greater loads than mono-piles and are therefore suitable for use in deeper waters (Wu et al., 2019).

Tripods are similar to jackets in that they consist of a lattice structure of steel pipes, but they have three legs instead of four. They are typically used in water depths of up to around 25 meters (Wu et al., 2019).

Floating platforms are a newer technology that is still being developed. They consist of a large platform that is anchored to the seabed using mooring lines. Because they are not fixed to the seabed like other foundation types, they can be used in water depths that are too deep for other types of foundations (Wu et al., 2019).

Overall, the choice of foundation type for an offshore wind park will depend on a variety of factors, including water depth, soil conditions, wind and wave conditions, and the size of the turbines. Each foundation type has its own advantages and disadvantages, and the most appropriate choice will depend on the specific circumstances of each project (Wu et al., 2019).

As the Dutch sea waters are part of the North Sea continental shelf, the depths are relatively shallow and uniform. This can be seen in Figure 2.2, which shows there are barely any sharp depth gradients. This makes it a suitable location for bottom-fixed structures, even further offshore. The same distance offshore in, for example, Ireland and Denmark, would require floating wind structures (Lavidas & Polinder, 2019).

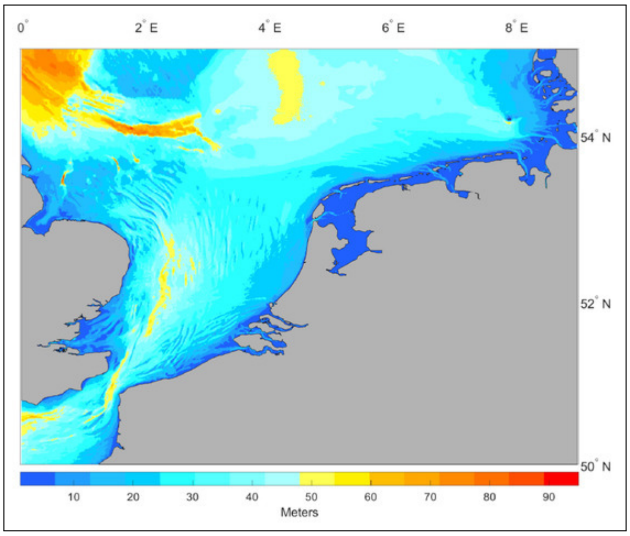

Figure 2.2: Bathymetry of North Sea continental shelf, depth in meters (Lavidas & Polinder, 2019)

A crucial aspect of the offshore wind foundation is scour protection. It prevents soil erosion around the foundation caused by water currents (Fazeres-Ferradosa et al., 2021). Measures to prevent scour are necessary to avoid issues with the structural integrity of offshore wind turbines and to safeguard the inter-array cables (Matutano et al., 2013).

An inter-array cable is a cable that is used to connect the individual wind turbines within an offshore wind farm to one another and to the AC substation. The cables are typically buried in the seabed to protect them from damage and to reduce the visual impact of the wind farm (RVO, 2022a). Generally, the efficiency of inter-array cables can range from around 97% to 99% (Breunis, 2021). Figure 2.3 gives an overview of how electricity is further transported from the offshore turbines to the electricity system onshore. This will be explained in detail in the following paragraphs.

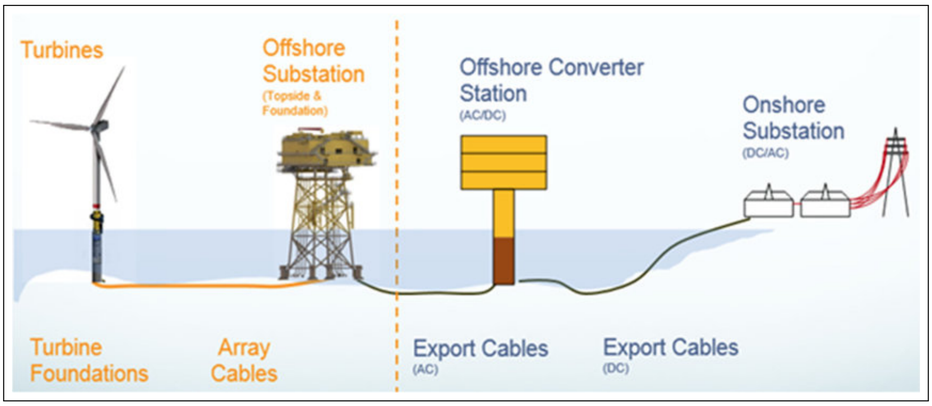

Figure 2.3: Overview of electricity transport from the turbine to (AC) offshore substation to (DC) offshore converter station to (DCAC) onshore converter (Warnock et al., 2019)

2.2. AC Substation & Transport (Sub-system)

2.2.1. AC Substation (Element)

An AC substation is a facility that is used to collect the alternating current (AC) electricity generated by the wind turbines and to step down the voltage to a level that is suitable for transmission and distribution to the point of use. Its main function is to convert the medium voltage electricity generated by the wind turbines to a higher voltage, which is done using a large transformer (RVO, 2022a).

2.2.2. AC Collection Cable (Element)

An AC collection cable is a cable used to collect the alternating current (AC) electricity converted by the AC substation and transmit it to the next substation or converter. These cables are designed to transmit large amounts of electricity and withstand the harsh marine environment. They can be made of copper or aluminium, and are usually insulated with a material that can withstand salt water (RVO, 2022a). Generally, the efficiency of AC collection cables is between 95% and 99% (Breunis, 2021).

2.3. Converter & Transport (Sub-system)

2.3.1. HVDC Converter Substation (Element)

A High-Voltage Direct Current (HVDC) substation is a facility that is used to convert alternating current (AC) electricity to high-voltage (HV) direct current (DC) electricity. Usually, an HVDC substation is used when the electricity needs to be transmitted over long distances, as DC electricity is more efficient for this (RVO, 2022a). Furthermore, DC electricity has a constant voltage characteristic, which makes it ideal for electrolysis units as they require a constant voltage and current for optimal performance. In contrast, AC electricity has a constantly changing voltage, which can make it difficult to control the voltage and current required for electrolysis (S. Rodrigo et al., 2021).

2.3.2. HVDC Cable (Element)

A High-Voltage Direct Current (HVDC) cable is a type of cable that is used to transmit electricity from offshore wind turbines to the power grid or electrolysis system. The use of these cables allows for more efficient long-distance power transmission (S. Rodrigo et al., 2021; RVO, 2022a). The average efficiency of HVDC cables is typically around 95-98% (Eeckhout et al., 2009). It is important to note that losses in the cable increase with the distance over which the electricity is transmitted, as is shown in Figure 2.4 (Eeckhout et al., 2009).

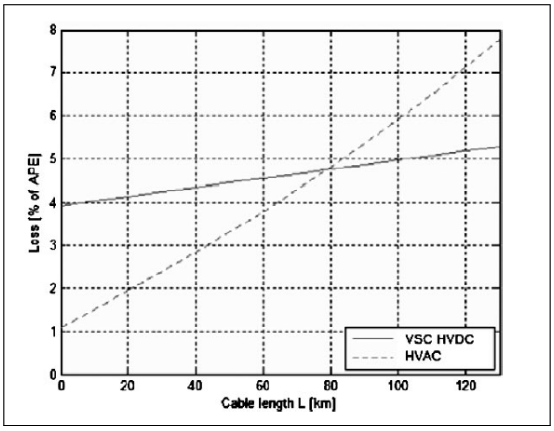

Figure 2.4: Loss percentage $l_{\%}$ for VSC HVDC and HVAC cables as a function of cable length for a 300 MW wind farm Eeckhout et al., 2009

2.4. Electrolysis, Electricity & Transport (Sub-system)

Depending on the considered supply chain investments must be made in an electrolysis system, a DCAC converter (electricity) or both. This includes the infrastructure to transport the energy into the grid.

2.4.1. Electrolysis System (Element)

An electrolysis system, also known as an electrolyser, is a device that uses electricity to split water molecules into hydrogen and oxygen. It is used to convert the electricity generated by the wind turbines into hydrogen gas, which can be stored and transported for use in various applications, such as fuel for transportation or power generation. An electrolysis system typically consists of several main components (RVO, 2022a).

Electrolyser

This is the core component of the system where the water splitting occurs. It contains electrodes, typically made of a conductive metal such as nickel, which are submerged in a water-based solution, typically in an alkaline solution. The electrodes act as the anode and cathode, and the electrical current passing through the cell causes the water molecules to split into hydrogen and oxygen (Zoulias et al., 2004). Generally, an electrolyser requires around 50 kWh of electricity for 1 kg hydrogen, which is equal to an efficiency of 78% (Burton et al., 2021).

Desalination Unit

This is a device that removes salt and other minerals from seawater or brackish water, making it suitable for use in electrolysis. The presence of salts and minerals in water can interfere with the electrolysis process and reduce its efficiency. A desalination unit removes these impurities, producing high-quality water that is ideal for use in electrolysis (Belessiotis et al., 2016).

Compressor Unit

This is a device that compresses gas, increasing its pressure and reducing its volume. In an electrolysis system, the compressor unit is used to compress hydrogen gas produced during the electrolysis process, which can then be stored for later use or transported to other locations. Compressing hydrogen gas is important for several reasons. First, it increases the energy density of the gas, making it easier and more cost-effective to store and transport. Second, it ensures that the gas can be safely transported without leakage, which can pose safety risks (Siemens Energy, 2023).

Storage Unit

This is a device used to store hydrogen gas produced during the electrolysis process. Hydrogen gas has a low energy density, which means it takes up a lot of space. Therefore, it is important to store hydrogen gas in a safe and efficient manner. There are several types of hydrogen storage units, including compressed gas storage, liquid hydrogen storage, and solid-state hydrogen storage. Compressed gas storage involves storing hydrogen gas in high-pressure tanks, while liquid hydrogen storage involves storing hydrogen as a liquid at extremely low temperatures. Solid-state hydrogen storage uses materials such as metal hydrides to store hydrogen in a solid form (Makridis, 2017).

Compressor After Storage

A compressor after storage is used to further compress and store the hydrogen gas after it has already been produced and kept in a tank for storage. For instance, the hydrogen gas produced in an offshore electrolyser is typically kept in a tank under high pressure. After being stored, the compressor is then used to further raise the pressure of the hydrogen to the level necessary for its intended use, such as injection into a gas pipeline. However, as the hydrogen is usually already stored under high enough pressure, a compressor after storage is often not needed (Makridis, 2016).

2.4.2. DCAC Converter (Element)

A Direct Current to Alternating Current (DCAC) converter is a device that converts direct current (DC) electricity, such as that produced by a wind turbine, into alternating current (AC) electricity, which is the form of electricity that is used in most power grids (RVO, 2022a). Generally, the efficiency of a DCAC converter can range from 85% to 95% (Breunis, 2021).

2.4.3. Facility Location (Element)

In the case of an offshore electrolysis system, a facility location or ’hub’ is required. It should be large enough to host the HVDC substation and the electrolysis system. This could be in the form of an offshore platform or an artificial sand island. It is believed that a sand island is the most financially reasonable material option for such a hub in shallow waters (NSWPH, 2019). Both hub types must be designed to withstand the harsh marine environment, including high winds, waves, and salt corrosion. The platform would be built like any other offshore platform, while the artificial island would be built through dredging and land reclamation. When choosing an artificial island, other components are required as well such as: shoreline protection, a breakwater, and a harbour.

2.5. Import into Energy Grid (Sub-system)

Depending on the chosen supply chain, the generated energy must be either transported through hydrogen pipelines or electricity cables.

2.5.1. Hydrogen Pipeline (Element)

This is a system of pipelines used to transport hydrogen gas from the point of production to the point of use. From the storage unit, the gas can be transported to other locations via a hydrogen pipeline. Hydrogen pipelines are similar to natural gas pipelines in many ways, but they require special materials and safety measures due to the unique properties of hydrogen gas. For example, hydrogen gas is highly flammable and can embrittle certain metals, so pipelines must be made of materials that can withstand the high pressures and corrosive effects of the gas. Additionally, safety measures such as leak detection systems and emergency shutdown valves are necessary to prevent accidents and ensure the safe transportation of hydrogen gas (US Dep. of Energy, 2023). Generally, the efficiency of a hydrogen pipeline can range from 85% to 98% (Breunis, 2021).

Ongoing research and discussion surround the ability of current gas infrastructure and end-use equipment to handle hydrogen-natural gas mixtures in a safe and reliable manner. The European Gas industry’s technical association recently shared their perspectives on the current and near-future capacity of different gas network components to accept hydrogen-natural gas blends. Most gas network components and end-uses can tolerate natural gas mixed with 5-10% hydrogen (depending on the end-use) without requiring any adjustments. However, with modifications and equipment returning, it may be possible to increase the hydrogen concentration to 15-20% (Kanellopoulos et al., 2022).

2.5.2. Electricity Cable (Element)

After the DCAC converter has converted the direct current (DC) electricity produced by the power source into alternating current (AC) electricity, the electricity is then transmitted through an AC electricity cable into the energy grid. The electricity cable must be designed to handle the specific voltage and current requirements of the system, and it must be installed in a safe and efficient manner to ensure reliable operation. The cable is typically made of copper or aluminium and is surrounded by insulation to prevent electrical leakage or short circuits. Once the electricity enters the grid, it can be distributed to homes, businesses, and other end-users. The successful transmission of electricity from the DCAC converter to the grid is crucial for the effective use of renewable energy sources in the energy system (Crabtree et al., 2011). Generally, the efficiency of an AC electricity cable ranges from 90% to 98% (Breunis, 2021).

Based on the definitions and descriptions of the supply chains' elements considered in this research the next step towards an industry-wide adopted comparison method can be taken. For the following chapter, stakeholders were interviewed to learn more about their objectives in the industry and what their desires are for such a method. Throughout these interviews, the supply chains considered in this chapter were discussed using the defined terminology to enhance standardisation.

3
Stakeholder Analysis

The goal of this research is to determine the best way to construct a comparison model that can be used to facilitate an open and constructive discussion in the Dutch offshore wind and hydrogen market. In order to achieve this, it is necessary to analyse the perspectives and needs of various stakeholders involved in this market. Thus, a stakeholder analysis was conducted, which serves as the basis for this chapter.

Then the methodology used for conducting the stakeholder interviews is discussed, including the selection of interviewees, the interview questions, and the data collection and analysis process. Finally, the last part of this chapter presents the results of the stakeholder analysis, highlighting the key requirements and concerns expressed by the interviewees with respect to the development of a standard model. These results provide valuable insights for the subsequent chapters of this research, which aim to identify and develop a suitable model for the offshore wind and hydrogen market.

3.1. Objectives

The objectives of this stakeholder analysis are to answer the following research questions:

1. *What critical aspects do stakeholders involved in the energy transition believe a comparison model could help to better understand, and how can the development of such a model facilitate discussions among these stakeholders towards identifying the most feasible solutions?*
    - Method: stakeholder interviews.
2. *How can the model be developed in a way that incentivises stakeholders to both use and contribute to the model? What are the key factors that influence stakeholder willingness to contribute, and what measures can be taken to address potential barriers to contribution?*
    - Method: desk research and stakeholder interviews.

The stakeholder interviews will be conducted to learn more about their willingness to participate in the development of the model, and their reasons to or to not use the model. Based on the defined stakeholder categories and Van Oord's industry expertise, a number of important stakeholders per category was identified, which can be found in section A.1 and section 3.2. Through the analysis of the desk research and stakeholder interviews recommendations can be made about stakeholder engagement in the development of a comparison model.

3.2. Stakeholders

As this research is done in cooperation with Van Oord, their expertise is used to get a clear overview of the different stakeholder categories. According to them, the Dutch offshore wind to hydrogen market can be split up into ten different categories. These categories are based on future concepts, which would allow the generation of green hydrogen through offshore wind energy. Per category, an example stakeholder will be given.

1. *Energy infrastructure.* These are the stakeholders responsible for the gas pipelines and electricity cables. An example would be Gasunie or Tennet.
2. *Energy supplier.* These are the stakeholders selling the generated energy. An example would be Shell or Eneco.
3. *Offshore dredging company.* These are the stakeholders involved in the construction of offshore wind farms and/or energy islands. An example would be Van Oord.
4. *Offshore project developer.* These stakeholders are responsible for the construction and operation of offshore wind farms. An example would be Iberdrola or Vattenfall.
5. *Governmental organisation.* These are the stakeholders responsible for the allocation of subsidies and grants. Furthermore, they decide on offshore locations for future wind/hydrogen projects. An example of this would be the Dutch Ministry of Economic Affairs (EZ).
6. *Research institute.* These stakeholders conduct independent research, intended to contribute to the innovations required to accelerate the development of hydrogen. An example of this would be TNO.
7. *Electrolyser manufacturer.* These stakeholders are responsible for the development and manufacturing of electrolysers, required to produce hydrogen using wind energy. An example of this would be Siemens Energy.
8. *Wind turbine manufacturer.* These stakeholders are responsible for the development and manufacturing of wind turbines, required to generate wind energy. An example of this would be Siemens Energy.
9. *Engineering consultant.* These stakeholders are independent consultancy firms which assist the project developers to come to a feasible project plan. An example of this would be Royal Haskoning DHV or Guidehouse.
10. *Port.* The ports will play a big role in the import and export of electricity and hydrogen. The most relevant stakeholder in this category is the Port of Rotterdam.

For an overview of the 38 considered stakeholders in this research, please refer to section A.1.

3.3. Interview Methodology

The goal of this research is to develop a model that provides relevant insights for collaboration and strategic decision-making in the pre-feasibility stage. Therefore, it is valuable to understand the stakeholders' objectives, incentives, and views. For this, two options were considered. The first option was to conduct private interviews with every stakeholder. This is a time-consuming process for the 38 identified stakeholders. Therefore, a selection was made of the most important stakeholder per category resulting in 10 stakeholders. This would still require a fair amount of time. The second option is a workshop. In this form, multiple stakeholders would be brought together to have a group discussion about their objectives. Even though this option would be much more time-efficient, this might not be the best choice. The offshore hydrogen market is a competitive field, and confidentiality issues could arise causing stakeholders not to be 100% open about their incentives. Therefore, it was decided to conduct private interviews with 10 stakeholders.

In advance of each interview, an interview guideline was shared with the interviewee, introducing the model research, and a range of questions, which could be discussed. The questionnaire form is a 'semi-structured interview' (SSI). The SSI is made to get people's subjective views on a specific subject. When there is enough objective knowledge about a topic but insufficient subjective knowledge, this method may be utilised (McIntosh & Morse, 2015). It makes use of a very extensive interview guide. During the interview, interviewees are free to bring in other topics that they deemed important. From each interview, a transcript is made. These are anonymised and confidential.
For the interview protocol and questionnaire, please refer to subsection A.2.1 and subsection A.2.2.

This will be a qualitative study. As the interview only allows for open answers, it was difficult to quantify the results. Analytically, the SSI is characterised by comparing participants' responses by item. Because all participants are asked the same questions in the same order, data collected are comparable, and could be numerically transformed and quantified (McIntosh & Morse, 2015).
This would be done through a thematic framework analysis. This method is used for qualitative analysis and involves using an organised structure of themes to understand patterns within and across different cases of a phenomenon of interest. The overall goal is to identify, describe and interpret key patterns within and across the different cases and themes being studied (Goldsmith, 2021).

However, it is important to note that a reasonable amount of interviews is required for such an analysis, while only 10 interviews were planned for this research. It was therefore unclear whether this method could be used to analyse the interviews conducted for this research.
In order to ensure the validity and reliability of the results obtained from the stakeholder interviews, a different method was employed. Following each interview, the transcripts were carefully analysed, and key takeaways were documented. To enhance the accuracy of the analysis, the documented conclusions were shared with the respective interviewees to validate the accuracy of the researcher's findings. This approach served as a crucial quality control step to ensure the truth value of the analysis and to mitigate the risk of any misinterpretation or bias. As a result, the methodology applied in this research is highly replicable, and the outcomes generated are more robust, scientifically sound, and trustworthy.

For the summarised interview answers, please refer to section A.3.

3.4. Preliminary Interviews

The aim of the stakeholder interviews conducted for this study was to gather insights and perspectives on how to set up an acceptable comparison model for the industry. However, upon reflection and analysis of the collected data, it was determined that the initial set of questions used during the interviews failed to obtain the desired information and did not result in the expected level of detail.

In retrospect, the questions could have been more clearly defined and tightly focused, and follow-up questions could have been planned to get deeper and more specific responses. Additionally, the desired outcomes and results of the interviews could have been better defined and aligned with the research objectives prior to the initiation of the interview process. As research mentions (Carey et al., 1996), a comprehensive study design is a crucial requirement for successful qualitative analysis. Prior to data collection, it is advisable to develop a systematic plan for data management and analysis to help one avoid many of the challenges that face qualitative data analysis.

This highlights the importance of thorough planning and preparation in the design and execution of qualitative research methods such as stakeholder interviews and the need for continuous reflection and adaptation throughout the research process.

To address the limitations of the initial stakeholder interview process, additional follow-up questions were developed and sent to the interviewees via email. These questions were designed to obtain more detailed and specific responses, and aimed to provide a deeper understanding of the stakeholders' views on a comparison model. The goal was to extract valuable information that was not captured in the initial interviews. This would enhance the data collected and improve the quality and usefulness of the results.

The following list represents the additional follow-up questions sent to the interviewees via email:

- *If you would use the comparison model, with what objective would that be?*
- *If you do not plan to use the model, why is that?*
- If the stakeholder was not willing to share input data for the model: *What would make you willing to contribute to the model and trust us?*
- If the stakeholder was not willing to share input data for the model: *Would you be willing to verify price ranges based on open sources?*

- If the stakeholder was not willing to share input data for the model: *What do you see as a threat to sharing data?*

The results obtained from the follow-up questions were analysed and compared to the data collected in the initial stakeholder interviews. This allowed for a more complete and nuanced understanding of the issue under investigation and provided a stronger basis for drawing conclusions and making recommendations.

As not all interviews were conducted yet, the interview questionnaire was redefined for the remaining interviews by adding the above-described follow-up questions.

3.5. Results

In the study of the offshore wind and hydrogen market, a variety of stakeholders were interviewed to gain insight into their perspectives and interests. Given the diversity of stakeholder categories represented, it was anticipated from the outset that the responses would be diverse and reflective of each group's unique incentives.

Therefore, a two-step analysis was conducted to fully understand the industry's views on a comparison model and its requirements for adoption. Firstly, a general analysis of the results was performed to determine the collective opinion of the industry on the comparison model. This analysis provided an overview of the common themes and concerns that emerged from the stakeholder interviews.

Following the general analysis, a comparative analysis was performed to examine the differences in opinions and incentives between different stakeholder categories. This approach allowed for a more nuanced understanding of the diverse perspectives and motivations within the industry and provided a comprehensive overview of the different opinions and incentives in the offshore wind and hydrogen market.

In conclusion, the two-step analysis provided a thorough understanding of the industry's views on a comparison model and its requirements for adoption. The results of the analysis will be valuable in the development of a model that is inclusive of the needs and interests of all stakeholders, and in turn, will contribute to the growth and sustainability of the offshore wind and hydrogen market.

As mentioned in section 3.3, the documented takeaways from interviews were shared with the respective interviewee to validate the accuracy of the researcher's findings. In total, 13 interviews were conducted out of which 13 statements were formulated. 10 stakeholder categories were defined, but for some categories, multiple parties were interviewed. 100% of these formulated statements were shared with the interviewees and 100% was validated. Using these takeaways, the following results and conclusions were drawn.

3.5.1. General Analysis

The stakeholder interviews conducted as part of this study aimed to gather insights and perspectives on the use and potential benefits of a comparison model for offshore wind to hydrogen concepts. The results of these interviews provided valuable insights into the reasons for using the model, as well as concerns and suggestions for improving its reliability and usefulness.

One of the key reasons for using the model is its potential to serve as a benchmark for comparison with alternative (in-house) models. Some stakeholders, such as consultancy firms, develop their own models so they would be less interested in using the model developed through this research. However, if this model is validated or adopted by the industry, it could be interesting for these consultancy firms to use the model to compare their assumptions. The model could also be used to evaluate the cost levels of hydrogen production and inform policy decisions. Additionally, the model could provide a standard calculation method for the industry to compare different concepts and demonstrate the cost advantages of using a stakeholder's asset (e.g. turbine). For example, a port could show the added value of using them for the import or export of hydrogen if the model would show a lower LCOH than for a different port. Furthermore, the model could have educational value in providing a better understanding of both the financial and technical structure of a green hydrogen supply chain.

However, there are also concerns and suggestions for improving the reliability and usefulness of the model. The market is still in the R&D phase, making it too risky for many stakeholders to share data. A solution could be to hide input data and assumptions for other stakeholders using the model. However, engineering consultants on the other hand may be less interested if calculations and assumptions are not transparent. Additionally, the R&D is not advanced enough to make clear predictions on prices and other data in the future. The rapid pace of developments in the electrolysis space could also result in inaccurate predictions. Manufacturers may have difficulty providing accurate predictions at an unprecedented scale. To enhance the reliability of the model, it should be tested by independent experts.

Additionally, it is important to note that governmental organisations consider both financial and environmental impacts when making decisions. For them, the model should be independent and transparent, with accurate data validated by stakeholders. It is unclear whether all these aspects can be integrated into one model. However, a way to increase transparency, suggested by a stakeholder, was to be clear about the assumptions behind the model. Examples of this are the type of costs considered, the financial methodology, and project characteristics, such as duration. Transparency can also be provided by defining and sharing the sensitivity of the used parameters, which could be done through a Monte Carlo simulation. Finally, some stakeholders suggested to designate an owner to maintain and update the model on behalf of the industry.

During the interviews, some threats were raised regarding the use of a model. One such concern was that the model may reveal that a manufacturer's product results in a less feasible supply chain, which could be detrimental to their business. This concern highlights the potential risk involved in using the model for bench-marking and decision-making purposes, as stakeholders may be hesitant to share sensitive information that could negatively impact their business.

Another concern was the difficulty in obtaining input data from manufacturers and suppliers in the competitive and rapidly developing offshore wind and hydrogen market. Stakeholders expressed reluctance to share their prices and assumptions, as they perceive such sharing as too risky in the current market environment. This concern further underscores the challenges associated with developing and implementing a reliable and comprehensive model for the industry.

In response to the latter concern, some stakeholders suggested that price ranges or bandwidths could be verified. This verification could be based on public sources or interviews with stakeholders who are willing to share data ranges. This approach could address the concern about sensitive information sharing, while still providing valuable insights into pricing in the industry.

Moreover, it may be valuable for future research to focus more on interviewing manufacturers and suppliers, as they possess the most sensitive data that could be critical for the development of a reliable cost model. While obtaining input data from these stakeholders may be challenging, their insights could be invaluable in creating a comprehensive and accurate model that reflects the complex dynamics of the offshore wind and hydrogen market.

In addition, the verification process could also benefit manufacturers by providing them with a better understanding of pricing trends in the industry. By having access to verified price ranges and bandwidths, manufacturers could more effectively benchmark their products and make strategic decisions to improve their competitiveness.

Overall, the suggestion to verify price ranges/bandwidths offers a potential solution to the challenges associated with obtaining input data from manufacturers and suppliers. Further research could explore the feasibility and effectiveness of this approach, and how it could be integrated into the development and implementation of a reliable and comprehensive model for the industry.

In conclusion, the results of the stakeholder interviews provide valuable insights into the potential benefits and limitations of model. The concerns and threats should be carefully considered and addressed in the development and implementation of any such model, in order to ensure that it is effective, reliable, and acceptable to all stakeholders. These findings can inform the development and implementation of future models, as well as inform decision-making processes within the industry.

3.5.2. Comparative Analysis

The offshore wind and hydrogen market is influenced by a variety of stakeholders, each with its own unique incentives and interests. In order to achieve a model that is accepted and supported by the industry, it is crucial to consider the perspectives and needs of each stakeholder category.

To that end, it is essential to perform a thorough analysis of the results per category in order to accurately capture the complex and nuanced interactions between these stakeholders. This analysis can help identify areas of alignment and areas of conflict between different groups, allowing for the development of a model that addresses the concerns of all stakeholders and achieves a more comprehensive and sustainable outcome.

Given the importance of stakeholder engagement in the development of the model, it is important to undertake a detailed and systematic examination of the interests and incentives of each stakeholder category. Only through a comprehensive and inclusive process can we hope to achieve a model that is truly reflective of the needs and desires of all involved parties.

For the energy infrastructure stakeholder, the main objective is to compare the financial feasibility of different offshore wind to hydrogen concepts and the influence of their product on the final costs. Although they are willing to verify price ranges, they are not willing to share exact data and calculations.

The energy supplier and offshore project developer would like to use the model to compare projects on a like-for-like basis and see how other parties are looking at hydrogen value chains. However, the model would be less relevant for internal decision-making as they use their own models. They are comfortable in validating the model in terms of how it is set up but are less comfortable in directly sharing specific cost data. They would only be willing to do that in an anonymised industry consortium. As they do not know the exact values yet, they are afraid of negative reputational implications regarding their assumptions. They would be willing to verify number assumptions and help with the setup of the model.

The offshore dredging company's objective is to compare the financial feasibility of different offshore wind to hydrogen concepts and to convince the government what the most feasible one is. Further, they believe an industry-wide adopted model is necessary to accelerate the energy transition. They are willing to share data, but only in a confidential way so that it is protected from competitors.

Governmental organisations usually outsource their calculation and modelling work to consultancy firms. If they would use the model, it must be transparent and set up independently (not by one company). Furthermore, a comparison model could be interesting for them if it also integrates geospatial data, which could help them in their analysis of the environmental impact of offshore projects. As a governmental organisation, the only information they can provide to contribute to the model is tender data. However, the submitted business cases are confidential and they are not allowed to disclose that.
Governmental organisations define the need for a baseline to see how certain choices affect the LCOH. The model would be used to understand which innovations trigger what cost impact. This can help in bringing focus to the innovation-related plans.

The research institute develops its own models, so it might be less interested in using the model. However, if they were to use the model, it would be to get a better understanding of the influence of price developments of different parts of the supply chain on the levelised cost of hydrogen. The research institute is willing to verify price ranges and is in favour of sharing data to accelerate the energy transition.

The electrolyser manufacturer and wind turbine manufacturer's main objective is to compare the financial feasibility of different offshore wind to hydrogen concepts and the effect of their product on that feasibility. As the market is so competitive, exact data is too confidential to share. However, the manufacturers are willing to verify price ranges based on public data.

For engineering consultants, the model could serve as a benchmark for their own in-house developed models. However, the model must be open-source so that they can see the assumptions and calculations. If the model were open-source, the consultancy firms would be willing to help verify the model.

Ports find the model useful to show clients that working with them could result in lower hydrogen costs. Furthermore, this stakeholder sees the educational added value of a comparison model. They could get a better understanding of the financial structure of a supply chain and the effect of its elements on the price of hydrogen. It is valuable for them to be able to join the discussion with other parties. They do not have any relevant data to help set up the model but are willing to verify data ranges.

3.5.3. Conclusion

It became clear that each group has distinct objectives, perspectives, and concerns. This has resulted in a lack of understanding between stakeholders. The market for offshore wind and hydrogen is both competitive and fragmented, which hinders cooperation and progress in the energy transition. Solving that problem asks for a thorough and inclusive approach to creating a model that caters to the wants and needs of all stakeholders. The goal of this model is to bridge the different interests of the stakeholders. Without such a model, it might become difficult for stakeholders to understand each other's different perspectives. A comparison model could help stakeholders gain insight into their and others' roles in the larger energy system.

The key factors that influence stakeholder willingness to contribute are confidentiality, competition, and reputation. Manufacturers and suppliers are reluctant to share their prices and assumptions due to perceived competitive risks in the rapidly evolving market. Others would only be willing to share specific cost data in an anonymised industry consortium. As they do not know the exact values yet, they are afraid of negative reputational implications regarding their assumptions. Most stakeholders, however, are comfortable in verifying the model's assumptions and helping with its setup, but they are less willing to share specific cost data due to confidentiality concerns. They would also be willing to verify price ranges instead of exact numbers.

To address potential barriers to contribution, measures such as confidentiality agreements could be taken. However, this does not enhance an open discussion, for which transparency is needed. Another often suggested measure would be the verification of price ranges by stakeholders instead of sharing exact values. This is the opposite view, shared by other stakeholders. A way to increase transparency, suggested by a stakeholder, was to be clear about the assumptions behind the model. Examples of these are the type of costs considered, the financial methodology, and project characteristics, such as duration and supply chain type. A standard notation or coding system could be presented together with the results of the comparison model. This would allow users to quickly understand the assumptions behind the displayed numbers. A first suggestion for such a system is made in section 4.7. Finally, transparency can also be provided by defining and sharing the sensitivity of the used parameters, which could be done through a Monte Carlo simulation.

For now, it would be most useful to focus on the industry-wide adoption of the model, instead of only on the industry-wide contribution to the model. For this, it is important that the assumed prices and calculation methods are transparent, and are based on public research. With these assumed prices, certain base-case results can be obtained for various supply chains. This starting set of values should be clear and the same for everyone. Stakeholders should be able to change the prices in the model for their part of the supply chain, which allows a user to see what kind of cost reduction they can achieve compared to the starting point ('the standard'). The more stakeholders use the model for this purpose and thus trust it, the more the model will be accepted and thus validated. This was suggested by a governmental organisation with experience in setting up a cost model for the offshore wind industry.

4 Comparison Model Method

Based on the stakeholder analysis and literature review, a comparison model can now be set up. This chapter first discusses the definitions and formulas of the financial methodology most common in the industry. It then covers the common cost breakdown used in the offshore industry, facilitated by Van Oord and MTBS. Using those formulas and breakdowns in the model, and being transparent about it, increases industry-wide adoption. The same holds for being clear about the assumptions made, which are discussed in the next section. Then, the setup of the model in Excel is explained, and the limitations of this method. With these limitations known, an improved method will be developed and implemented. Finally, the improved model will be validated using existing research and a real-life project.

In previous research, it was difficult to determine what methodology was used to perform the financial calculations. The goal of this research is to strive for industry-wide adoption of the comparison model. Therefore, the functionalities, methods, and assumptions behind the model are first clearly defined in this chapter. At the end of the chapter, a standard notation system is introduced. Through literature research, it came forward that it can be difficult to know what financial and technical assumptions are considered by the authors. This in combination with stakeholders' desire for more transparency has led to the development of the standard notation system. It allows readers to quickly understand what supply chains are considered and with which financial assumptions the calculations were done.

4.1. Definitions and Formulas

Based on the literature review in section 1.3, it was concluded that most research assessed the financial feasibility of offshore energy supply chain elements through techno-economic analyses using LCOH and Net Present Value (NPV) measures. A feasibility cost model analyses supply chains' Capex and Opex as the foundation for determining their economic attractiveness. Other financial tools besides LCOH and NPV used to determine the financial feasibility are the LCOE, internal rate of return (IRR) and payback period. An overview of these analyses is presented through the financial statements: Profit & Loss, and Balance Sheet. These definitions are explained in this chapter.

Net Present Value (NPV)

The NPV is the actual value of capital. As future cash flows are analysed, the actual value of these changes over time due to inflation ('escalation'). NPV is used as a financial indicator to evaluate the feasibility of a project. The difference between the actual ('present') value of the profits and the investments is the net present value of the project (Kaldellis, 2022a).

The NPV is calculated in the following way (McDonagh et al., 2020).

$$NPV = \sum_{i=1}^{n} \frac{\textit{Net cash flows in year i}}{\textit{1 + Discount rate}^{i}} \tag{4.1}$$

Calculating the NPV of future cash flows is called the Discounted Cash Flow (DCF) method.

The final year cumulative NPV is the sum of all discounted cash flows that have been generated by a project up until the final year. Part of all cash flows is the revenues. A positive final-year cumulative NPV means that the present value of the cash inflows generated by the project exceeds the present value of the cash outflows (total costs) over the project's lifetime. This indicates that the project has created value for its stakeholders (Kaldellis, 2022a).

Discount Rate

The discount rate is a financial tool that is used to compute the value of future cash flows in present terms. It is used in the NPV formula. It represents an interest rate that helps reduce or discount the value of expected future cash flows to their present value. The discount rate reflects the return rate that compensates investors for the time value of money and investment risk (DePamphilis, 2022).
In most financial models, the discount rate is assumed to be constant over the project's duration. This implies that the risks associated with the project and the financing structure remain constant over its lifetime, but in reality, this is not the case (DePamphilis, 2022).

The WACC (Weighted Average Cost of Capital) represents the average cost of capital. In its calculation, the cost of equity and debt is weighted according to the company's capital structure. This structure is determined by the proportion of debt and equity in the company's capital mix (DePamphilis, 2022).

In financial modelling, WACC is often used as a discount rate for computing the present value of future cash flows. This is primarily due to the fact that WACC accurately represents the cost of capital for a company and also includes the risks linked to the investment. Thus, using WACC as the discount rate guarantees an appropriate adjustment of the present value of future cash flows for the cost of capital and investment risk associated with the project (DePamphilis, 2022).

IRR

The IRR measures a project's feasibility by identifying the discount rate that would render the project's net present value zero within a defined timeframe. This metric is widely used due to its simplicity and comprehensibility in assessing an investment's potential. A high IRR implies a higher return on investment, making it more attractive (Kaldellis, 2022b).

Payback period

The payback period shows how long it takes for an investment to recover its initial cost. It determines the number of years it takes for an investment to generate enough revenue to recoup its investment cost. The investment could be a wind turbine or a complete project. Once the investment has generated enough revenue to recover its initial cost, the payback period ends. A shorter payback period is more desirable because it means that the investment will recover its cost faster and generate positive cash flows in the future (Kiran, 2022).

Divestment and Depreciation

A common method to calculate the depreciation of an asset is through the straight-line method. With this method, an asset's value depreciates with the same amount every year of its useful life. That amount is calculated by dividing the asset's initial value (Capex) by its economic lifetime. For example, the total initial Capex of a turbine is €1 million, and the economic lifetime ('write-off time') of a turbine is 25 years. Then the annual depreciation value is €1 million / 25 = €40,000 (Blum, 1965).

When the project duration is shorter than the economic lifetime of an asset, there is still some value 'left' in the asset. For example, the project duration is 20 years. Then there is 5 more years of asset value left. In the case of the turbine that is 5 times €40,000, which equals €200,000. This is a proxy for the divestment value. The actual divestment value is the market value. It is the worth of an asset at the time it is sold (Blum, 1965).

Financial Statements

Financial statements are structured financial presentations with the objective to provide information about the financial situation, performance, or forecast of a project. This can be used to make economic decisions (Hasanaj & Kuqi, 2019).

Profit & Loss
The Profit and Loss statement provides a financial overview of a project's performance over a specific period, such as a month, quarter, or year. It summarises the profits generated from business operations and the losses incurred to generate revenue. Profit refers to the assets or money generated through the project's activities, while loss refers to the depreciation of assets or money utilised during the project's operation. The difference between profit and loss is the net income or net profit (Hasanaj & Kuqi, 2019).

Balance Sheet
The Balance Sheet presents a summary of a project's assets, capital, and liabilities. Liabilities are the debts that are owed to others. It represents the claims that creditors have on a project's assets. The balance sheet shows a balance between the total value of assets and the total value of capital and liabilities. This balance is expressed by the equation: Assets = Liabilities + Capital (Equity) (Hasanaj & Kuqi, 2019).

Supply Chain Efficiency and Losses

For an energy-related project, supply chain efficiency is an important metric. For an offshore wind to hydrogen project, it is calculated with the following formula, which is defined by the author. Here, a hybrid supply chain is assumed that produces both hydrogen and electricity.

$$\eta[\%] = \frac{\textit{(Total hydrogen onshore } * 141.8\,\text{MJ kg}^{-1}\textit{) + (Total electricity onshore } * 3.6\,\text{MJ kW}^{-1}\,\text{h}\textit{)}}{\textit{Total wind energy production } * 3.6\,\text{MJ kW}^{-1}\,\text{h}} \tag{4.2}$$

The supply chain efficiency directly impacts the project's costs. By optimising the supply chain, investments can be reduced to get the same desired output. Or by generating the same amount of wind energy, the project's profitability can be increased.

The latter touches upon the Jevons Paradox, which is an interesting theory regarding the energy transition. According to the Jevons Paradox, over time, improving the efficiency of energy usage leads to an increase in energy consumption instead of a decrease. In other words, if wind energy becomes more efficient and cheaper to produce, it may encourage higher consumption and utilisation of wind energy, thus offsetting any potential energy savings. It challenges the ideas behind the energy transition and strives for improvements in energy efficiency. Furthermore, this phenomenon may impact the financial analysis of energy projects as it suggests that simply improving efficiency may not necessarily lead to cost savings (Giampietro & Mayumi, 2018).

The supply chain efficiency is determined by the energy losses over the supply chain's elements. Based on the information provided in chapter 2, the following efficiencies are assumed for the transportation of energy.

Parameter	Value	Unit	Source
Inter-Array Cable Efficiency	99	%	Van Oord; Breunis, 2021; Lucas et al., 2022
AC Collection Cable Efficiency	95	%	Van Oord; Breunis, 2021
HVDC Cable Efficiency	100 - (0.00005*(x) + 4)	%	Eeckhout et al., 2009 (Fig B.1)
H2 Pipeline Efficiency	95	%	Breunis, 2021
DCAC Converter Efficiency	90	%	Breunis, 2021
Electrolysis Efficiency	50	kWh/kg	V. N. Dinh et al., 2021; Breunis, 2021

Table 4.1: Assumed values for elements' efficiencies with their sources

4.2. Cost Breakdown

To identify an acceptable and standardised cost breakdown and method, a combination of literature (section 1.3) and the expertise of MTBS and Van Oord was used. MTBS, a financial consultant in the maritime and transport sector, has a lot of experience in determining the financial feasibility of projects in this sector. Van Oord, a contractor active in the offshore industry, also has a good view of the industry's common practices through its experience with tenders and cost estimations. The structure of the cost breakdown is the same for every sub-system and element of the work breakdown (chapter 2).

4.2.1. Capex

Capex, or capital expenditure, refers to the investments by a company to acquire or improve its fixed assets, such as buildings, property, and equipment. In the construction industry, Capex typically refers to the funds used to invest in long-term projects, such as the construction of offshore platforms or the purchase of specialised equipment. The offshore construction industry often involves larger and more complex projects, which can require significant capital expenditure. These funds may be used to build infrastructure, develop new technology, or acquire the necessary equipment and materials to complete offshore construction projects. These investments are typically done to generate future benefits, such as increased revenue or cost savings (Designing Buildings, 2021).

Development and Project Management

In the offshore industry, development and project management refers to the process of planning, organising, and overseeing the various activities involved in the construction and operation of an offshore project. This can include activities such as site selection and acquisition, engineering and design, and ongoing operations and maintenance. Development and project management also involve coordinating the efforts of various teams and stakeholders, including engineers, contractors, regulators, and other parties involved in the project. The goal of development and project management is to ensure that the project is completed safely, efficiently, on time and within the budget (Offshore Technology, 2022).

Procurement

Procurement refers to the process of acquiring goods, services, and materials necessary for the construction and operation of an offshore project. This can include activities such as identifying and selecting suppliers, negotiating contracts, placing orders, and managing the flow of materials and equipment to the project site. Procurement is an important part of the offshore development and project management process, as it helps to ensure that the necessary resources are available when needed and that the project stays on track. Procurement can also involve managing the risks associated with the acquisition of materials and services, such as ensuring that suppliers are reliable and that materials meet quality standards (Pagabo, 2022).

Installation and Commissioning

Installation and commissioning refers to the process of assembling and preparing an offshore project for operation. This can include activities such as installing pipelines, platforms, and other offshore structures, as well as the equipment and systems necessary for production, and processing of offshore energy. Installation and commissioning also involves testing and verifying that all systems are functioning properly, and making any necessary adjustments or repairs. The goal of installation and commissioning is to ensure that the project is ready for operation and can safely and efficiently produce energy (Opus Kinetic, 2022).

Residual Value or Divestment value

In the offshore construction industry, residual value refers to the estimated value of an asset (such as an offshore platform) at the end of its useful life. This value is determined by estimating the amount of money that can be reasonably expected to be obtained from the sale or disposal of the asset, taking into account its age, condition, and any potential liabilities associated with it. Residual value is an important consideration in the offshore industry, as it can impact the overall economics of a project and help companies to plan for the decommissioning of offshore assets (Thakur, 2022).

4.2.2. Opex

Opex, or operating expenditure, refers to the funds used by a company to cover its ongoing expenses, such as salaries, utilities, and maintenance. In the offshore construction industry, Opex typically refers to the funds used to cover the costs of running offshore construction projects on a day-to-day basis. This may include expenses such as the cost of fuel and supplies, insurance, the salaries of workers and support staff, and the maintenance of equipment. Unlike Capex, which is used to invest in long-term assets, Opex is used to cover the ongoing costs of operating a business. In this research, the Opex is expressed as a percentage of the total Capex (DW Insights, 2022).

Yearly Variable Costs

The yearly variable costs, also known as operation and maintenance (O&M) costs, refer to the costs associated with the operation of an offshore project that can vary from year to year. These costs can include expenses such as labour, materials, and services that are needed to maintain and repair equipment and to support the ongoing generation and production of energy. Yearly variable costs can also include expenses such as taxes, and other fees that are related to the operation of the project. The amount of yearly variable costs can vary depending on factors such as the amount of energy generated, the number of platforms in operation, and the age and condition of the project's equipment and facilities (EWEA, 2022).

Insurance Costs

Insurance costs refer to the premiums paid by a company to an insurance provider to protect against financial losses resulting from various risks, such as property damage, liability claims, business interruption, and natural disasters. In offshore construction projects, insurance costs are a significant component of operating expenses (Opex) as they provide protection against unforeseen events that could disrupt the project and result in financial losses. These costs typically include marine and liability insurance and can vary depending on the project's size, complexity, and level of coverage required (O'Connor & Dalton, 2012).

Decommissioning

Decommissioning costs refer to the expenses associated with the process of safely and permanently removing an offshore platform and other associated infrastructure from service. It occurs at the end of the economic lifetime of an asset (re-investment) or at the end of a project. These costs can include things like the expenses of disconnecting the platform from any underwater pipelines, removing any remaining hazardous materials, and either dismantling the construction on-site or transporting it to a decommissioning facility for further processing. Decommissioning costs can be significant and are typically factored into the overall cost of operating an offshore construction throughout its lifespan. In this research, it is expressed as a percentage of the total Capex (PetroWiki, 2022).

4.3. Financial Assumptions

In order to ensure accurate financial calculations for a renewable energy project, certain assumptions are incorporated into the model. These assumptions take into account factors such as construction costs, project lifespan, and financing costs.

The Opex values, including yearly variable costs, decommissioning, and insurance costs, are calculated as a percentage of the total Capex. However, it is important to note that this ”total Capex” is the summation of the escalated Capex values. The Opex values calculated as a percentage from this total Capex are escalated as well.

Yearly variable costs are the operation and maintenance costs and are defined as a percentage of the Capex. These costs include labour, materials, and services that are needed to maintain and repair equipment and to support the ongoing generation and production of energy.

Furthermore, the decommissioning costs are considered part of the Opex to maintain a balanced balance sheet. This is because, unlike Capex, decommissioning does not increase asset values. Instead, it occurs at the end of the project and the economic lifespan of the asset.

It is assumed that the base year for NPV calculations is the construction year of the project. Even if a certain asset is built, for example, 10 years later, the base year for NPV calculations stays the same. This also holds for the escalation (inflation), which is applied uniformly to both Capex and Opex. Furthermore, the escalation rate is assumed to be 2% and constant over the project's lifetime (European Central Bank, 2021).
While the weighted average cost of capital (WACC) is assumed to be equal across all stakeholders and supply chain segments, it is acknowledged that in reality, WACC may vary depending on differing commercial incentives and risk profiles. The WACC was calculated using MTBS' method and was set to be 9.84%. One of the parameters defining the WACC is the 'Unlevered Beta', which measures the market risk for a company based on the industry it operates in (NYU Stern, 2023). For this model, the chosen industry was 'Green & Renewable Energy'.

If the asset's economic lifetime is shorter than the project duration, a reinvestment should be made to replace the asset and keep the project operational. The assumption in the model is that if the asset replacement is needed in year X, the last Capex investment will be made in year X-1. This way, a revenue stop or gap is prevented as the project can stay operational.

The depreciation rate of an asset is calculated by dividing 1 by the asset's economic lifetime, which starts in the first operational year of an asset. Divestment at the end of the project, if it happens, occurs in the last operational year of an asset, and the same holds for decommissioning at the end of the project. It is assumed to be ”instantaneous” at the end of the last operational year.

During reinvestment years, the Opex based on the initial summed escalated Capex is paid. From the first operational year of the replaced asset, the new Opex is paid, which is a percentage of the summed escalated reinvestment Capex.

As shown in Equation 1.2 and Equation 1.3, the LCOH and LCOE are calculated by considering the costs specifically related to the production and transport of hydrogen and electricity, respectively. When a supply chain produces both hydrogen and electricity, the right costs should be allocated. For the costs of an electrolyser, which produces hydrogen, it is rather simple. But for the offshore wind park costs, for example, the energy conversion ratio is taken into account. When 70% of the generated wind energy is used for electrolysis (hydrogen production), it is assumed that 70% of the offshore wind farm costs will be allocated to the LCOH calculation. The remaining 30% is allocated to the LCOE calculation. Table 6.1 presents an overview of how the costs are allocated per element.

Element	Cost allocation
Turbine	Proportional to conversion rate
Foundation & Cables	Proportional to conversion rate
AC Substation	Proportional to conversion rate
AC Collection Cable	Proportional to conversion rate
HVDC Converter	Proportional to conversion rate
HVDC Cable	Proportional to conversion rate
Electrolyser	Hydrogen
Desalination Unit	Hydrogen
Compressor Unit	Hydrogen
Storage Unit	Hydrogen
Compressor After Storage	Hydrogen
DCAC Converter	Electricity
Mainland	Proportional to conversion rate
Artificial Island	Proportional to conversion rate
Hydrogen Pipeline	Hydrogen

Table 4.2: Cost allocation per supply chain element for LCOH and LCOE calculation

All costs are defined as cost per unit. Units are MW (megawatt), and for cables and pipelines meters. This was also done in the studied literature. Energy project Capex is typically defined in price per MW instead of price per unit because power output is a crucial factor in the design and operation of energy projects. It determines the amount of energy that can be produced and delivered to customers. Using price per MW enables a standardised measurement of cost across projects with varying power output capacities, making it easier to compare different energy projects and technologies. In contrast, price per unit is a more general term that can have different interpretations depending on the context and may not provide enough information on the specific characteristics of an energy project. Cables and pipelines are often defined in price per meter, which is more relevant to their physical properties.

Moreover, the model assumes that the prices of assets are based on current price ranges, regardless of when the asset is built. For an overview of all assumed prices per component and the accompanying sources, kindly refer to section B.2.

Finally, it is worth mentioning that the model does not take government subsidies into account. The reason for this is that considering subsidies would be unfair when comparing renewable supply chains with non-renewable supply chains. However, if one would want to include this in the financial model, a workaround would be to include this subsidy as a positive Capex or to extract the subsidy value from a component's Capex.

Energy Prices

It is important to note that a sensitive parameter in determining the financial feasibility of a project is the energy market price. As green hydrogen is not sold yet on the market, a price must be assumed. According to S&P Global Platts, the price of green hydrogen produced in The Netherlands in 2022 would be €13.43 / kg H_2 (S&P Global Platts, n.d.). The European Commission expect €1.80 / kg H_2, while the ICCT expect €6 / kg H_2 (Ortiz-Cebolla et al., 2022; Zhou & Searle, 2022). In this research and cost model, a price of €6 / kg H_2 will be assumed. This parameter can be changed in the model.

For electricity, the market price is assumed to be €0.18 / kWh. This is based on the average purchase price of electricity for March 2023 in The Netherlands (€0.10 / kWh) plus the a feed-in-premium (FIP) tariff (Anciaux, 2019; Nieuwe Stroom, 2023). The Dutch electricity system supports energy investments by these tariffs, which are added to the market price. This means that energy producers (usually renewables) receive a premium on top of the spot-market price for the produced and delivered electricity. The premium is to compensate for the difference between the market price of fossil fuel-generated electricity and renewable energy-generated electricity. The FIP for wind is €0.05 - 0.08 / kWh depending on the type, size and wind speed. In this research, a FIP of €0.08 / kWh is assumed, resulting in a market price of €0.18 / kWh.

It should be noted that in reality, these prices fluctuate over time. Assuming that this parameter is constant over a project's lifetime is a sensitive assumption, which adds uncertainty to the results.

4.4. Model Setup

Having defined the common practice methodology for determining the feasibility of a project, the theoretical knowledge could now be implemented into an actual comparison model. As mentioned at the beginning of this chapter, the research and especially this chapter was conducted in collaboration with MTBS, using their financial expertise. Excel is their preferred software tool, so the model was first established in Excel. This allowed MTBS to monitor the model configuration and ensure the structure is correct.

To begin the process of setting up the model, an input sheet was created in Excel to gather all the required data. For the scope of this research, data gathered from open sources and previous research was used. The goal is to develop a functioning model, but not to retrieve the most accurate data. Please refer to section B.2 for the sources behind the assumed and adopted cost data. This input sheet consists of general system input numbers, such as the weighted average cost of capital (WACC), inflation rate, total wind park capacity, wind turbine capacity per unit, cable length (including HVDC, AC Collection), pipeline length for hydrogen transportation, and transport losses. But also input data regarding the costs of the elements, such as development and project management costs, procurement costs and yearly variable costs rate. These input values will be used in the model calculations to determine the capital expenditures (Capex), operating expenditures (Opex), cash flows, and the present value of these for each subsystem of the supply chain. For the total system, the net present value (NPV) is calculated. An example of an input sheet for general system numbers and one element is provided below in Figure 4.1.

Category	Sub-system	Element	Component	Description	Number	Unit
System input	Wind energy source & Transport	Offshore wind park	-	Total Windpark Capacity	X	MW
System input	Wind energy source & Transport	Offshore wind park	Turbine	Windturbine Capacity per unit	X	MW
System input	Wind energy source & Transport	Offshore wind park	Inter-array cable	Length	X	m
System input	AC Substation & Transport	AC Substation & Transport	AC Substation	Capacity per unit	X	MW
System input	AC Substation & Transport	AC Substation & Transport	DC collection cable	Length	X	m
System input	Converter & Transport	Converter	HVDC Converter	Capacity per unit	X	MW
System input	Converter & Transport	Converter	HVDC cable	Length	X	m
System input	Electrolysis, Electricity & Transport	Electrolysis	Electrolyser	Stack size capacity	X	MW
System input	Electrolysis, Electricity & Transport	Electricity	DCAC Converter	Capacity per unit	X	MW
System input	Electrolysis, Electricity & Transport	Facility location	Artificial island	Footprint	X	m2/MW
System input	Electrolysis, Electricity & Transport	Facility location	Mainland	Footprint	X	m2/MW
System input	Electrolysis, Electricity & Transport	Facility location	Artificial island	Distance from shore	X	m
System input	Electrolysis, Electricity & Transport	Transport	H2 Pipeline	Length	X	m
System input	Electrolysis, Electricity & Transport	Transport	Electricity cable	Length	X	m
System input	Wind energy source & Transport	Offshore wind park	Inter-array cable	Transport loss	X	%
System input	AC Substation & Transport	AC Substation & Transport	DC collection cable	Transformation loss	X	%
System input	Converter & Transport	Converter	HVDC Cable	Conversion loss	X	%
System input	Electrolysis, Electricity & Transport	Electrolysis	Electrolyser	Conversion MWh to tons Hydrogen	X	kWh / kg
System input	Electrolysis, Electricity & Transport	Transport	H2 Pipeline	Transport loss 2	X	%
System input	Electrolysis, Electricity & Transport	Transport	Electricity cable	Transport loss 3	X	%
System input	-	-	-	WACC	X	%
System input	-	-	-	Escalation rate	X	%
System input	-	-	-	Escalation base year	X	-
Capex	Wind energy source & Transport	Offshore wind park	Foundation & cable	Foundation & cable costs (Development and Project Management)	X	EUR / MW
Capex	Wind energy source & Transport	Offshore wind park	Foundation & cable	Foundation & cable costs (Procurement)	X	EUR / MW
Capex	Wind energy source & Transport	Offshore wind park	Foundation & cable	Foundation & cable costs (Installation and Commissioning)	X	EUR / MW
Capex	Wind energy source & Transport	Offshore wind park	Foundation & cable	Number of units	X	MW
Capex	Wind energy source & Transport	Offshore wind park	Foundation & cable	Construction duration	X	years
Capex	Wind energy source & Transport	Offshore wind park	Foundation & cable	Share of Investments in Year 1	X	% of Capex total
Capex	Wind energy source & Transport	Offshore wind park	Foundation & cable	Share of Investments in Year 2	X	% of Capex total
Capex	Wind energy source & Transport	Offshore wind park	Foundation & cable	Share of Investments in Year 3	X	% of Capex total
Capex	Wind energy source & Transport	Offshore wind park	Foundation & cable	Economic Lifetime	X	years
Capex	Wind energy source & Transport	Offshore wind park	Foundation & cable	Depreciation Flag	X	flag
Capex	Wind energy source & Transport	Offshore wind park	Foundation & cable	Depreciation Rate	X	% of Capex total
Opex	Wind energy source & Transport	Offshore wind park	Foundation & cable	Yearly Variable Costs Flag	X	flag
Opex	Wind energy source & Transport	Offshore wind park	Foundation & cable	Yearly Variable Costs Rate	X	% of Capex total
Opex	Wind energy source & Transport	Offshore wind park	Foundation & cable	Insurance Flag	X	flag
Opex	Wind energy source & Transport	Offshore wind park	Foundation & cable	Insurance Rate	X	% of Capex total
Abex	Wind energy source & Transport	Offshore wind park	Foundation & cable	Decommissioning Flag	X	flag
Abex	Wind energy source & Transport	Offshore wind park	Foundation & cable	Foundation & cable decommissioning	X	% of Capex total
Residual value	Wind energy source & Transport	Offshore wind park	Foundation & cable	Foundation & cable residual value	X	% of Capex total

Figure 4.1: Screenshot of an example of an input sheet for the cost model, including the general system input and the input lines for the element 'Foundation & Cable'

Once the input data was collected, an Excel model was set up to perform the calculations for each sub-system, which was split up into elements. The names of the sub-systems and elements exactly matched the names defined in chapter 2. To ensure the accuracy and quality of the model, MTBS provided their template and supervision. MTBS' template contains all required functionalities mentioned in section 4.1. The supervision and control of MTBS helped to identify any errors or inconsistencies in the model, which could then be corrected before proceeding to the next step.

MTBS' model template consists out of 'blocks', which have the same structure for every sub-system and element. This allows users to copy-paste and build the model quickly. An example of two of these blocks (Yearly Variable Costs and Insurance Costs) is provided below in Figure 4.2.

	Constant	Unit
Yearly Variable Costs		
Opex - Escalation Factor	-	factor
Wind energy source & Transport - Offshore wind park - Foundation & cable - Depreciation - Depreciable Balance - Start	-	EUR
Opex - Wind energy source & Transport - Offshore wind park - Foundation & cable - Yearly Variable Costs Flag	1	flag
Opex - Wind energy source & Transport - Offshore wind park - Foundation & cable - Yearly Variable Costs Rate	2%	% of Capex total
Project Operations Period Flag		flag
Wind energy source & Transport - Offshore wind park - Foundation & cable - Yearly Variable Costs - POS		EUR per annum
Wind energy source & Transport - Offshore wind park - Foundation & cable - Yearly Variable Costs		EUR per annum
Insurance Costs		
Opex - Escalation Factor	-	factor
Wind energy source & Transport - Offshore wind park - Foundation & cable - Depreciation - Depreciable Balance - Start	-	EUR
Opex - Wind energy source & Transport - Offshore wind park - Foundation & cable - Insurance Flag	1	flag
Opex - Wind energy source & Transport - Offshore wind park - Foundation & cable - Insurance Rate	0,50%	% of Capex total
Project Operations Period Flag		flag
Wind energy source & Transport - Offshore wind park - Foundation & cable - Insurance Costs - POS		EUR per annum
Wind energy source & Transport - Offshore wind park - Foundation & cable - Insurance Costs		EUR per annum

Figure 4.2: Screenshot of an example of a calculation block for the cost model: Yearly Variable Costs and Insurance Costs for the element 'Foundation & Cable'

After setting up every cost block for all elements of the considered supply chains, the total costs and revenues are displayed in a Financial Statement sheet. This gives a clear overview of all operational cash flows and investment cash flows.

	Constant	Unit
Operational Cash Flows		
Revenues		
Project - Total Revenues	CF	EUR
Project – Total Revenues		**EUR per annum**
Operational Costs		
Wind energy source & Transport - Yearly Variable Costs - Total Costs	CF	EUR per annum
Wind energy source & Transport - Insurance - Total Costs	CF	EUR per annum
Wind energy source & Transport - Decommissioning - Total Costs	CF	EUR per annum
AC Substation & Transport - Yearly Variable Costs - Total Costs	CF	EUR per annum
AC Substation & Transport - Insurance - Total Costs	CF	EUR per annum
AC Substation & Transport - Decommissioning - Total Costs	CF	EUR per annum
Converter & Transport - Yearly Variable Costs - Total Costs	CF	EUR per annum
Converter & Transport - Insurance - Total Costs	CF	EUR per annum
Converter & Transport - Decommissioning - Total Costs	CF	EUR per annum
Electrolysis, Electricity & Transport - Yearly Variable Costs - Total Costs	CF	EUR per annum
Electrolysis, Electricity & Transport - Insurance - Total Costs	CF	EUR per annum
Electrolysis, Electricity & Transport - Decommissioning - Total Costs	CF	EUR per annum
Project – Total Operational Costs		**EUR per annum**
Operational Cash Flows		
Project - Total Revenues	-	EUR per annum
Project - Total Operational Costs	-	EUR per annum
Project – Operational Cash Flows		**EUR per annum**
Investment Cash Flows		
Wind energy source & Transport - Investments - Total Costs	CF	EUR per annum
Wind energy source & Transport - Divestment at end of Project	CF	EUR per annum
AC Substation & Transport - Investments - Total Costs	CF	EUR per annum
AC Substation & Transport - Divestment at end of Project	CF	EUR per annum
Converter & Transport - Investments - Total Costs	CF	EUR per annum
Converter & Transport - Divestment at end of Project	CF	EUR per annum
Electrolysis, Electricity & Transport - Investments - Total Costs	CF	EUR per annum
Electrolysis, Electricity & Transport - Divestment at end of Project	CF	EUR per annum
Project – Total Investment Cash Flows		**EUR per annum**

Figure 4.3: Screenshot of the lines included in example cash flow statement

By converting these cash flows into their net present value (NPV), the Levelised Cost of Hydrogen (LCOH) and the Levelised Cost of Energy or Electricity (LCOE) can be calculated using the total production of the considered supply chain according to the method described in subsection 1.1.3.

	Constant	Unit
Levelised Cost of Hydrogen		
Project - Total Operational Costs - PV - Total	(3.917.645.563)	EUR
Project - Total Investment Cash Flows - PV - Total	(12.854.727.534)	EUR
Project - CAPEX + OPEX - PV - Total - POS	**16.772.373.097**	**EUR**
Project - Financial - Discount Rate	-	Rate
Total Hydrogen Production	6.884.853.584	kg
Total Hydrogen Production PV	**1.800.833.597**	**kg**
Levelised Cost of Hydrogen	**9,31**	**EUR / kg**

Figure 4.4: Screenshot of an example calculation of the levelised cost of hydrogen (LCOH) - NB: used numbers are fictional

The model allows you to indicate which cost elements are included in the cost price. If, for example, the user wants an LCOH that does not include decommissioning, that would be possible. This way, it is clear which cost elements are included. The possibility of excluding certain cost elements from the calculation of the cost price makes it possible to compare an LCOE or LCOH with cost prices in other research that also exclude these elements. This leads to a fair comparison of the cost price.

4.5. Limitations of Excel Model

As the energy transition becomes increasingly important, parties involved in the process are seeking comprehensive analysis to help them make informed decisions. These decisions can not be based solely on financial analysis but might require different angles such as meteorological, ecological, and geographical circumstances. This was something mentioned in the interviews, among others by the government body assessing the tenders for future projects. Stakeholders also shared the desire for transparency in the model, allowing them to clearly see the assumptions and calculations behind the results. To accelerate the energy transition, an open discussion between all relevant parties is needed. An open-source model would help with this. However, while the current method of using Excel spreadsheets is easy to work with, it may have several limitations for these desires.

Excel sheets can become large and complex, which can make it difficult for users to understand the underlying assumptions and calculations behind the results. Additionally, Excel's limited debugging tools can make it challenging to identify errors. Moreover, when handling large datasets, Excel can slow down and struggle to work efficiently with data from multiple sources.

Another limitation is reproducibility. Users may struggle to reproduce the same results consistently due to the complexity of an Excel sheet. This can arise from hidden formulas or macros, manual changes to the data, or changes to the formatting. Additionally, Excel offers limited tools to perform probabilistic calculations, and it may struggle with handling large datasets. For instance, when performing Monte Carlo simulations to determine the influence of a supply chain element on the total cost and LCOH, which is something that stakeholders wish to get more insight into.

Furthermore, Excel's ability to handle spatial data is limited, which can pose challenges when performing spatial analysis tasks, particularly with large datasets. In such cases, third-party add-ins may be necessary to perform these types of analyses. Although Excel has built-in functions for financial analysis, it may struggle to perform more complex price scenario analysis tasks. Additionally, Excel files can become complex and difficult to understand, especially when multiple users are involved, limiting its capabilities for sharing the analysis process.

To address the limitations of Excel, Python could be considered as an alternative option. However, it should be noted that Python notebooks may not be easily understood by everyone, and coding can be complicated. Nonetheless, when people understand coding, the written code is clear and transparent. Python has robust debugging tools that can identify the source of errors, which simplifies the process of resolving complex issues.

Furthermore, Python is highly scalable and efficient in handling massive datasets and diverse data sources. It provides a structured and robust approach to analysis, enabling other users to reproduce consistent results effortlessly. Python also offers several libraries that provide numerous statistical functions for performing probabilistic calculations, and open-source tools such as 'pvlib' and 'windpowerlib', which simulate the performance of solar energy systems and wind power plants, respectively (Halden et al., 2021; Holmgren et al., 2018; Tanvir, 2023). Another example is 'oemof', which can be used for energy system modelling (Krien et al., 2020).

Figure 4.5: Example of geographical data being used in Python code from author

In addition, for deep financial analyses and modelling Python offers numerous libraries (Greenwood, 2023; Lewinson, 2020; Sblendorio, 2021). Further, Python has libraries that are specifically designed for spatial analysis, providing tools for working with spatial data such as creating maps (Prapas, n.d.). For price scenario analyses, Python offers libraries that provide tools for working with time-series data, performing predictive modelling, and simulating different scenarios (J. A. Rodrigo & Ortiz, 2021). This can be used for electricity price forecasting (Dimitriosroussis, 2021). It should be noted that these kinds of libraries and tools require a certain level of computer science and programming knowledge. However, the examples show the possibilities Python offers.

Examples of the application of Python for financial engineering and techno-economic analyses can be found in the literature as well. One study created an integrated energy finance evaluation tool, based on LCOE values of solar photovoltaic investment, using Python (Halden et al., 2021). A second one developed an open-source Python model for the techno-economic analysis of 5G network projects using geospatial data (Oughton et al., 2019). And finally, a study used multiple open-source Python tools to model weather predictions and energy production forecasts for their analysis of the LCOH for hydrogen production and export from Colombia (Burdack et al., 2023). By using Python, parties involved in the energy transition can have a more comprehensive analysis than with Excel, which can help them make informed decisions.

However, Python has its downsides. Firstly, it requires coding skills, which not everyone possesses. Python may have a steeper learning curve than Excel, and users may need to invest time in learning the language and its associated tools and libraries. Secondly, opening notebooks requires certain installed programs that might be difficult for new users. In addition, some users may find notebooks to be intimidating, which can make it challenging for them to grasp the calculations and assumptions behind the model. Finally, while Python is highly scalable, it can be computationally intensive. Complex calculations might require more processing power than Excel.

In conclusion, while Excel is currently the most used tool in the industry for the financial analysis of projects, its limitations make it difficult to address the wishes of stakeholders. These include transparency, reproducibility, scalability, and efficiency in handling large datasets and diverse data sources. Python seems to be a suitable alternative for this. Although it may require some coding skills and potentially more processing power for complex calculations, it offers comprehensive analysis capabilities. Therefore, an improved version of the comparison model using Python will be set up to meet the needs of the stakeholders.

4.6. Addressing the Limitations Using Python

Section 4.5 described the limitations of an Excel-based model and explained how Python could be used to improve the model. This chapter describes the implementation of some of these improvements.

4.6.1. Iterative Implementation

Based on the desired functionalities that came forward through the stakeholder interviews and the mentioned limitations of Excel (section 4.5), Python was deemed the most suitable tool to set up an improved cost model. Having integrated the correct financial methodology and assumptions in the Excel model, thanks to MTBS' supervision, an iterative method was used to implement the improvements in Python.

The same financial calculations (Capex, Opex, cash flow analysis) were coded in Python. After the setup of a supply chain element was completed in Excel, the input data defined in Excel was imported into Python to perform these calculations (see Figure 4.6). The results (see Figure 4.7) would then be compared with the Excel results.

1. prepare input data and generate objects

```
foundation_data = get_object_data(Inputs=Inputs,
                              subsystem='Wind energy source & Transport',
                              element='Offshore wind park',
                              component='Foundation & cable')
foundation_data['depreciation_rate']=1/foundation_data['economic_lifetime']
display(foundation_data)
```

```
{'sub_system': 'Wind energy source & Transport',
 'element': 'Offshore wind park',
 'component': 'Foundation & cable',
 'escalation_base_year': 2023,
 'escalation_rate': 0.02,
 'capex_per_unit': 971621,
 'capex_per_unit_units': 'EUR / MW',
 'unit': 3000,
 'unit_units': 'MW',
 'construction_duration': 3,
 'share_of_investments': [0.2, 0.4, 0.4],
 'economic_lifetime': 30,
 'depreciation_flag': 1,
 'depreciation_rate': 0.03333333333333333,
 'yearly_variable_costs_flag': 1,
 'yearly_variable_costs_rate': 0.015,
 'insurance_flag': 1,
 'insurance_rate': 0.005,
 'decommissioning_rate': 0.35,
 'residual_value': 0.01}
```

Figure 4.6: Screenshot of Python code importing input data from the Excel model

```
# Print Foundation values (without revenues)
display(Foundation.df)
```

years	years	capex	opex	revenue	cashflow	cashflow_sum	npv	npv_sum
2023	2023	-5.946321e+08	0.000000e+00	0	-5.946321e+08	-5.946321e+08	-5.413620e+08	-5.413620e+08
2024	2024	-1.213049e+09	0.000000e+00	0	-1.213049e+09	-1.807681e+09	-1.005443e+09	-1.546805e+09
2025	2025	-1.237310e+09	0.000000e+00	0	-1.237310e+09	-3.044992e+09	-9.336779e+08	-2.480483e+09
2026	2026	0.000000e+00	-6.591994e+07	0	-6.591994e+07	-3.110912e+09	-4.528712e+07	-2.525770e+09
2027	2027	0.000000e+00	-6.723834e+07	0	-6.723834e+07	-3.178150e+09	-4.205468e+07	-2.567825e+09
2028	2028	0.000000e+00	-6.858311e+07	0	-6.858311e+07	-3.246733e+09	-3.905296e+07	-2.606878e+09
2029	2029	0.000000e+00	-6.995477e+07	0	-6.995477e+07	-3.316688e+09	-3.626550e+07	-2.643143e+09
2030	2030	0.000000e+00	-7.135386e+07	0	-7.135386e+07	-3.388042e+09	-3.367699e+07	-2.676820e+09
2031	2031	0.000000e+00	-7.278094e+07	0	-7.278094e+07	-3.460823e+09	-3.127325e+07	-2.708093e+09
2032	2032	0.000000e+00	-7.423656e+07	0	-7.423656e+07	-3.535059e+09	-2.904107e+07	-2.737134e+09
2033	2033	0.000000e+00	-7.572129e+07	0	-7.572129e+07	-3.610781e+09	-2.696822e+07	-2.764103e+09
2034	2034	0.000000e+00	-7.723572e+07	0	-7.723572e+07	-3.688016e+09	-2.504332e+07	-2.789146e+09
2035	2035	0.000000e+00	-7.878043e+07	0	-7.878043e+07	-3.766797e+09	-2.325581e+07	-2.812402e+09

Figure 4.7: Screenshot of Python code displaying the results of the financial calculations

This step is crucial as it involves testing to check if the Python module works as expected and to verify that the output is consistent with that of the Excel model. The most important part of this step is to ensure that the values calculated in Python match those calculated in Excel for the Capex, Opex, and Cash Flows per year. This is necessary to ensure that the model is reliable and can be used to make informed decisions. The way this is tested is called 'unit testing'. A unit test is a type of software test that focuses on testing a specific "unit" or component of code in isolation from the rest of the system. During a unit test, the unit is exercised and its output is compared to the expected result. This helps to ensure that the unit is functioning correctly and producing the desired output (Olan, 2003).

2. Test values - Turbines

2.1 - CAPEX values

```
MTBS_values = {'years': [2023, 2024, 2025],
               'values': [-697_667_148, -1_423_240_982, -1_451_705_802]}
```

```
for index, year in enumerate(MTBS_values['years']):

    print('CAPEX value testing in {}: MTBS: {} TUD/VO: {}'.format(year, MTBS_values['values'][index], Turbine.df[Turbine.df.i
    np.testing.assert_almost_equal(MTBS_values['values'][index],  Turbine.df[Turbine.df.index==year].capex.item(), 0)
```

```
CAPEX value testing in 2023: MTBS: -697667148 TUD/VO: -697667148.0
CAPEX value testing in 2024: MTBS: -1423240982 TUD/VO: -1423240981.92
CAPEX value testing in 2025: MTBS: -1451705802 TUD/VO: -1451705801.5584
```

Figure 4.8: Screenshot of Python code performing unit testing, comparing the values calculated in the Excel model ("MTBS") with the values calculated in Python ("TUD/VO")

Although unit testing has been criticised for being time-consuming and costly, it remains a crucial verification activity as it enables the testing of individual software components for errors and ensures that all code is exercised adequately. Earlier research, where errors were detected through unit testing on three separate projects, implies that unit testing is necessary and cannot be eliminated from the development process (Ellims et al., 2006). It also indicates that unit testing can accomplish what other testing methods may not be able to achieve, as supported by previous research (Dupuy & Leveson, 2000).

However, maintaining unit tests throughout a project's lifecycle can be challenging. Therefore, a practical approach is needed to integrate the use of unit tests with the user's and owner's goals of reducing time and cost, as they often aim for faster, better, and cheaper results. This could be a good recommendation for future development of the model (Ellims et al., 2006).

By 'copying' MTBS' methodology into Python, it is clear that the calculations are set up correctly.

Through testing, the reliability of the Python model can be determined. To achieve this, the cash flows in Python will be compared to those of Excel to ensure that they match 1:1. Initially, this comparison will be done for just two elements of the supply chain, namely 'Foundation & Cables' and 'Turbines'. This approach will help to identify any discrepancies between the Excel and Python models and enable us to make any necessary adjustments to ensure that both models produce consistent and accurate results.

Once the comparison for the two elements is complete, and there are no discrepancies between the Excel and Python models, the analysis will be scaled up to a full supply chain. This will include all the relevant elements, such as 'Foundation & Cables', 'Turbines', 'AC Substation', 'AC Collection Cable', 'DCAC Converter', and 'Facility Location - Mainland'.

In summary, the testing step involving the comparison of Excel and Python models for Capex, Opex, and cash flows is crucial to ensure the reliability and accuracy of the model. By scaling up the analysis, we can ensure that the model is robust and can be used to make informed decisions about the offshore wind to hydrogen supply chain.

Identified Errors and Challenges

As mentioned above, testing and iterating are crucial steps when setting up a reliable and accurate model. Through testing, errors or issues with the model can be identified, allowing for corrections to be made before the model is put into use. Furthermore, testing provides users with confidence in the results it produces. During the testing period, numerous errors were found.

One of the errors was the mismatch of names between sub-systems or elements in the Python notebook and the Excel input sheet. This highlighted the importance of ensuring that the defined names match exactly between the two platforms to avoid such errors. For instance, the word 'Foundation & Cables' should match in both Excel and Python when summarising all costs for this item.

Another error was identified, which was caused by Python exporting exact values from the Excel cells. This meant that cells with formulas or references to different sheets could not be loaded by Python. Therefore, cells had to be hard-coded to avoid this error.

During testing, it was also discovered that the Opex costs were not escalated, even though they are future costs that should have been escalated. This was due to a workaround in the MTBS sheet. Such errors highlight the importance of testing and iteration to identify and resolve issues before the model is put into use. Through these processes, the errors were corrected, ensuring that the model produces reliable and accurate results that users can have confidence in.

4.7. Standard Notation System

Once the setup of the model is finished, it is important to consider how the usability of the model can be enhanced and how the underlying assumptions and calculations can be communicated clearly. This is especially valuable when interpreting results. As mentioned in the literature research (section 1.3), standardisation in the comparison of systems is lacking. Furthermore, stakeholders mentioned the desire for transparency in a comparison model. One way to do this is through the use of a standard notation system. This standard notation should give users a quick overview of what kind of supply chain is considered in the model and what kind of financial assumptions are behind the results.

The clarity that such a notation offers can be especially important when presenting the model and its results to non-experts or decision-makers who may not be familiar with the technical and financial details of the model. Furthermore, it allows for efficiency as users can quickly identify the included elements of the supply chain. Finally, a standard notation system can facilitate comparisons between different concepts or scenarios, allowing users to easily identify the similarities and differences between them. This can be especially useful for decision-making.

The suggested standard notation for the model in this research is based on the queueing theory. This is a mathematical theory that deals with the study of waiting lines, or queues, especially in ports. A shorthand notation was created by Kendall to classify queueing systems as *a/b/c*, where every letter represents a key assumption. Here, *a* stands for the inter-arrival time distribution, *b* specifies the service time distribution, and *c* the number of servers (Adan & Resing, 2002).

Based on the research and stakeholder interviews, a notation system is proposed that includes the following information: system type, model assumptions, energy conversion rate, and financial considerations. Clarity around these factors has been lacking in previous research. However, these are important to know when studying the feasibility of energy projects. Also, it allows for a fair comparison of projects when all assumptions and considerations are known.

The system type should describe the supply chain being modelled, while the energy conversion rate should indicate the proportion of hydrogen and electricity generated. The first affects the total investment costs, and the second is the generated revenues as electricity and hydrogen are sold for a different prices. The model assumptions should describe any key parameters or methods used in the model, while the financial considerations should include factors such as escalation and decommissioning. In previous research, it was not always clear what financial considerations were taken into account, which makes it difficult to compare the results with other analyses.

Using a standard notation system could enhance the usability of the model and enable clear communication of the underlying assumptions and calculations, leading to more transparent results. The standard notation system suggested will be in the form of *A/B*, where:

- *A* represents the system type and model assumptions, with:
  - W2|H = Offshore Wind to Onshore Hydrogen
  - W2H| = Offshore Wind to Offshore Hydrogen (note that '|' represents the coastline)
  - W2|E = Offshore Wind to Onshore Electricity
  - PD = Project duration followed by the number of years
  - WC = Windpark capacity followed by the number of GW
  - Example: W2H| (70%) - W2|E (30%) - PD30 - WC3 = Offshore Wind to Offshore Hydrogen (70%) and Onshore Electricity (30%), Project duration of 30 years, Windpark capacity of 3 GW
- *B* represents the financial considerations, with:
  - C(D) = Development and project management costs (Capex)
  - C(P) = Procurement costs (Capex)
  - C(IC) = Installation and commissioning (Capex)
  - C(R) = Residual value (Capex)
  - O(Y) = Yearly variable costs (Opex)
  - O(I) = Insurance costs (Opex)
  - O(D) = Decommissioning costs (Opex)
  - E = Escalation included
  - DCF = Discounted Cash Flow included
  - Example: C(D, P, IC, R) - O(Y, I) - E - DCF = Development and project management costs, Procurement costs, Installation and commissioning costs, Yearly variable costs, Insurance Costs, Escalation, Discounted cash flow

In the stakeholder interviews, it was often mentioned that the added value of a comparison model would be to get more insight into the various green hydrogen supply chains. When results are presented, it could be useful to also display the considered supply chain elements. An extra letter could be added to represent these. 'T' would be 'Turbine', 'E' would be electrolyser, 'HV' would be HVDC Converter, and so on. Adding the supply chain elements to the standard notation leads to more transparency and clarity, but might be unnecessary and will result in a long code. In this study, these letters are not added to the standard notation.

However, if desired for future research, a suggestion is provided.

- *C* (in ’A/B/C’) could represent the considered supply chain elements, with:
  - T = Turbine
  - F = Foundation & Cables
  - AC = AC Substation
  - ACC = AC Collection Cable
  - HV = HVDC Converter
  - HC = HVDC Cable
  - AI = Artificial Island
  - E = Electrolysis System
  - DCC = DCAC Converter
  - ML = Mainland
  - HP = Hydrogen pipeline

Another option could be to present a schematic overview of the different supply chains that can be compared with the model. Every supply chain is represented by a code, which could be added to the notation. The second will be easier to understand, but adding the supply chain element codes to the notation might be better for industry-wide adoption of the system.

4.8. Validation of the Improved Model

With an improved version of the cost model in Python, it is important to test and validate the functionality of the model. For this, the idea was to use public research papers that did a techno-economic analysis of an offshore wind to hydrogen concept. The papers must provide data regarding the Capex, Opex, discount rate, utilised methods, and of course the LCOH. As described in the research gap (section 1.3), this was a challenge. Two papers were found that contained sufficient data to validate the model (Jang et al., 2022; McDonagh et al., 2020).

If the model could be validated using the research papers, the next step would be to look at a ’real-life’ project. Usually, financial information about existing offshore wind projects is confidential and not publicly available. But, this MSc research is done in cooperation with Van Oord: an offshore wind project contractor. They were willing to share the financial data of a future project, on the condition that the exact numbers would not be made public. This data was entered into the model, and the calculated results (LCOE and cost structure) were then checked by Van Oord.

The cases used for validation are simple supply chains, but they serve the purpose of this research.

4.8.1. Validation with Public Research Papers

The first paper, ’*Techno-economic analysis and Monte Carlo simulation for green hydrogen production using offshore wind power plant*’, used the following data (Table 4.3) to calculate the LCOH. It considers a case where an offshore platform is installed for an electrolysis system near a wind park. All wind-generated energy is used to produce hydrogen, which is transported onshore through a gas pipeline (Jang et al., 2022).

Item	Value	Unit
Wind park capacity	160	MW
Foundation & Cables	1,371,000	$/MW
Turbines	1,823,000	$/MW
Electrolysis system	882,000	$/MW
Offshore platform for electrolysis	112,000	$/MW
Gas pipeline	885,000	$/km
AC Collection cable	403,200	$/km
Wind park distance from shore	50	km
Distance between wind park and offshore platform	5	km
Discount rate	8	%
Project duration	20	years

Table 4.3: Assumed input data retrieved from a comparable research paper (Jang et al., 2022)

In their paper, Jang, Kim et al. stated an LCOH of 13.85 $/kg H_2 for the above input data. Using these numbers in our Python cost model, an LCOH value of 15.24 $/kg H_2 was calculated. This is a 9% deviation. The annual production of hydrogen per year calculated in the research paper is 11,063,076 kg compared to 11,740,261 kg in the Python model. The difference in production could be due to efficiency assumptions that were not clearly defined by the authors. The lower LCOH in the research paper must thus come from a lower total project cost.

Even though not all assumptions are stated clearly, some suggestions can be done that might explain this difference in LCOH. First of all, the Python model calculates the Opex as a percentage of the *escalated* Capex, whereas the Opex in the research paper is calculated based on the initial non-escalated Capex. This results in a lower Opex. Further, for the cables and pipelines, the authors considered an Opex price per km, whereas in the Python model, a percentage of the total Capex is considered again. The latter results in a higher Opex. Finally, the authors consider a tax imposed on the net income and a tax redemption imposed on the Opex. These numbers are not defined, but the tax redemption could explain the lower total lifetime costs. Because not all underlying calculations and assumptions are visible in the paper, it is difficult to exactly match the LCOH from the study. Therefore, the 9% is an acceptable deviation.

The second paper, *'Hydrogen from offshore wind: Investor perspective on the profitability of a hybrid system including for curtailment'*, used the following data (Table 4.4) to calculate the LCOH. It considers a case where an offshore wind park generated energy to produce hydrogen onshore. All wind energy is used for electrolysis (McDonagh et al., 2020).

Item	Value	Unit
Wind park capacity	504	MW
Turbines	1,500,000	€/MW
Electrolysis system	850,000	€/MW
Wind park distance from shore	14.5	km
Discount rate	6	%
Project duration	25	years

Table 4.4: Assumed input data retrieved from a comparable research paper (McDonagh et al., 2020)

In their paper, McDonagh, Ahmed et al. stated an LCOH of 3.77 €/kg H_2 for the above input data. Using these numbers in our Python cost model, an LCOH value of 3.68 €/kg H_2 was calculated. This is a 2% deviation. The formula for the LCOH calculation by the authors is the same as the one used in the Python model. As the costs are rather clear, the deviation in LCOH could be explained by a difference in assumed hydrogen production. The authors of the research paper calculated the offshore wind energy based on hourly wind speed data and the characteristics of the assumed turbine type. The resulting energy production nor the hydrogen production is defined in the paper, but the used calculation method could lead to a lower energy production than the one in the Python model. There, the energy production is calculated in a more simple way where the wind park capacity is multiplied by a number of hours (4380) per year. This simplification probably results in higher energy production. The difference in calculation method could thus be an explanation for the deviation of the LCOH. Again, because not all underlying calculations and assumptions are visible in the paper, it is difficult to exactly match the LCOH from the study. Therefore, the 2% is an acceptable deviation.

4.8.2. Validation with a Real-Life Project

The displayed numbers in Table 4.5 are based on the data provided by Van Oord. But, the values are adjusted due to confidentiality reasons. The considered project is an offshore wind farm, 100% dedicated to electricity production.

Item	Value	Unit
Wind park capacity	>1000	MW
Foundation & Cables	1,100,000	€/MW
Turbines	1,500,000	€/MW
Offshore wind farm Balance of Plant (BoP)	420,000	€/MW
AC substation (offshore)	300,000	€/MW
AC collection cables & connection fee	450,000	€/MW
Discount rate	9.84	%
Project duration	30	years

Table 4.5: Assumed input data retrieved from Van Oord

Using these numbers in our Python cost model, an LCOE value of 0.176 €/kWh electricity was calculated. Van Oord's in-house assessment resulted in an LCOE value of 0.180-0.190 €/kWh. This is a 2-7% deviation. Due to confidentiality, the shared values were not the exact values used by Van Oord but rounded for this research. Furthermore, the assumed Opex was not shared. And finally, it is not possible to view the calculation method used by Van Oord as this could not be shared. These uncertainties and differences could explain the deviation in the calculated LCOE values. However, the deviation seems acceptable, also according to Van Oord.

4.8.3. Conclusion

The deviation of the LCOH values ranges from 2% to 9%, while the LCOE deviation ranges from 2% to 7%. As the comparison model is used to study green hydrogen projects in the pre-feasibility stage, such a deviation is acceptable. The deviation can be explained by a difference in assumptions made, but also by a lack of transparency of them in the papers. This lack of transparency strengthens the added value of a standard notation system, as defined in section 4.7. If such a system would be used in research papers, it would be easier to understand the underlying assumptions. This would result in more accurate comparisons of calculated LCOH and LCOE values.

It is also important to keep in mind that the model will be used as a comparison tool. In other words, the purpose of the model is to compare the LCOH and LCOE values of different projects rather than to deliver precise and accurate estimates of the LCOH and LCOE. In this stage of project development, the aim is to identify promising options and eliminate less feasible ones. Additionally, the fact that the deviation falls within the range of those presented in considered research papers indicates that the model's performance is consistent with existing literature, which supports the validity of the model as a comparison tool.

5
Demonstrating Capability of Comparison Model

In the previous chapter, a comparison model was set up using Excel. Its limitations were addressed using Python, which resulted in an improved comparison model. Furthermore, a standard notation system was defined to increase the transparency of the model's results. By being open and clear about the assumptions behind the model, the model could become a standardised comparison model that facilitates discussion in the green hydrogen industry.

Now that the model is validated using public research papers and Van Oord's data, its capability can be demonstrated. To examine this, the next step is to recreate a more complex project, such as an offshore energy island. Data for this was retrieved both through literature research and stakeholders. Furthermore, an uncertainty analysis was conducted to identify the critical factors that have the greatest impact on the model's outcomes. This information can then be used to make recommendations for optimising the financial feasibility of offshore wind to hydrogen concepts.

5.1. Energy Island Concept

5.1.1. Background

The energy island concept has generated considerable interest and discussion within the offshore renewable energy sector of the North Sea region. This 'energy hub' would be connected directly to one or more wind parks, and would have energy converters on the island. Instead of transporting the wind energy all the way onshore with cables, this energy could be used to produce hydrogen on the artificial island. The Danish government has already agreed to build two of these, which will be connected with 4 GW of wind power, which would be the first in the world. In total, the island will be capable of handling 10 GW of offshore wind energy. In the North Sea, another one is under construction with a minimum of 2 GW offshore wind power connected by 2030 (IEA, 2022; WindEurope, 2022). More recently, the construction of an artificial island 45 kilometres off the Belgian coast was announced. It will serve as a connection between a 3.5 GW offshore wind zone and the country's onshore electricity grid (Buljan, 2023). The North Sea Wind Power Hub (NSWPH) consortium is considering a project that would consist of an offshore energy island capable of integrating an unknown capacity of future offshore wind power to multiple countries (Denmark, The Netherlands, and Germany) after 2035 (NSWPH, 2018).

To understand the rising interest in offshore electrolysis and energy islands, we first discuss the reasoning behind converting wind energy to hydrogen again. Due to the intermittency of wind energy and the lack of battery storage options, hydrogen is considered as a promising option to carry this energy. Furthermore, as more renewable electricity will be generated in the future, grid capacity constraints will arise. This would mean that not all generated electricity could be used, and would thus be lost.

Converting that electricity into hydrogen could be a solution to that problem. Now, with increasing distances of wind parks from the shore new supply chains are considered. Supply chains that include offshore electrolysis instead of onshore electrolysis. As electricity cables are expensive, using hydrogen pipelines to transport this energy onshore could be more feasible. Finally, the required space for onshore electrolysis (in ports) is becoming scarce (Port of Rotterdam, 2019). Therefore, even though onshore electrolysis could be the more feasible option for now, offshore electrolysis might be necessary in the future.

Many supply chains are being considered, with varying factors such as the electrolysis location, the distance from the shore of the wind park, the wind park capacity, and the electrolysis location (offshore or onshore). As most of these concepts have not been realised yet, it is important to have the ability to compare them. By comparing projects in the pre-feasibility stage, the industry can determine which to focus on. Small changes, such as the timing of investments, can have an impact on the feasibility and success of renewable energy projects. However, this factor is often overlooked in discussions, despite its importance. Therefore, it is crucial to also consider these kinds of factors when evaluating various green hydrogen options to determine the most feasible approach.

The Python comparison model allows us to analyse these sorts of concepts. These lie far ahead in the future, which comes with uncertainty. However, using the model we can learn more about the price structure of these kinds of new ideas and compare their financial feasibility with other 'traditional' concepts.

5.2. Techno-Economic Analysis

5.2.1. Data

To learn more about the feasibility of an energy island, it will be compared with a 'traditional' offshore wind to onshore hydrogen/electricity concept. Two main cases have been set up based on the offshore wind park capacity and distance from the shore:

- Case 1: 6 GW wind park capacity, 100 km offshore
- Case 2: 12 GW wind park capacity, 180 km offshore

The wind park capacity and distance for Case 1 are based on the offshore wind roadmap, proposed by the Dutch government (Figure 1.1, Project 7). For Case 2, it is assumed that the wind park capacity will increase with the distance. We expect wind parks to become larger in the future, but the required space will be further offshore.

For these cases, no specific location on the North Sea has been chosen as the aim of this analysis is to determine the influence of certain variables on the financial feasibility of a concept, and not to determine the financial feasibility of a specific location. For both cases, the islands are located 30 km from the wind park. So, respectively 70 km and 150 km from shore. Furthermore, the assumption is made that the construction of these projects starts in 2030. This year has been chosen as, according to the Dutch government, no energy islands are expected to be realised before 2030 (van Algemene Zaken, 2022).

Another variable is the conversion rate from electricity to hydrogen. Case x.a considers a 70% conversion rate and case x.b considers a 30% conversion rate. This distribution is random. However, its goal is to show how the decided conversion influences the financial feasibility of the concept.

Table 5.1 shows an overview of the four main cases with their characteristics.

Case	Wind park capacity [GW]	Distance wind park [km]	Conversion rate [H_2/electricity]
1a	6	100	70% / 30%
1b	6	100	30% / 70%
2a	12	180	70% / 30%
2b	12	180	30% / 70%

Table 5.1: Overview of cases that were used for techno-economic comparison analysis of energy islands

It should be taken into account that the artificial island represents the least mature and most uncertain element of the project, as no such energy hub has been realised to date. Some research has been done into estimating the costs of these islands: €200-500m for a 2.1 km^2 island and €2.22bn for an island capable of integrating a 12-30 GW capacity of wind power (Gerrits, 2017; Jansen et al., 2022). These reports are from 2017 and 2018 respectively so it is unsure how accurate the provided information is.

But, similar energy island cases have also been studied by TNO in 2020. Just like in this research, TNO distinguished between a 70% and a 30% hydrogen conversion rate. The relevant cases that will be used for this research are given in Table 5.2. Based on the size of the required components for hydrogen production, TNO assumed that a 70% conversion rate resulted in a larger island surface (van der Veer et al., 2020).

Case	Conversion rate [H_2/electricity]	Wind park capacity [GW]	Construction depth [m]	Surface island [m^2]	Volume sand [m^3]
1a	70% / 30%	5	30.00 m LAT	558,700 m^2	24,980,000 m^3
1b	30% / 70%	5	30.00 m LAT	434,464 m^2	19,420,000 m^3
2a	70% / 30%	20	23.00 m LAT	1,596,770 m^2	58,240,000 m^3
2b	30% / 70%	20	23.00 m LAT	1,014,890 m^2	37,010,000 m^3

Table 5.2: Overview of comparable cases studied by TNO (van der Veer et al., 2020)

Based on this data, TNO calculated the following Capex:

- 5 GW island, 70% H_2: €1,111,700,000
- 5 GW island, 30% H_2: €990,620,000
- 20 GW island, 70% H_2: €1,761,150,000
- 20 GW island, 30% H_2: €1,409,925,000

These cost estimates are the most recent, and most detailed. Therefore, these will be used in this analysis. As we are looking at the pre-feasibility stage, the numbers are slightly adjusted due to simplicity for the considered cases in this research:

- Case 1a (6 GW island, 70% H_2): €1,110,000,000
- Case 1b (6 GW island, 30% H_2): €990,000,000
- Case 2a (12 GW island, 70% H_2): €1,760,000,000
- Case 2b (12 GW island, 70% H_2): €1,410,000,000

As mentioned, TNO has studied similar energy island cases (TNO, 2020a, 2020b; van der Veer et al., 2020). However, none of these studies considers the variable 'time'. Now that we are able to recreate the more complex case of an energy island in the comparison model it is interesting to investigate when an energy island could become more feasible. Perhaps this is the case when two wind parks are built in different years, but the energy island is built simultaneously with the first wind park. Then, the connecting infrastructure would already be present when the second wind park is built. But perhaps, the upfront Capex will be so high that the revenues generated by just one wind park will not be enough.

To investigate this, the four scenarios shown in Table 5.3 will be considered.

Scenario	Wind parks [#]	Location H_2 production	Construction year		
			Wind park 1	Wind park 2	Energy island
1	2	Onshore	2030	2030	N/A
2	2	Onshore	2030	2035	N/A
3	2	Offshore	2030	2030	2030
4	2	Offshore	2030	2035	2035

Table 5.3: Overview of scenarios that were used for techno-economic comparison analysis of energy islands

The chosen years are arbitrary and aim to show the influence of the construction years on the financial feasibility of the project.

A schematic overview of the scenarios can be seen in Figure 5.1 and Figure 5.2.

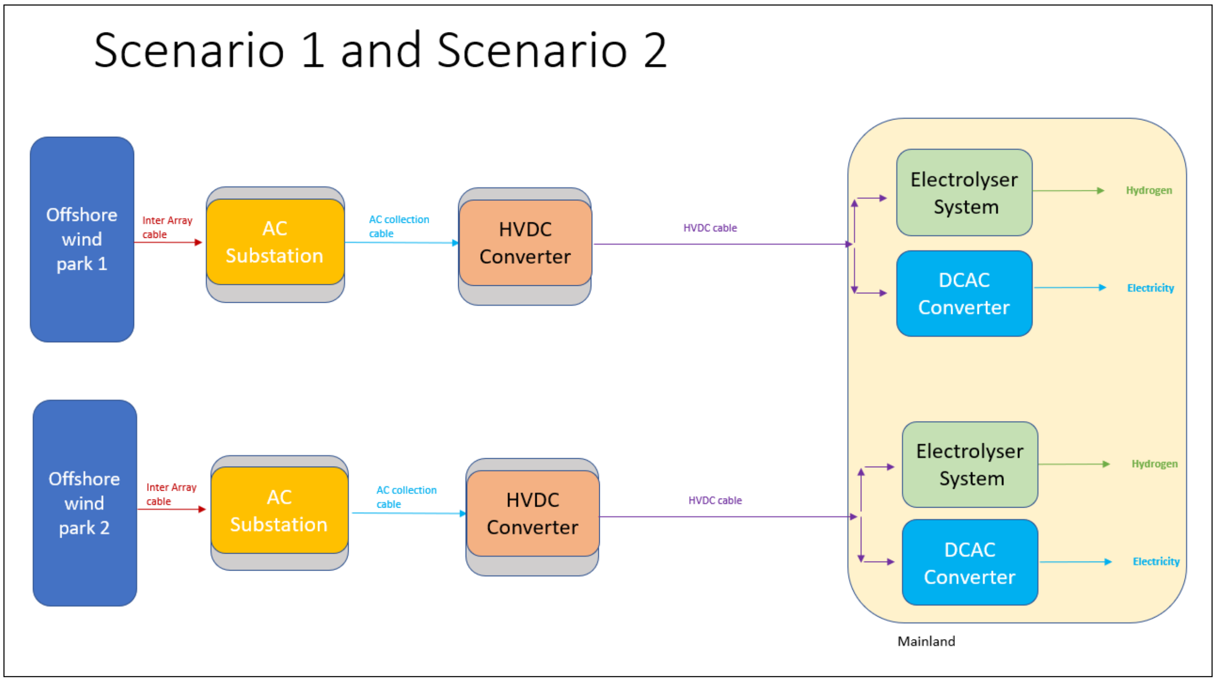

Figure 5.1: Supply chain of Scenario 1 and Scenario 2 - overview

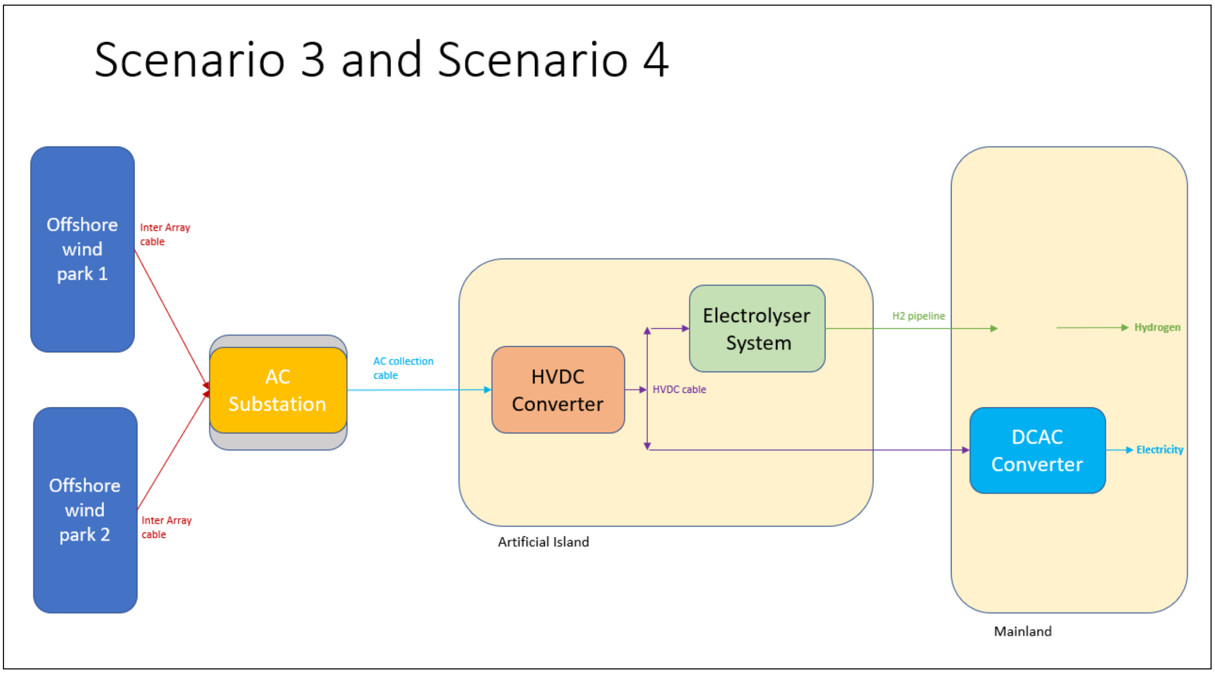

Figure 5.2: Supply chain of Scenario 3 and Scenario 4 - overview

5.2.2. Results

The Python model is able to provide the following results:

- Levelised Cost of Hydrogen (LCOH) - [€/kg]
- Levelised Cost of Energy (LCOE) - [€/kWh]
- Total discounted investment costs - [€]
- Final-year cumulative NPV with revenues - [€]
- Internal Rate of Return (IRR) - [%]
- Payback period - [years]
- Supply chain efficiency and Losses - [%]

For an explanation of these terms, refer to section 4.1.

Furthermore, the model allows us to visually interpret the cost structure and financial feasibility of a project. Getting more insight into the cost structure of these kinds of projects was a wish mentioned by multiple stakeholders (section 3.5). In total, four cases were analysed with four scenarios per case resulting in 16 pie charts (cost structure), 16 cash flow charts (financial feasibility project), and 16 times the above-mentioned metrics. Please refer to Appendix C for an overview of all charts and the supply chain efficiencies.

To demonstrate the functioning of the Python model, two cost structure pie charts and four cash flow charts will be shown for Case 1a. One pie chart for Scenario 1, and one pie chart for Scenario 3. This is because the variable time does barely influence the cost structure of those supply chains. The aim of these two graphs is to show the difference in cost structure when an energy island is built. However, the influence of this time variable is visible in the cash flow chart. Therefore, that chart will be displayed and the results will be presented for every scenario.

To determine the feasibility of an energy island, and maybe discover a tipping point for that feasibility, all scenarios and cases are compared per key metric. The considered key metrics for this analysis are supply chain efficiency, LCOH, LCOE, total discounted costs over the project's duration, and final-year cumulative NPV with revenues. The last two metrics will be displayed in the same chart, as both must be compared to say something about the financial feasibility of a project. A project could have lower total costs, but also a lower final-year NPV. If the final-year cumulative NPV with revenues is positive, it generally indicates that the project is financially feasible. It suggests that the project is expected to generate more cash inflows than outflows over the project's duration. The revenues are expected to exceed the total costs of the project, even when considering the time value (discounting) of money.

For a discussion of the results, please refer to section 6.1.

Cost Structure Pie Charts

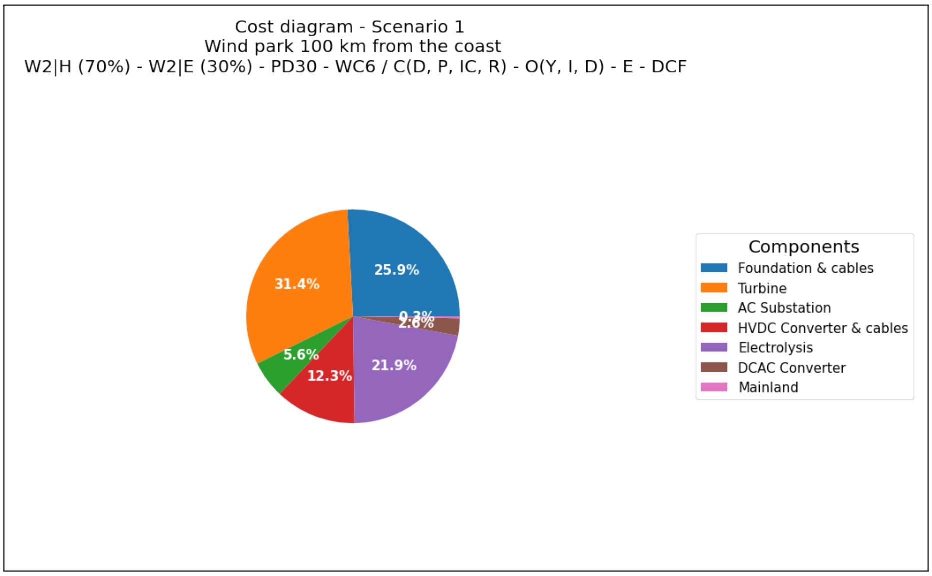

Figure 5.3: Scenario 1 - cost pie chart for Case 1a

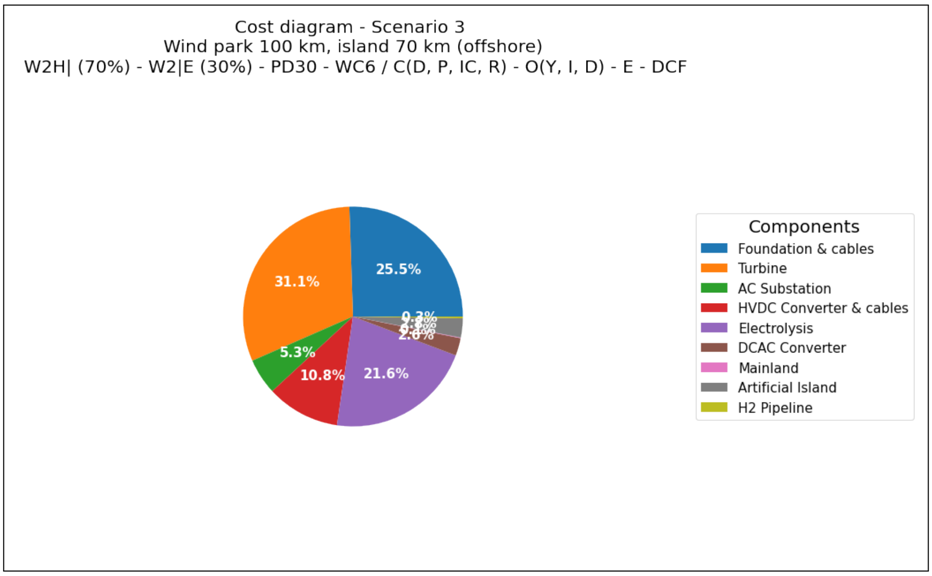

Figure 5.4: Scenario 3 - cost pie chart for Case 1a

Figure 5.3 and Figure 5.4 display the cost breakdown for two different types of supply chains. The total costs (PV) for Scenario 1 are €27.9 billion and for Scenario 3 €28.7 billion. This is all money spent on Capex and Opex over the total project lifetime. The first chart is for a supply chain with onshore electrolysis, and the second is for a supply chain with offshore electrolysis on an artificial island. For the latter, the component 'artificial island' and 'H_2 pipeline' add up to the total costs.

For both scenarios, "Turbines" and "Foundation & Cables" make up for the biggest part of the total costs (55-57%), followed by the costs for "Electrolysis" (21-22%). These findings suggest that making electrolysis more cost-efficient could have a positive effect on the total costs. The actual influence of these components on the total costs will be investigated in section 5.3.

Cash Flow Charts

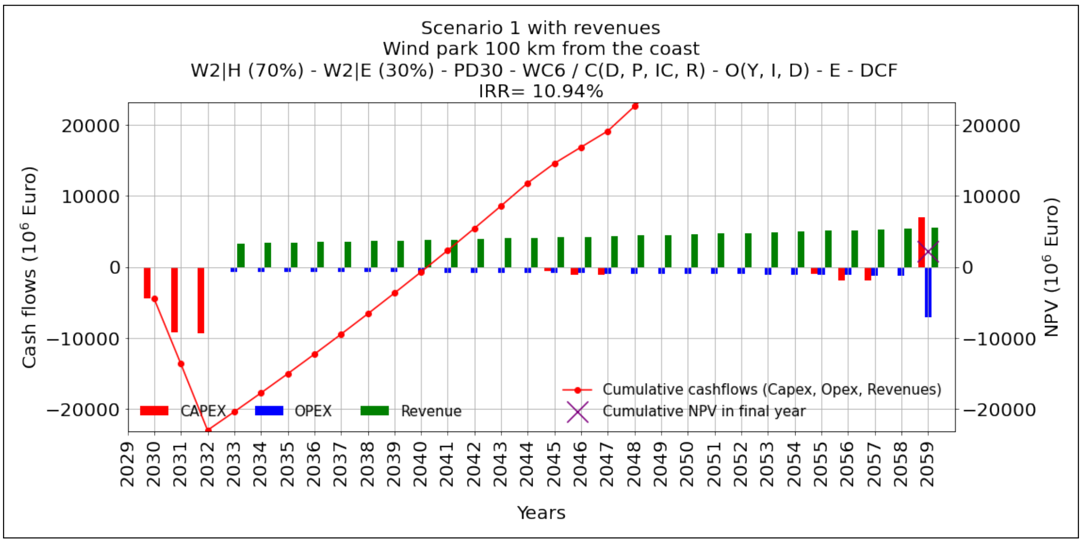

Figure 5.5: Scenario 1 - cash flow chart for Case 1a

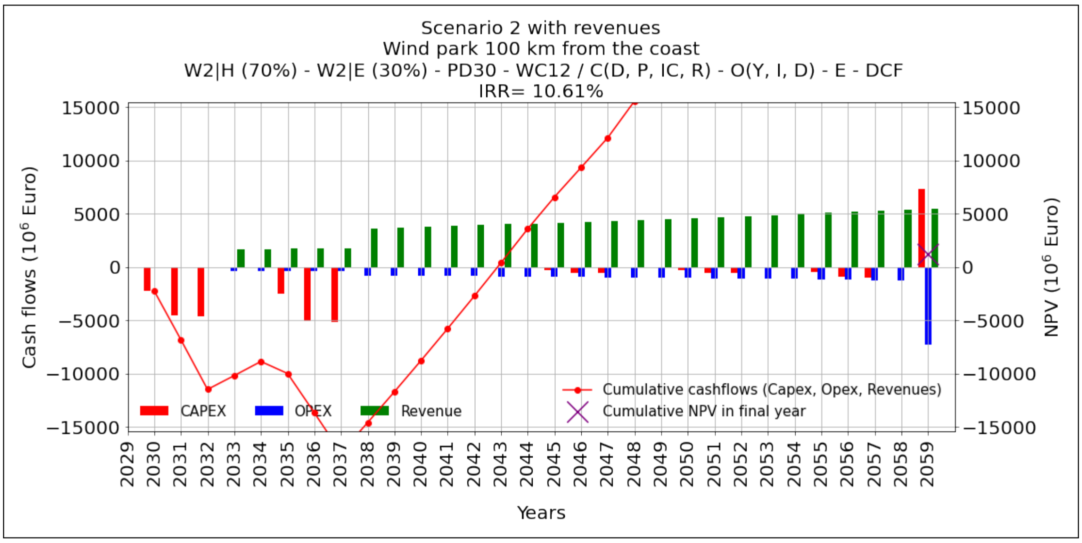

Figure 5.6: Scenario 2 - cash flow chart for Case 1a

The cash flow charts show the initial Capex required for the construction of the project, reinvestment costs, total divestment value of the project (red bar in final year), and total decommissioning costs (blue bar in final year). It is important to note that the timing of the construction has a significant impact on the cash flows and the project's overall financial performance. For example, if both wind parks are built simultaneously, the payback period is shorter as revenues are higher from the first year of operation.

The difference in payback period between Scenario 1 and 2 is 3 years, while for Scenario 3 and 4, the difference is 2.5 years. On the other hand, a planned investment delay of the second wind park means less time for generating the potential revenues of two wind parks to recover costs, resulting in a lower final-year NPV and IRR. This is mainly the case if the two wind parks are part of the same concession and thus both have the same ending year, which is assumed in this research. The entire supply chain follows this project duration and expiration timeline. Phasing investments, or delaying Capex, has the potential to benefit a project by reducing the initial funding requirements and allowing the opportunity to assess project feasibility before committing to the full investment amount.

It is worth mentioning that the size of the revenues is based on market prices for electricity and hydrogen, which can fluctuate and impact the financial outcome of the project. So, this is a sensitive assumption (Table 4.3) that needs to be taken into consideration.

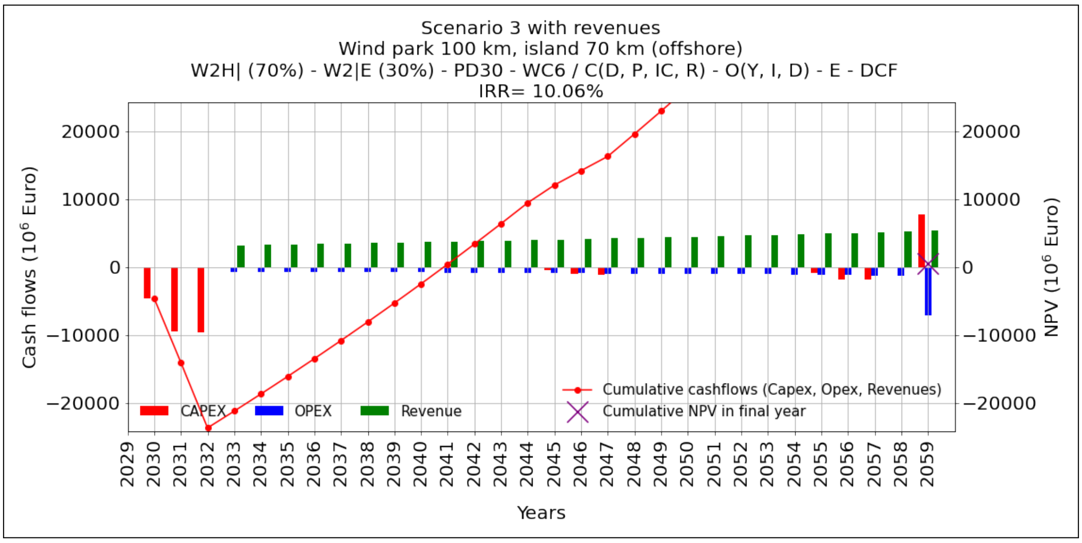

Figure 5.7: Scenario 3 - cash flow chart for Case 1a

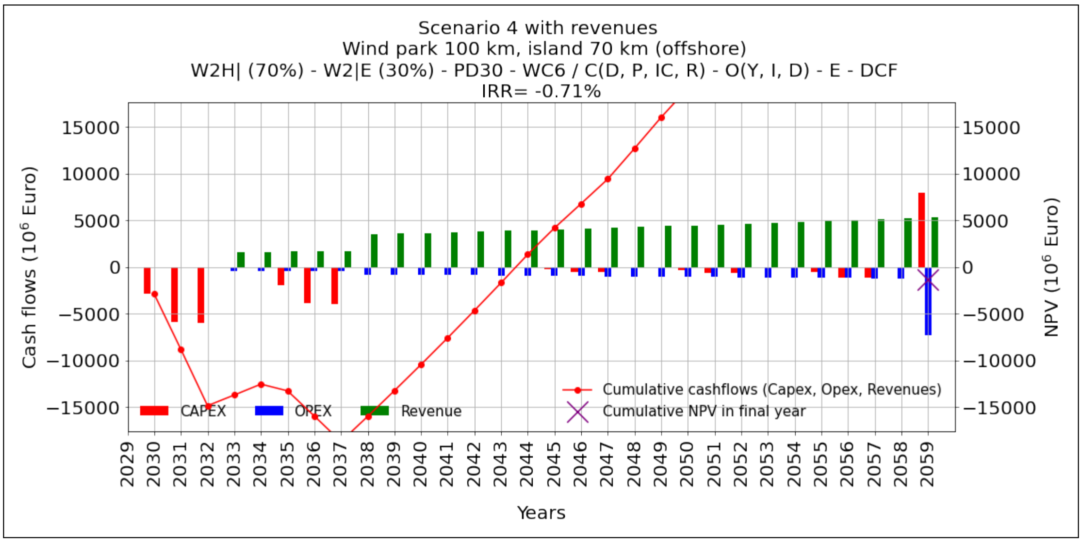

Figure 5.8: Scenario 4 - cash flow chart for Case 1a

Suppply Chain Efficiency and Losses

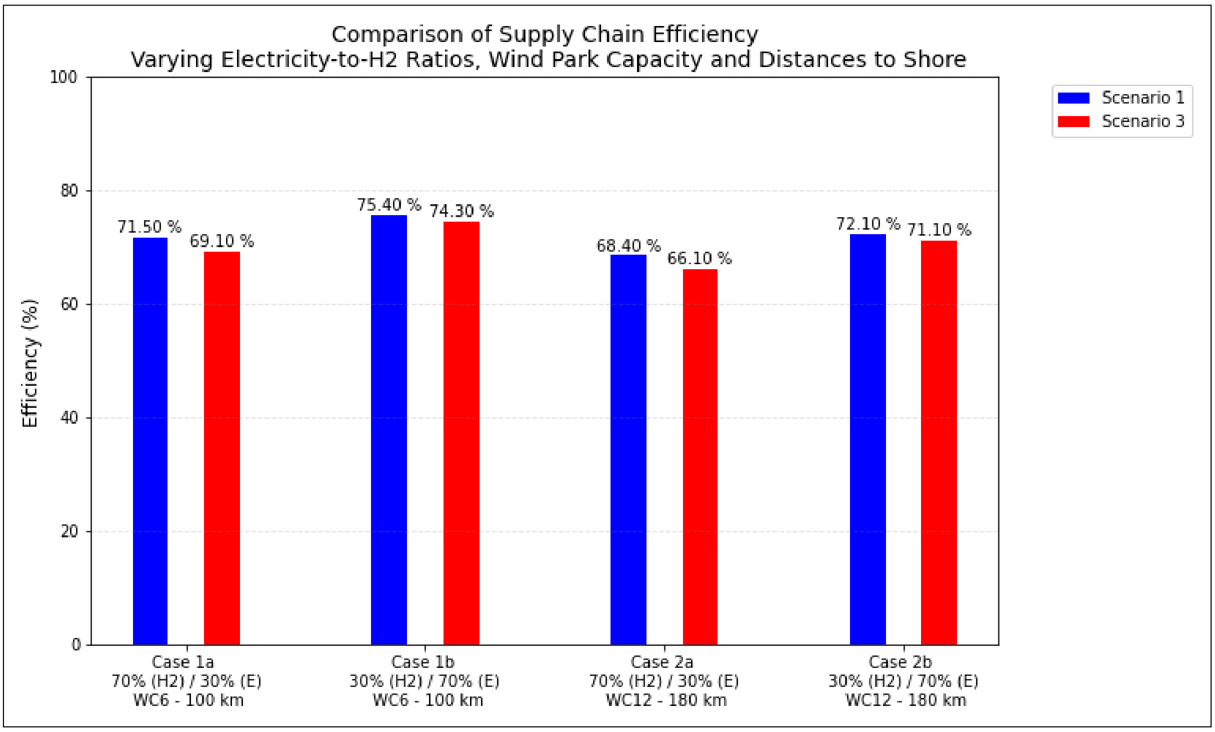

Figure 5.9: Overview of the supply chain efficiency for Scenario 1 and Scenario 3 per case, in %

The supply chain efficiency is the total energy transported onshore (hydrogen and electricity, in MJ) divided by the total generated offshore wind energy (in MJ). This metric is crucial when determining the feasibility of an energy project, as it affects the LCOH, LCOE, and NPV. The LCOH and LCOE, as this is the ratio between total project costs and total energy transported onshore. The NPV, as the total energy transported onshore determines the generated revenue by a project. The efficiency was calculated for four different supply chain scenarios. When the supply chain stays the same but the construction timing is changed (Scenario 1 vs 2 and Scenario 3 vs 4), the supply chain efficiency is not affected. Therefore, the efficiencies are only shown for Scenario 1 (onshore electrolysis) and Scenario 3 (offshore electrolysis on island). The results showed that onshore electrolysis had a higher supply chain efficiency for all cases compared to offshore electrolysis. The efficiency of a supply chain increased when the hydrogen conversion rate decreased. It is interesting to note that for Case 2b, with an increased distance, the efficiency is higher than for Case 1a, which is closer to the shore. The supply chains were most efficient for Case 1b.

The efficiency of a supply chain is determined by the energy losses over that supply chain. As an example, Figure 5.10 shows how the energy (in MJ) decreases over the supply chain for Scenario 1 when 70% of the generated electricity is used for electrolysis. For an overview of the energy losses for all Scenarios and Cases, refer to section C.3.

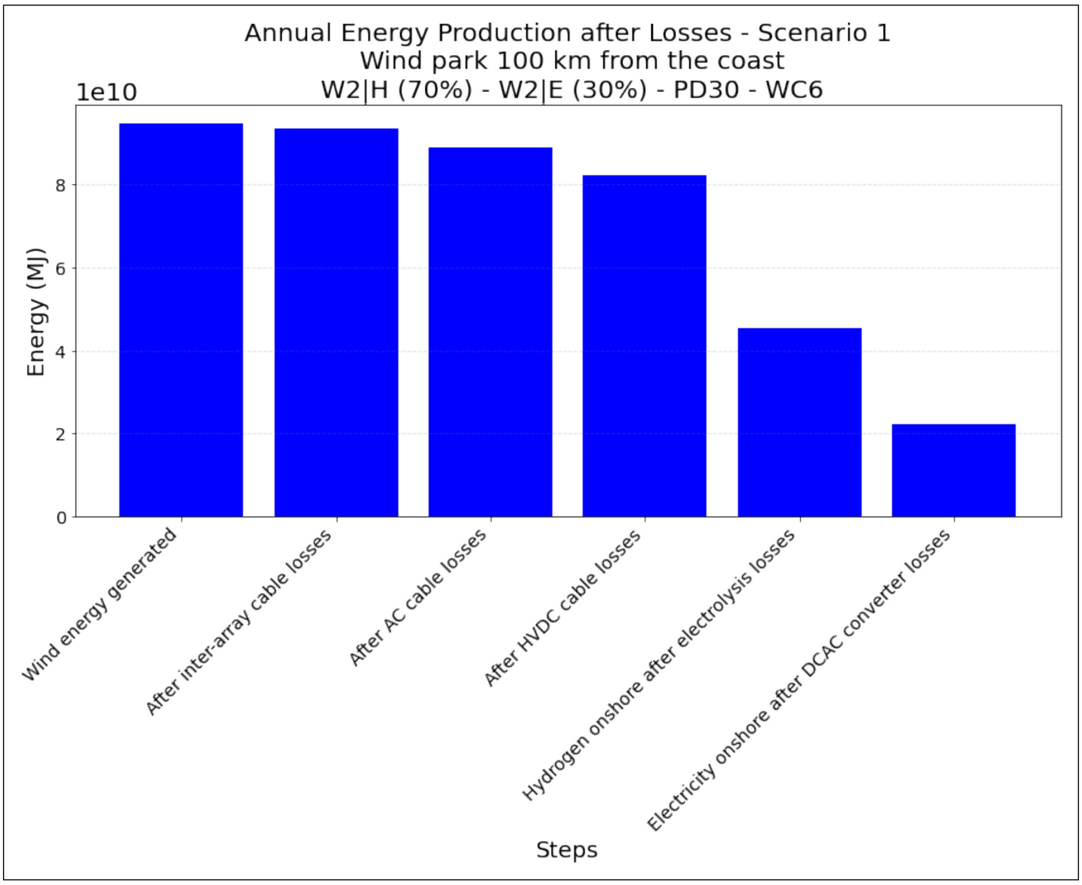

Figure 5.10: Annual energy after losses for Scenario 1, Case 1a

The loss percentages over supply chain Scenario 1 are shown in Figure 5.11 for Case 1. These losses are set parameters. So they do not change when the conversion rate is changed. Only the HVDC cable loss is dependent on the length of the cable, so that becomes larger when the distance increases (Scenario 3).

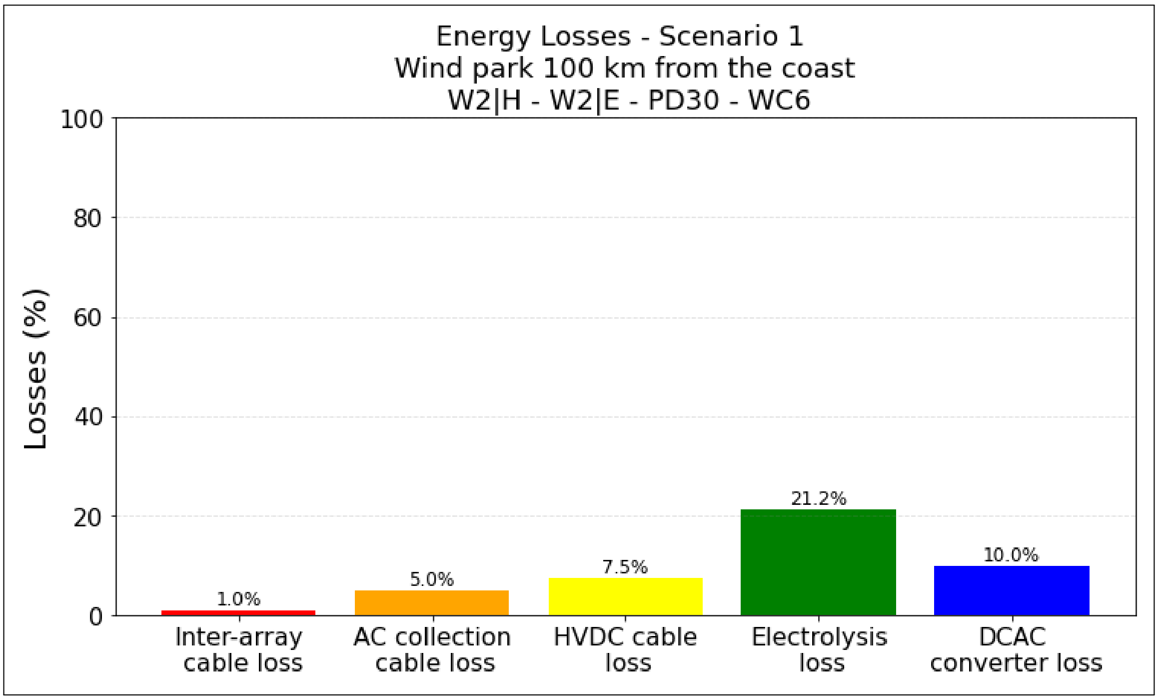

Figure 5.11: Losses per element for Scenario 1, Case 1

The loss percentages over supply chain Scenario 3 are shown in Figure 5.12 for Case 2. An extra loss is caused by the hydrogen pipeline. This explains the lower supply chain efficiency for Scenario 3 for all cases. As the HVDC cable loss is dependent on the length of the cable, the loss percentage is larger for Case 2.

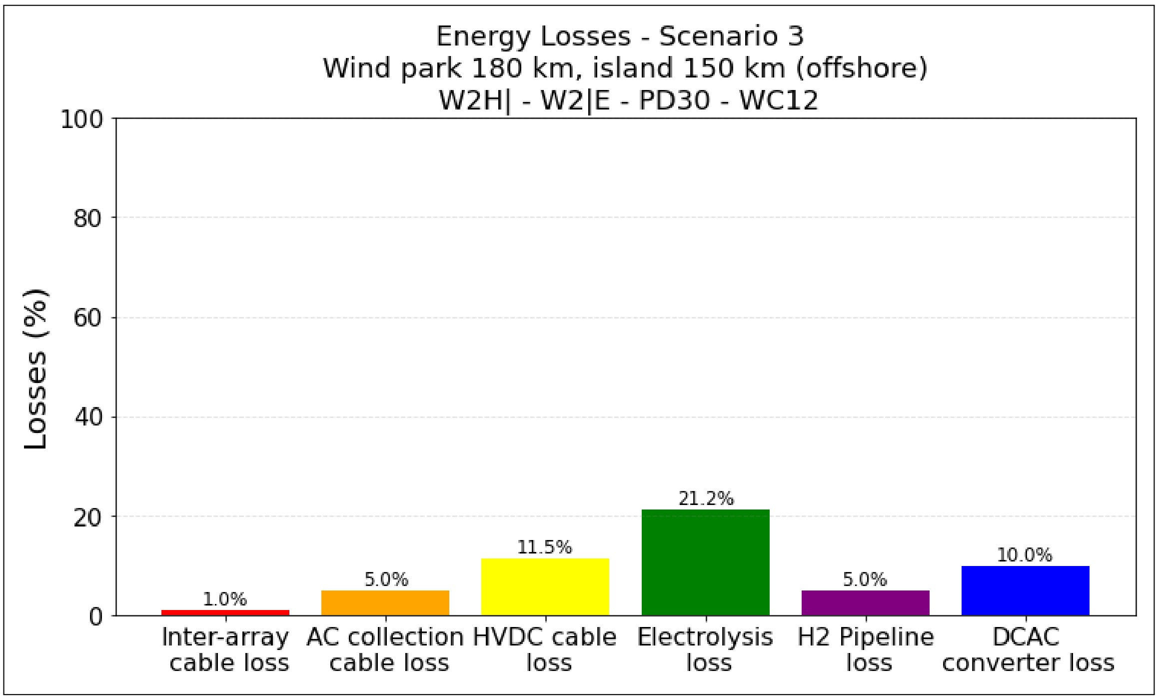

Figure 5.12: Losses per element for Scenario 3, Case 2

For an overview of the loss percentages for all Scenarios and Cases, refer to section C.3.

LCOH

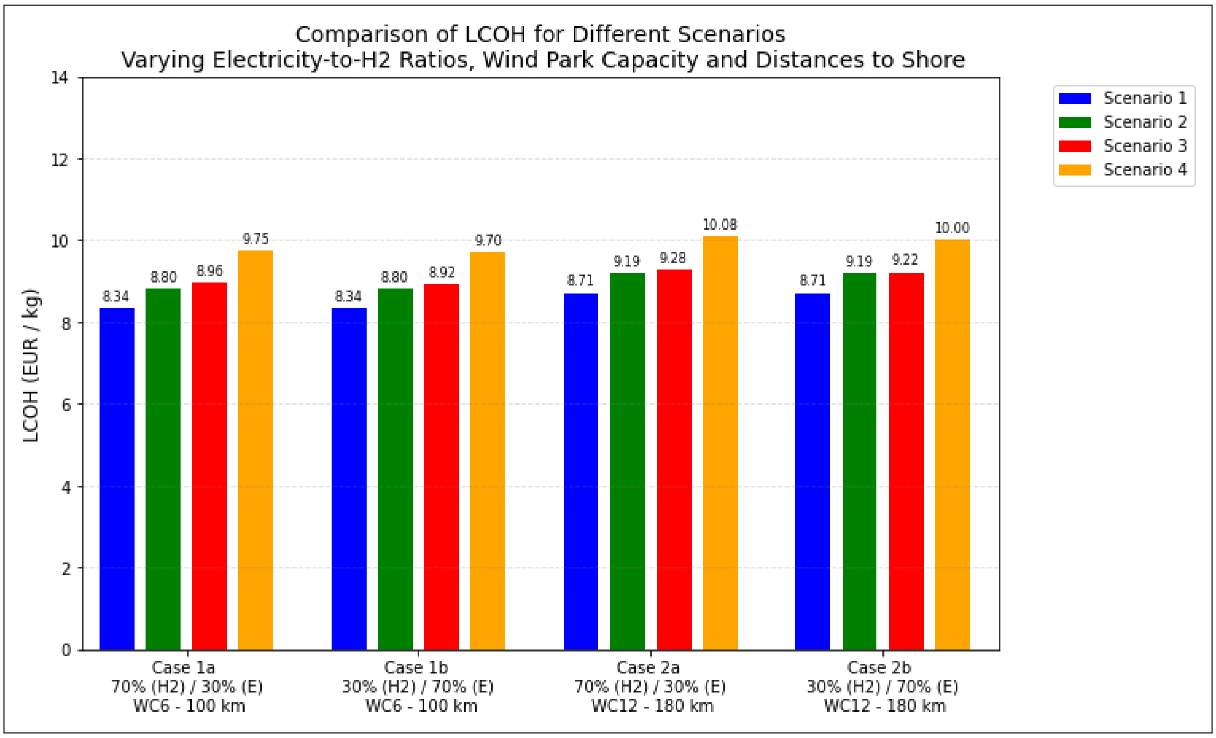

Figure 5.13: Overview of the supply chain efficiency for every scenario per case, in EUR / kWh

The LCOH represents the total cost of producing and transporting a unit (kg) of hydrogen over the project's lifetime, divided by the total amount of hydrogen produced. In this study, LCOH was calculated for four different supply chain scenarios for offshore and onshore electrolysis. The results showed that onshore electrolysis had a lower LCOH for all cases compared to offshore electrolysis. This is due to the higher investment costs that come with offshore electrolysis, such as the artificial island and hydrogen pipelines, in combination with the lower supply chain efficiency due to transportation losses. Furthermore, a delay in construction caused a higher LCOH for all cases as less energy was generated over the project's lifetime due to the delay of the second wind park. The LCOH for onshore electrolysis stayed equal when the conversion distribution was changed, while for offshore electrolysis scenarios, the LCOH changed. This was because the artificial island component in the offshore supply chain had a fixed price that did not change proportionally with the change in production and costs.

LCOE

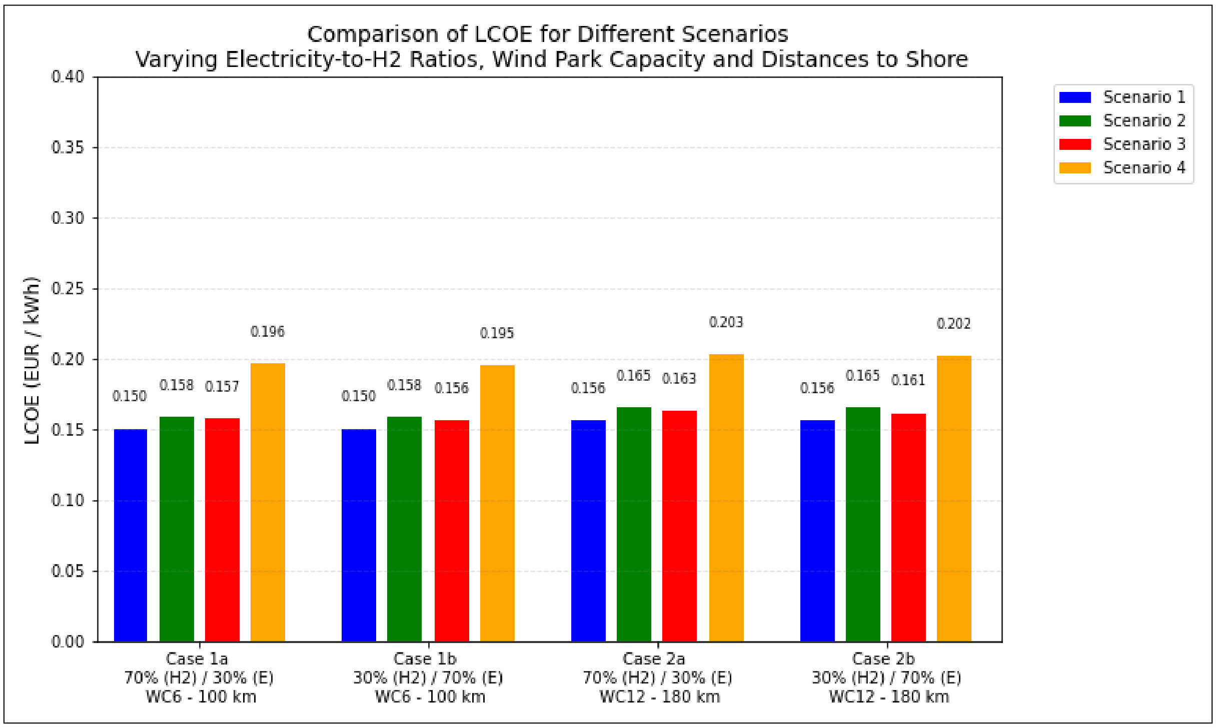

Figure 5.14: Overview of the LCOE for every scenario per case, in euro / kWh

The LCOE for Scenario 1, 2, and 3 were found to be almost equal, as shown in Figure 5.14. Changing the conversion rate had no influence on the LCOE for Scenarios 1 and 2 (Case 1a vs. Case 1b), which is similar to what was observed for the LCOH. This is due to the fact that the electricity-related costs are proportional to the electricity production for this supply chain. However, for Scenarios 3 and 4, increasing the electricity to electricity conversion to 70% slightly decreased the LCOE. Just like for the LCOH, this can be explained by the fact that the artificial island price did not change proportionally with the change in production and costs.

Scenario 4 had a much higher LCOE than the other three scenarios, for all cases. This suggests that the delay in construction between the first wind park and energy island and the second wind park negatively affected the LCOE. Interestingly, the LCOE for Scenario 3 was slightly cheaper (0.001 - 0.004 €/kWh) than Scenario 2 for all four cases. This implies that building an energy island in the same year as both wind parks is more cost-efficient than just two wind parks of which one is built 5 years later, purely based on the price to produce electricity and the electricity production. However, the differences in LCOE are relatively small, making it difficult to draw conclusive results.

Total Costs and Final-Year NPV

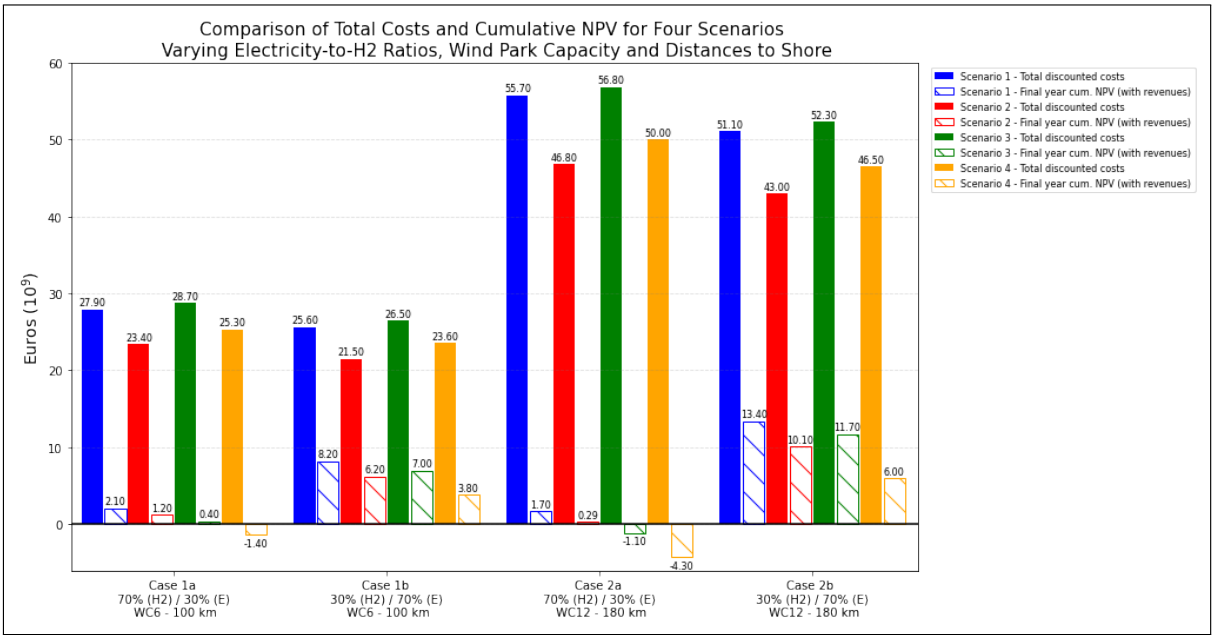

Figure 5.15: Comparison of total discounted costs and final-year cumulative net present value (NPV) with revenues for four different scenarios. The filled bars represent the total discounted costs of the different scenarios. The hatched bars represent the final-year cumulative NPV with revenues.

Figure 5.15 shows that a planned delay in construction results in a lower NPV for all four scenarios. Comparing Scenario 2 and 4, which have a construction delay, to Scenario 1 and 3, which do not, Scenario 2 and 4 consistently result in the lowest NPV. At the end of subsection 5.2.1, it was questioned if an energy island could be a more economical option if two wind parks are built in separate years. To answer that question, Scenarios 2 and 4 must be compared. For all four cases, Scenario 2 results in the highest NPV. Therefore, an energy island does not appear to be more economical when there is a construction delay.

As the time variable does not seem to have a positive influence on a project's NPV, a new chart (Figure 5.16) will be used to further analyse onshore electrolysis (Scenario 1) and offshore electrolysis (Scenario 3) while comparing the two main cases. A reference case with 100% electricity transport to shore is used to benchmark the outcomes.

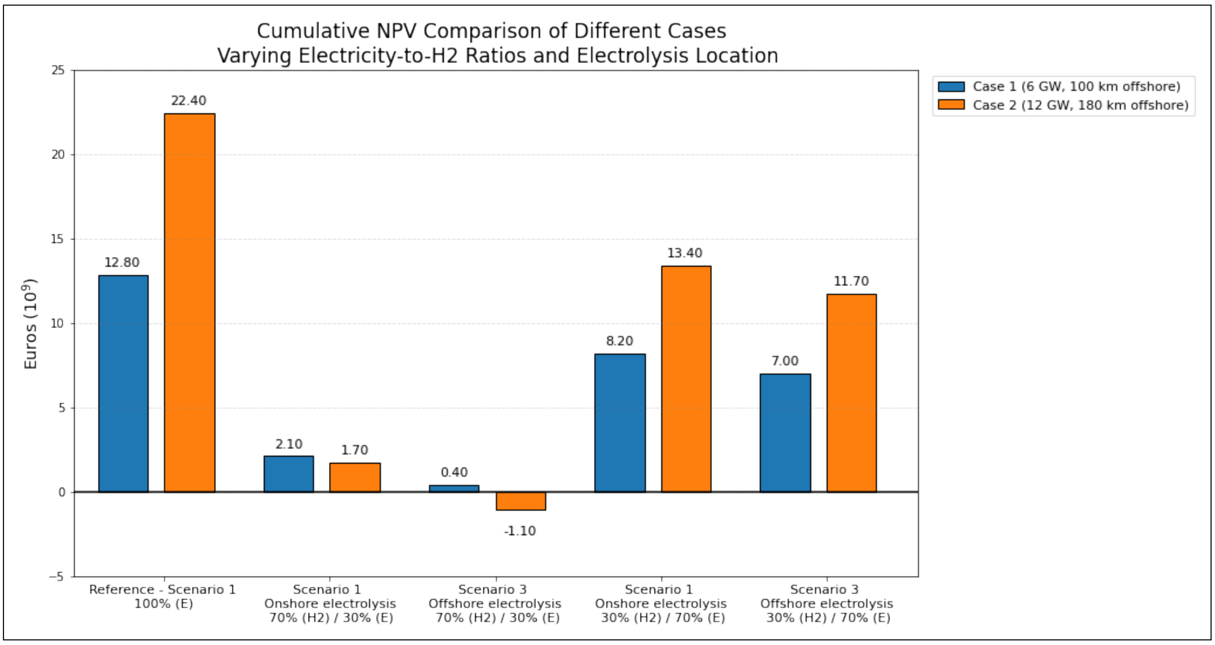

Figure 5.16: A bar chart comparing the cumulative NPV of Scenario 1 and 3 with varying electricity-to-H_2 ratios and electrolysis locations.

When comparing onshore electrolysis (Scenario 1) and offshore electrolysis (Scenario 3), Case 1 with 70% H_2 conversion rate has a higher NPV than Case 2 with 12 GW for both scenarios. However, when the H_2 conversion rate is reduced to 30%, Case 2 has a higher NPV than Case 1 for both scenarios.

5.2.3. Conclusion

Based on the LCOE, LCOH, and final-year cumulative NPV for all cases, it seems that the 30% hydrogen cases (1b and 2b) are financially the most feasible. When comparing these metrics for the four scenarios, it seems that a 5-year construction delay (Scenario 2 and 4) has a negative influence on the financial feasibility of a project. For the scenarios with no construction delay (Scenarios 1 and 3), onshore electrolysis seems to be more financially feasible than offshore electrolysis on an energy island. However, as mentioned earlier, onshore space (in ports) is expected to become more scarce. This would increase the costs to acquire or rent properties for onshore electrolysis. It is questionable, though, whether this increase will be high enough to make offshore electrolysis more feasible in the future. Perhaps, properties can simply not be acquired anymore at some point, which would leave no other option than offshore electrolysis. In this case study, only sandy artificial islands were considered for offshore electrolysis. For follow-up research, we could look at the financial feasibility of other options for this, such as caissons, platforms, and in-turbine electrolysis.

5.3. Uncertainty Analysis

The results described in subsection 5.2.2 are based on the assumption that all input parameters of the comparison model are accurately known. The largest part of these input parameters is the Capex of the components of the supply chains. Even though the component costs are based on literature and interviews, these values will never be 100% accurate and reliable. First of all, as the offshore wind and hydrogen market is competitive, the retrieved numbers will not be the exact numbers currently used in the industry. This is due to confidentiality. Furthermore, prices change. For example, global supply chains have been under pressure from the COVID-19 pandemic and the Ukraine war, causing material prices to increase (Bettoli et al., 2023). Technological developments and economies of scale, on the other hand, cause prices to decrease (Taibi et al., 2020).

The comparison model thus considers various input parameters that are characterised by change and uncertainty. The goal of this section is to study that uncertainty.

5.3.1. Monte Carlo Simulation

A useful method for this is the Monte Carlo approach. So far, the calculations performed in the model were done with exact price values. However, as mentioned, in reality, these prices are not exact and are uncertain. A probabilistic analysis of the levelised cost of hydrogen while taking into account uncertainties in cost items can be conducted using a Monte Carlo simulation.

This approach has been effectively used to conduct uncertainty-based analyses to study the financial feasibility of a number of energy technologies. In this context, researchers used a Monte Carlo simulation to calculate and analyse the impact of external costs like a carbon tax on LCOE density functions for gas projects (Geissmann & Ponta, 2017). Others performed a Monte Carlo analysis to determine the key factors impacting the LCOH in off-grid stand-alone photovoltaic installations (Yates et al., 2020). And more recently, the approach was used to investigate the impact of economic and technical factors on the success of the Polish green hydrogen strategy (Benalcazar & Komorowska, 2022).

The added value of the improved model is that Python allows for more complex calculations handling large data sets, which is needed for a Monte Carlo simulation. This is more challenging with Excel. The simulation model generates random numbers for each selected component price to then perform a number of calculations ('simulations') to determine the LCOH with these randomly generated values. Due to time, the influence of price uncertainty will be studied for four components: Turbines, Foundation & cables, Electrolyser, and Artificial Island. The first three, because they have a substantial contribution to the costs. Looking at Figure 5.4, it can be seen that Turbines make up for almost 30% of the total costs and Foundation & cables for almost 25%. The 'Electrolysis' part of the pie chart makes up for almost 21%, which is the second largest contributor after the offshore wind park. Furthermore, this technology is less mature than that of the offshore wind farm. Therefore, future technological improvements of this component could reduce the costs of electrolysers and thus green hydrogen (Taibi et al., 2020). It is expected that the components with the largest contribution to the total cost will have the largest influence on the LCOH, but this should be tested. Finally, the artificial island represents the least mature and most uncertain component of the considered projects. Some research has been done, but an actual artificial island for energy generation purposes has not been realised today. So, the first two components will be analysed because of their large contribution to the price. The third is for that reason as well, but also because of the large potential of price reductions for this technology. And the fourth, because it is the most uncertain component.

For the Monte Carlo simulation, first, the statistical distribution of each parameter that is subject to uncertainty has to be decided. In this research, a Gaussian distribution was assumed for every parameter. The Gaussian or 'normal' distribution is common when the distribution of the parameter is unknown (SUNY College, 2021). Furthermore, in a study that performed a Monte Carlo simulation to determine the financial feasibility of green hydrogen concepts, this distribution was also assumed for the cost items (Jang et al., 2022). An example of a Gaussian distribution can be seen in Figure 5.17. To generate a random sample of numbers, the parameter's mean and standard deviation should be set. This approach involves randomly selecting values from the probability distribution for each cost component. These selected values are then added together to create a single random sample representing the total cost estimate. This process is repeated multiple times to generate a probability distribution of possible cost estimates (Anderson & Cherwonik, 1997).

For every component, the initial assumed Capex price was set as the mean. For the standard deviation, observational data or historical data can be used. If these are hard to retrieve, or when historical data are not expected to mirror future developments then estimates should be collected from experts that can contribute domain knowledge (Onnen, 2021). A potential problem with this approach is that these experts have inherent biases that can affect their decision-making, including being overly confident in their ability to assess uncertainty. Additionally, there is limited understanding of how experts are asked to provide their opinions in professional literature related to costs and risks (Galway, 2007).

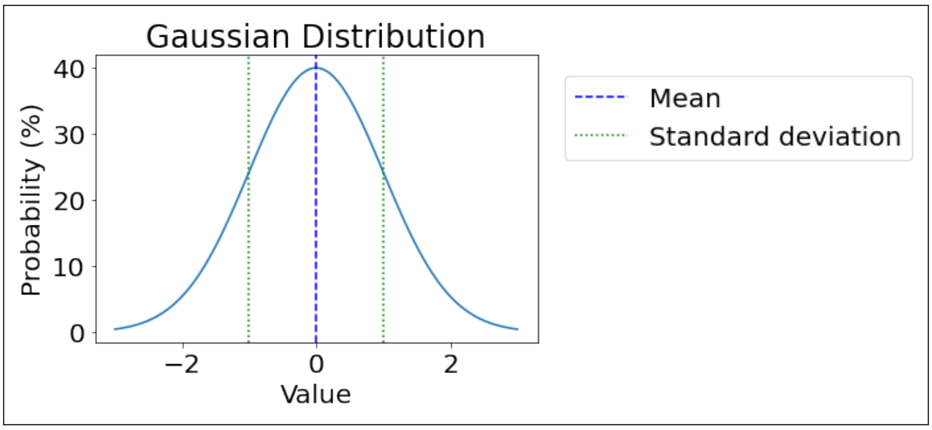

Figure 5.17: Example of a Gaussian distribution (created in Python by the author of this thesis)

5.3.2. Sensitivity Analysis

The goal of the Monte Carlo simulation in this study is not to calculate the probability of the financial feasibility of a project. The goal is to determine the influence of price uncertainty on the LCOH. And specifically, the influence of the price uncertainty for four components: Turbines, Foundations & Cables, Electrolysis system, and the Artificial Island. Therefore, we do not need to find observational data, historical data or expert estimates. However, we do have to decide what standard deviation aligns with what kind of price certainty. We, therefore, assumed the following ranges. It should be noted that these ranges are not based on literature, but are made up by the author. The aim of these ranges is to get a sense of the influence of certain standard deviations on the LCOH. The standard deviation ranges are the following:

- High price certainty: 5-10% standard deviation
- Moderate price certainty: 10-20% standard deviation
- Low price certainty: 20-50% standard deviation

To analyse the influence of the uncertainty of certain components on the LCOH, a sensitivity analysis can be performed. It follows these steps (Christopher Frey & Patil, 2002):

1. A set of LCOHs is calculated using the initial assumed Capex price as the mean value for all components with a 10% standard deviation (moderate certainty). This standard deviation is assumed as a base case.
2. Write down the mean and standard deviation of the calculated LCOHs. If the data set exhibits a normal distribution, represented by a bell-shaped curve, then the mean and standard deviation calculated from the data set can be considered reliable estimates of the actual mean and standard deviation (Anderson & Cherwonik, 1997).
3. A new set of LCOHs is generated using the same mean values for all components, but with a new standard deviation for one of the selected components (Turbines, Foundation & Cables, Electrolyser, Artificial Island). To investigate the influence of price uncertainty, the standard deviation will be increased from 10% to 30% (low certainty) and decreased from 10% to 5% (high certainty).
4. Compare the mean and standard deviation of the new set of LCOHs to the mean and standard deviation of the base case.
5. Calculate the percentage change in the standard deviation. This is the sensitivity analysis.

For the sensitivity analysis through a Monte Carlo simulation, Scenario 3 will be considered as this features the artificial island. Furthermore, Case 2b will be analysed: a 12 GW wind park, 180 km offshore, with a 30% hydrogen conversion. This was the case for Scenario 3 with the highest calculated NPV (Figure 5.16). It is a supply chain that has not been realised yet, thus with a lot of uncertainty.

5.3.3. Results

For the first step, the Monte Carlo simulation is run 1000 times to calculate a set of LCOHs for the base case (10% standard deviation, both negative and positive, for all components). A general rule of thumb is to run at least 1000 realisations to get a fair sense of the distribution of possible outcomes (Heijungs, 2019). The resulting data set (Figure 5.18) exhibits a normal distribution, so the mean and standard deviation can be considered reliable estimates of the actual mean and standard deviation. Based on the Monte Carlo simulation, the mean LCOH estimate is €9.19 / kg with a standard deviation of €0.39 / kg. Therefore, we see a 68.27% chance that the true LCOH will fall within the mean plus or minus one standard deviation (€8.80 - 9.59/ kg).

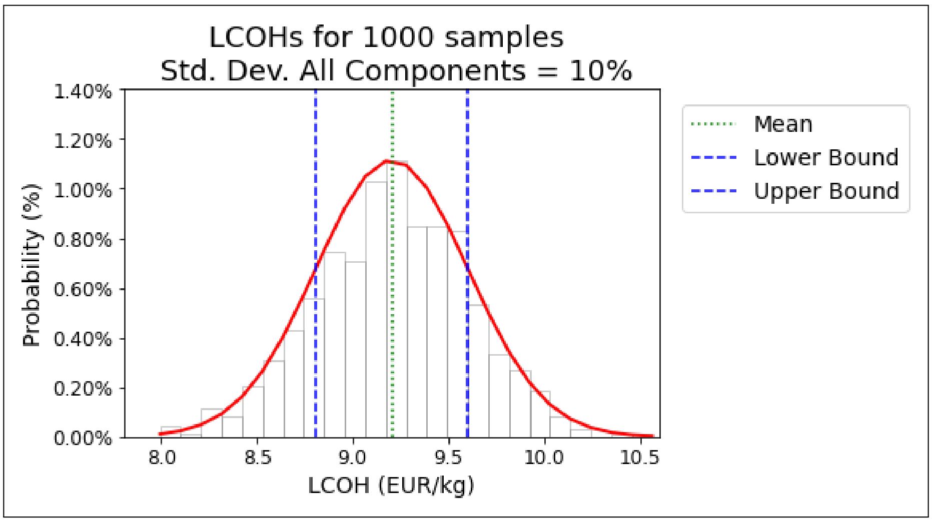

Figure 5.18: Probability density function for the LCOH, using a standard deviation of 10% for all components. For a Gaussian distribution, approximately 67% of the values fall within one standard deviation of the mean (between the bounds), 95% within two standard deviations, and 99.7% within three standard deviations (Raychaudhuri, 2008).

For the sensitivity analysis of the components, the calculated values are summarised in Table 5.4 below. The resulting probability density functions can be found in section C.4. The sensitivity in the last column shows the percentage change in the standard deviation compared to the base case.

Component (standard deviation range)	LCOH - mean	Standard deviation	LCOH range	Sensitivity
All components (10%)	€9.20 / kg	€0.39 / kg	€8.81 - 9.59 / kg	N/A
Foundation & Cables (30%)	€9.23 / kg	€0.72 / kg	€8.51 - 9.95 / kg	+85%
Foundation & Cables (5%)	€9.22 / kg	€0.36 / kg	€8.86 - 9.58 / kg	-8%
Turbines (30%)	€9.23 / kg	€0.87 / kg	€8.36 - 10.10 / kg	+123%
Turbines (5%)	€9.23 / kg	€0.33 / kg	€8.90 - 9.56 / kg	-15%
Electrolysis system (30%)	€9.22 / kg	€0.59 / kg	€8.63 - 9.81 / kg	+51%
Electrolysis system (5%)	€9.22 / kg	€0.37 / kg	€8.85 - 9.59 / kg	-5%
Artificial island (30%)	€9.22 / kg	€0.42 / kg	€8.80 - 9.64 / kg	+8%
Artificial island (5%)	€9.23 / kg	€0.41 / kg	€8.82 - 9.64 / kg	+5%

Table 5.4: Impact results of sensitivity analysis per component, varying the standard deviation range from 30% (uncertain) to 5% (certain). A simulation with all components having a 10% standard deviation serves as a base-case.

For a better analysis, the results in Table 5.4 were visualised using error bars (Figure 5.19) and a different bar chart (Figure 5.20).

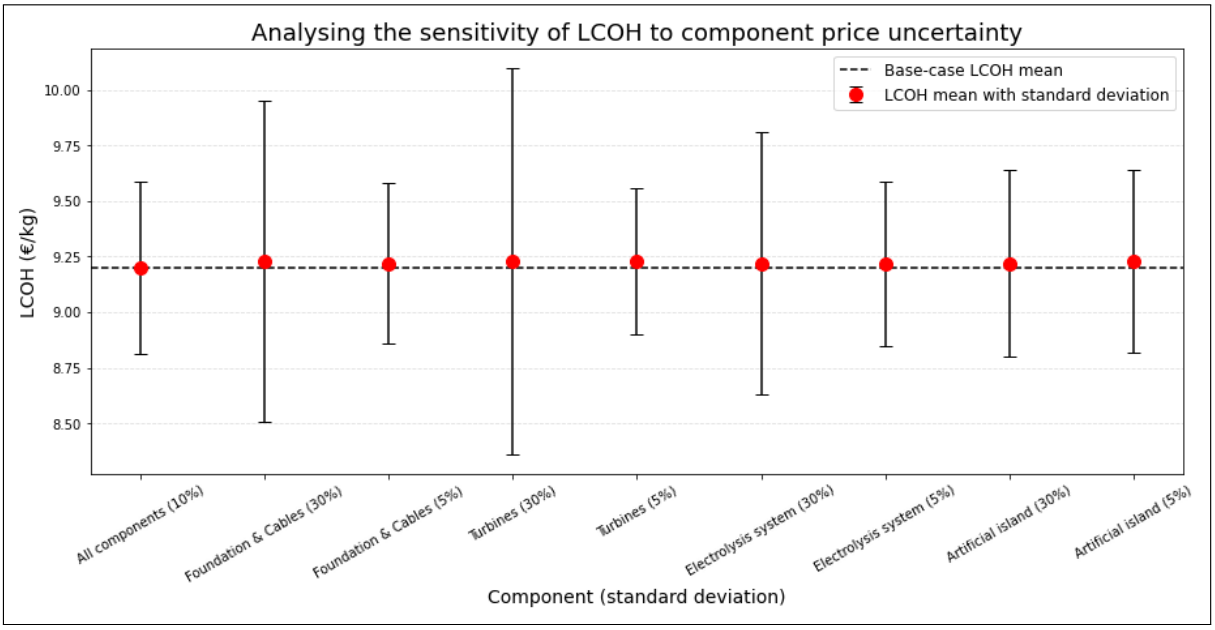

Figure 5.19: Sensitivity analysis of LCOH to component price uncertainty, with error bars representing standard deviations. The base-case LCOH mean is indicated by a dashed line. Component names and their respective standard deviations are shown on the x-axis. Error bars denote the range of component prices that have a 68% chance of occurring.

The sensitivity of LCOH to component price uncertainty varies among the considered components. The LCOH means range from €9.20-9.23/kg across all components, but their standard deviations differ greatly. Turbines and Foundation & Cables components have larger standard deviations, implying that their price uncertainty has a greater influence on overall LCOH uncertainty. However, increasing the standard deviation of a component did not lead to an increase in LCOH. The LCOH increase was expected, as a higher price uncertainty leads to higher risk and higher costs for a project. The stable mean LCOH could be explained by the fact that a full LCOH calculation considers the costs of 15 components. Thus, even if the price uncertainty for a particular component is high, its overall impact on the LCOH may not be as significant as expected, even if it represents a large portion of the total costs.

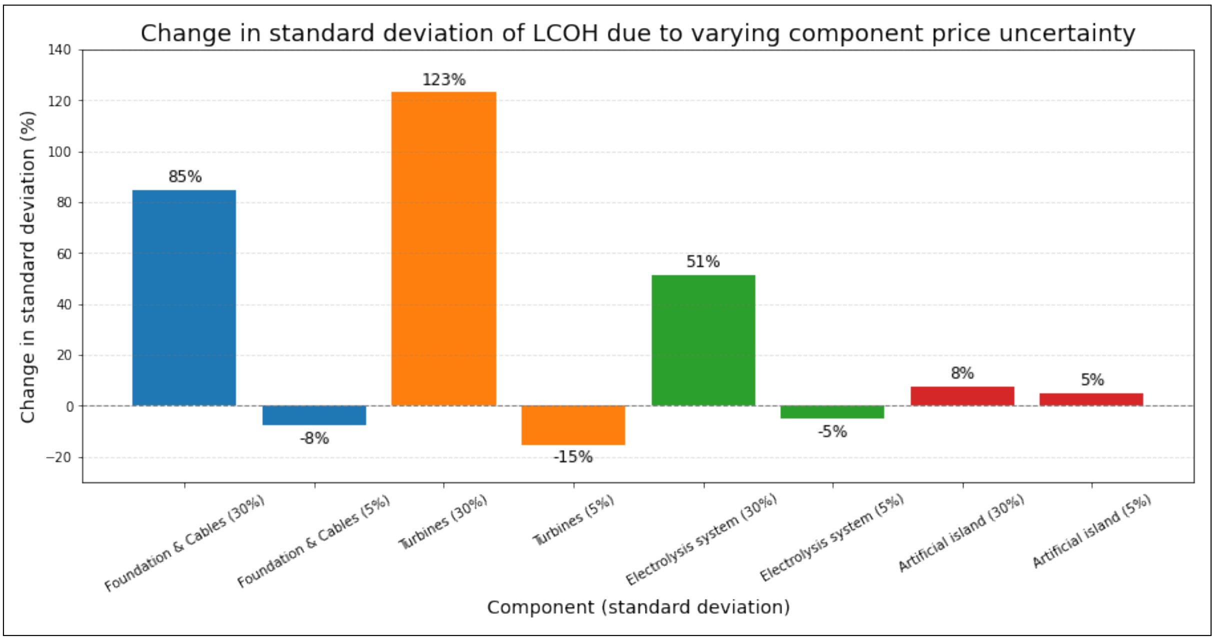

Figure 5.20: Impact of component price uncertainty on LCOH: percentage change in standard deviation from the base case. The bars represent the percentage change in the standard deviation of LCOH for different components at 30% and 5% levels of uncertainty. The base case corresponds to all components having a 10%. Error bars represent the standard deviation of the mean LCOH value.

Figure 5.20 confirms the conclusions that were drawn from Figure 5.19. The percentage change from the base case (all components with 10% price uncertainty) is shown for each component. The chart demonstrates the significant impact of price uncertainty on the LCOH. The Turbines and Foundation & Cables components were found to be the most sensitive, with percentage changes of 123% and 85%, respectively. In contrast, the artificial island component was relatively insensitive to price uncertainty, with percentage changes of only 8% and 5% for 30% and 5% price standard deviations, respectively. An increase in standard deviation had a greater impact compared to a decrease in standard deviation for all components, indicating that the risks associated with price uncertainty are more significant than the potential benefits of price stability. Price stability may have the potential to reduce price uncertainty, which could result in lower project costs and risks. However, in the present case, the impact of price uncertainty on project costs and risks seems to be more substantial than the potential advantages of price stability.

6 Discussion

In this chapter, the most important results obtained in this research are discussed. Then, the limitations of the research and the model are presented. The goal of this research was to develop a comparison method that will be adopted by the industry, which will facilitate greater cooperation between stakeholders within the offshore wind and hydrogen industry. As this research had a defined scope, choices had to be made based on available time and resources. This always results in limitations and uncertainty, due to assumptions. These shortcomings will be addressed in this chapter. It serves as a recommendation to further enhance the comparison method.

6.1. Discussion of Results

6.1.1. Case Study

Pie Charts

The Results section includes pie charts that illustrate the cost breakdown for two different types of supply chains. The findings indicate that Turbines and Foundation & Cables make up the biggest part of the total costs, followed by the costs for Electrolysis. These results are consistent with previous studies that have shown that the costs associated with wind energy and electrolysers are the most significant factors in determining the overall cost of hydrogen production (McDonagh et al., 2020; Singlitico et al., 2021; Taibi et al., 2020). The cost breakdown underscores the need to improve the cost efficiency of electrolysis, especially as the industry for offshore wind parks is already more developed (Berkeley Lab, 2020). Overall, the findings of this study are valuable for informing future decision-making related to hydrogen production and can contribute to the development of a more sustainable and cost-efficient energy system.

Cash Flow Charts

The cash flow charts provide valuable insights into the financial viability of the green hydrogen projects. The results indicate that the timely construction of both wind parks is critical for achieving a shorter payback period and higher final year NPV. Delayed construction can have a significant negative impact on the project's financial performance, as it reduces the time available for generating revenues to recover costs. Moreover, the assumed market prices for electricity and green hydrogen could have an impact on the financial performance of the project. As these prices are based on uncertain assumptions and could change due to various technological, geopolitical, and economic factors, it is essential to consider the sensitivity of the project's financial performance to these changes. Further analysis should be conducted to assess the project's financial viability under different market scenarios and to identify strategies for mitigating risks associated with market uncertainty.

Supply Chain Efficiency and Losses

The analysis of the supply chain efficiencies showed that onshore electrolysis (Scenario 1) has a higher efficiency than offshore electrolysis (Scenario 3) for all cases considered. This result is expected, as for offshore electrolysis the hydrogen has to be transported onshore through pipelines. This is an added source of energy loss, which is not present for onshore electrolysis.

The results also showed that the supply chain efficiency increases when the hydrogen conversion rate decreases. This can again be explained by the energy losses due to the transportation of hydrogen through pipelines. When a larger share of the total generated wind energy is converted into hydrogen, it also means a larger share of that energy is lost due to the hydrogen pipelines. However, it should be noted that these results rely on the assumed efficiency percentages.

Interestingly, the results also showed that the efficiency of the supply chain increases with distance for Case 2b (180 km) compared to Case 1a (100 km). This finding may seem counter-intuitive, as increasing the distance usually leads to higher energy losses. However, this difference can be explained by the different energy conversion rates. It proves the positive influence of a 30% hydrogen conversion rate on the supply chain efficiency.

LCOH

The LCOH is a useful metric to determine the cost-efficiency of a green hydrogen project. It compares all costs allocated to the production and transport of hydrogen over a project's lifetime with the total amount of hydrogen transported onshore. But, without considering energy market prices, the feasibility of a project cannot be determined solely based on the LCOH. However, it is a helpful tool to compare different supply chains in an equal way. The LCOH analysis showed that, based on the assumed prices, onshore electrolysis is more cost-efficient than offshore electrolysis for the considered cases and scenarios. Additionally, a construction delay leads to a higher LCOH, which highlights the influence of this variable.

It is interesting to observe that the LCOH for onshore electrolysis remained constant while the conversion distribution was changed, while for offshore electrolysis, the LCOH was affected. This is due to the fact that the costs associated with hydrogen production and transportation are distributed proportionally for the onshore electrolysis scenarios. However, the artificial island component in offshore electrolysis has a fixed price that changes for both cases, while the other components' prices are based on the wind park capacity and distance offshore (van der Veer et al., 2020). Unlike those components, the artificial island price does not change proportionally with changes in production and costs.

Additionally, the discovery that a lower LCOH was achieved when only 30% of electricity was used for hydrogen production instead of 70% is remarkable. As the conversion rate decreases by 57.14%, the production decreases by 57.14% as well. Due to the assumed decrease in the artificial island price (65.67%, see Figure 6.1) for Case 2a and 2b the total costs decrease by 57.43% instead of 57.14%. This makes sense, as the artificial island requires less space when it is dedicated for only 30% hydrogen production. These findings are relevant for future hydrogen production project design and planning as they suggest that onshore electrolysis and a lower proportion of electricity used for hydrogen production could lead to more cost-efficient projects.

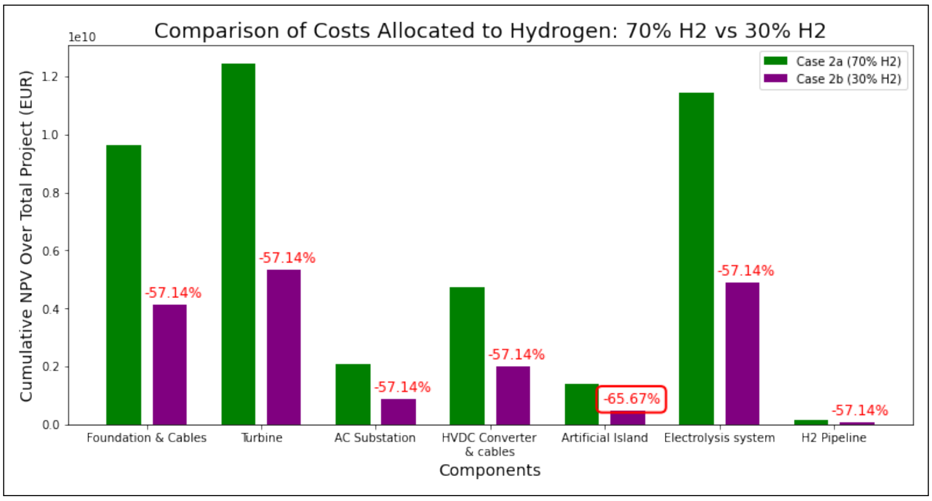

Figure 6.1: Visualisation of costs allocated to the production and transport of hydrogen for Case 2a and 2b

This research aims to model the production and transportation of electricity and hydrogen until they are integrated into the grid. So the model 'stops' where the energy gets onshore. This study has not considered the trade-offs between using hydrogen as a storage medium to generate electricity when electricity prices are higher or selling the hydrogen directly to customers. Customers could be steel factories that use hydrogen as a reductant substitute in their production process (Hoffmann, 2020). If hydrogen is to be produced for the electricity use case, it is important to consider the conversion loss of hydrogen to electricity. It is converted using fuel cells, which have an efficiency of around 50% (Energy Storage Association, 2021). In this research, it was assumed that 50 kWh of electricity is required to produce 1 kg hydrogen (Burton et al., 2021). Subsequently, if the hydrogen would be converted back to electricity, 1 kg hydrogen is assumed to contain 33.3 kWh of useable energy (V. N. Dinh et al., 2021). Taking into account the mentioned fuel cell loss, that means the round trip efficiency of electricity to hydrogen to electricity is less than 30% (50 kWh to 33.3 kWh to 16.7 kWh). For future research, the scope could be extended where the application (e.g. conversion to electricity) of the produced hydrogen would also be considered. In that case, it would be useful to also know the equivalent cost in €/kWh of the hydrogen (that is converted back to electricity at the end) supply chain for direct comparison of feasibility.

LCOE

Similar to the LCOH, the LCOE cannot be used to determine a project's financial feasibility without considering market prices for electricity. The results show that Scenario 4 had a significantly higher LCOE than the other scenarios, suggesting that planned delays in construction can have a negative impact on the overall cost of the project. The comparison between Scenario 2 and 3 shows that building an energy island in the same year as both wind parks is financially more feasible than just two wind parks of which one is built 5 years later, based purely on the price to produce electricity and the electricity production. However, the small differences in LCOE between the scenarios highlight the need for a more comprehensive analysis.

Total Costs and Final-Year NPV

A positive final-year cumulative NPV means that the present value of the cash inflows generated by the project exceeds the present value of the cash outflows (total costs) over the project's lifetime. The analysis of the results has revealed several key factors that influence the NPV of green hydrogen projects.

The time variable does not seem to have a positive influence on the NPV of a project, as a delay in construction consistently results in a lower NPV. Another finding is that increasing the distance and wind park capacity can have a positive effect on the financial feasibility of a project when the majority of the generated energy is used for electricity, but a negative effect when the majority of the generated energy is used for hydrogen.

Furthermore, the conversion distribution of the project plays a crucial role in its financial feasibility. Our analysis revealed that projects where 30% of the electricity is used for hydrogen production result in higher NPV outcomes than those with a 70% hydrogen production. In fact, for offshore electrolysis, the 70% hydrogen production case results in a negative NPV.

It is important to note that the financial feasibility of these projects relies heavily on assumptions made about supply chain costs and energy market prices. As R&D progresses and prices decrease, the feasibility of 70% hydrogen projects may improve in the future (Taibi et al., 2020). Additionally, the capacity of the electrical system to absorb intermittent renewable electricity may become strained, leading to congestion problems. In such cases, converting electricity into hydrogen could help alleviate the strain, but system costs for congestion and potential onshore electrical grid improvements are not currently factored into our analysis.

In a previous study by TNO an economic tipping point was found where hydrogen production seemed economically just preferable at an offshore location (energy island) for a 70% hydrogen conversion case (van der Veer et al., 2020). This shows the importance of having the ability to study alternative concepts in the pre-feasibility stage. It allows stakeholders to get a feel for the viability of different supply chains. The reason for the difference in results between the previous study by TNO and this research is that TNO provided a more detailed techno-economic analysis of the supply chain components. However, this research aimed to develop a standardised and transparent model that could facilitate discussions about green hydrogen options, rather than to achieve maximal accuracy. Consequently, certain costs were simplified in this model, which will be further discussed in subsection 6.2.2.

However, this highlights the importance of a thorough techno-economic analysis. The tipping point for offshore hydrogen production is largely determined by component prices such as those of the artificial island. Ultimately, a detailed technical analysis is needed to determine the correct prices and ensure optimal analysis of the financial feasibility.

6.1.2. Sensitivity Analysis

The results of the sensitivity analysis show that the uncertainty in component prices can have a significant impact on the LCOH of a project. The Turbines and Foundation & Cables components have a higher impact on the overall LCOH uncertainty due to their larger standard deviations. However, the impact of a single component on the overall LCOH calculation may be diluted by the other components with lower standard deviations.

Furthermore, it was unexpected that increasing the standard deviation of a component did not necessarily lead to an increase in LCOH. This may be explained by the fact that the overall impact of a component's price uncertainty on LCOH may be dampened by the other components costs. Nonetheless, the uncertainty of the LCOH value increases, making it harder to estimate the costs and thus LCOH of a project accurately. As such, it is important to consider the potential price uncertainty of all components when calculating LCOH to obtain reliable cost estimates.

It was expected that price stability (smaller standard deviation) may have the potential to reduce price uncertainty, resulting in lower project costs. However, in the present case, the impact of price uncertainty on project costs seems to be more substantial than the potential advantages of price stability.

The study's assumption of exact and constant energy production may have influenced the results, as the LCOH is the total costs divided by the energy production. In reality, energy production may vary due to several sources of uncertainty, such as sensor accuracy, uncertainty due to power curve, uncertainty due to electrical losses, and uncertainty due to wind availability (Lira, 2014). This is further discussed in section 6.2.

The sensitivity analysis results indicate that focusing on the Electrolysis System component may be effective to reduce the total costs of a project. Although the Turbines and Foundation & Cables components were found to be the most sensitive, there are more beneficial opportunities for cost reduction in the Electrolysis System. The offshore wind energy industry has become a mature technology, with prices declining but not as rapidly as for a new technology (Berkeley Lab, 2020). This is not the case for electrolysis, which is a relatively young technology with significant potential for rapid price decreases due to technological advancements and economies of scale (Taibi et al., 2020).

6.2. Limitations

6.2.1. Interviews

All interviews were conducted before or during the setup of the model. The aim was to learn more about the stakeholders' views on the market, their objectives for using the comparison model, and their willingness to contribute to the setup of it (e.g. data sharing). There are some shortcomings, which could be focused on to further improve the model and which could hopefully lead to industry-wide adoption and validation.

The first one is the number of conducted interviews. As mentioned in both subsection 1.1.2 and section 3.3, 10 stakeholder categories were defined. In light of available time, the goal was to interview only one stakeholder per category. In the end, 13 stakeholders were interviewed with some categories having more interviewees. To achieve industry-wide adoption, more stakeholders should be interviewed to learn about their views and desires. This will improve the scientific value of the conclusions drawn. Further, and more importantly, this will provide a better understanding of the offshore wind and hydrogen market and their desires for a comparison model.

If more interviews will be conducted, it would be valuable to focus on speaking with suppliers. Organising interviews with suppliers appeared to be more challenging than with other stakeholders. Governmental organisations, on the other hand, support an open discussion to accelerate the energy transition and were enthusiastic to help with the research. The suppliers' unwillingness could be due to the high level of competition in the offshore wind and hydrogen market. It is a rapidly developing market, where many opportunities arise. With the rapid development also comes a lot of uncertainty. Uncertainty around technologies and uncertainty around prices. Therefore, it seems that suppliers prefer keeping their cards close to their chests. However, the contribution to or validation of the model by the suppliers is necessary to achieve industry-wide adoption, as they are aware of the exact price assumptions of the supply chain. But, from the number of suppliers that were interviewed, it became clear that they are not willing to share these. For interviews, it would be good to focus on the verification of price ranges. Most suppliers seemed to be comfortable with contributing to the model in that way.

In addition, during the conducted interviews the model was still under development. In most interviews, a presentation showing the concept of the model was shared and in later interviews, the first Excel version was shown. The focus was to learn more about the stakeholders' desires for a comparison model. However, as we now have a functioning Python model which is able to calculate reasonable values for various projects, new interviews could be conducted. The goal of these should be to gather feedback by presenting the functioning model, or by first letting the stakeholders use the model. With this feedback, the model could be further developed and improved.

Implementation of Stakeholders' Desires

One of the results of the stakeholder interviews was a better understanding of their desires for a comparison model. Now, at the end of the research, the discussion is used to reflect on these and to analyse which of them have been implemented in this research' model.

#	Desire	Implemented in Model?
1	Transparency about model's assumptions	Yes
2	Insight into the element structure of different supply chains	Yes
3	Evaluate costs of energy production	Yes
4	Compare the costs and financial feasibility of different supply chains	Yes
5	Compare the efficiency of different supply chains	Yes
6	Compare the energy production of different supply chains	Yes
7	Hide stakeholder's input data for other users	No
8	Evaluate the environmental impact of the project through geospatial data	No
9	Cost data (e.g. price ranges) validated by stakeholders	No
10	Insight into the sensitivity of parameters through Monte Carlo analysis	Yes
11	Model set up independent of companies active in the industry	No
12	Model tested and validated by independent experts	No
13	Dynamic energy market prices	No
14	Dynamic supply chain element prices	No

Table 6.1: Overview of stakeholders' desires resulting from the interviews and whether they are implemented in the model

For the discussion, we focus on the desires that were not implemented. These desires were mentioned that were not implemented, either due to time or technical capacity constraints. The ability for a stakeholder to hide their input data for other users (#7) is not realised yet. However, stakeholders can download the model's notebook and work in their own version without other users seeing their changes. They could then share the results of the model when they use their own input data. In the future, the goal is to have a model that multiple users can work in simultaneously without seeing other stakeholders' confidential data. The other desires that were not implemented will be further discussed in subsection 6.2.2, as they can be seen as shortcomings of the current model.

6.2.2. Model

As the model was built to focus on the pre-feasibility stage of a project (see Scope - section 1.4), it was not required to provide a 100% accurate representation of the reality. A reality that is also difficult to represent, as it is so far ahead in the future. Therefore, assumptions were made to simplify the development and functionality of the model. However, it is good to be aware of these assumptions and the uncertainties that come with them. In this section, we evaluate the limitations of the model and the implications of the various assumptions underlying the model.

Price Uncertainty

The biggest assumptions behind the model with the largest influence on the results are the prices of the supply chains' assets. The assumed prices are based on publicly available research (section B.2) and were validated by a cost estimator of Van Oord. However, these prices will never be 100% similar to the prices used in the actual industry due to the confidentiality around pricing. A suggestion by stakeholders to overcome this was to let suppliers verify price ranges. This was not done for this research and serves as a recommendation for further improvement of the model. As we are looking at the pre-feasibility stage of projects, the impact of this uncertainty is moderate, but it is good to be aware of it. However, for the financial feasibility calculations in subsection 5.2.2, the prices were assumed to be exact and without a standard deviation. In other words, without taking into account the price uncertainty. Therefore, it is important to realise that to improve the reliability of the model it would be more realistic to perform all financial feasibility calculations with Monte Carlo simulations. As demonstrated in section 5.3, this allows you to gather price ranges instead of exact values.

When determining the financial feasibility through Monte Carlo simulations, a challenge is choosing the standard deviations of the cost components. For the uncertainty analysis, a base case was defined in which all components were assumed to have a 10% standard deviation. This simplification was chosen, because the actual standard deviations of the prices were unknown and retrieving more accurate values would be time-consuming. For further improvement of the model, a method suggested in previous research could be used to define the standard deviations more accurately (Galway, 2007). It proposed the following method when determining the probability distributions for new and untried technologies:

1. Define a group of multiple independent experts, that are willing to help.
2. Request each expert to provide a minimum, upper, lower, and most-likely value for the cost elements under consideration.
3. Create a simplified distribution for these three numbers, using the upper and lower values provided by each expert to bound 90% of the probability (when reasonable - to account for known biases in the obtained expert values).
4. Besides the upper, lower, and most-likely values, acquire at least two more percentiles (such as the 25th and 75th, as suggested by most current authors).
5. Use these values to calculate a range of total costs with nonzero probability, the median estimated cost, and the probability that the final cost will surpass the most-likely cost. Share these results with the experts, and allow them to use this feedback to adjust their provided values.
6. Carefully document the process and results and archive the data for future retrospective studies.

When the expert values are known, a distribution that could be used for further analysis is the PERT distribution (Onnen, 2021). With more accurate distributions, the Monte Carlo simulations will become more realistic. This is valuable for two reasons. First, it allows for a better understanding of the probability of the financial feasibility of projects. Second, it allows for a more accurate sensitivity analysis. To get closer to the integration of green hydrogen in the energy system, it is important to focus on technologies where there is much to gain in terms of innovation, but above all in terms of impact on the final hydrogen price.

Another option could be the use of price scenarios for supply chain components. The cost estimates for hydrogen rely on various factors, of which Capex prices have a large influence. Many technologies within the hydrogen value chain are undergoing development, innovation, and scaling up, which could lead to a reduction in Capex (economies of scale) and an increase in efficiency (Taibi et al., 2020). Furthermore, prices can also increase due to material scarcity, for example (Bettoli et al., 2023). Based on that, it is unrealistic to assume that the considered prices stay constant over the project's lifetime. It is therefore also unrealistic to assume that the model is able to calculate an exact LCOH value for a 30-year-long energy project.

To improve the model, these price developments should be considered. Implementing such price scenarios into the model would allow the users to get a better view of the financial feasibility of a project, as it will be closer to reality. Furthermore, by considering both optimistic and pessimistic scenarios, financial risks could be mitigated.

Discount Rate and Escalation

In the model, the discount rate was assumed to be equal to the weighted average cost of capital (WACC). This WACC was calculated using MTBS' method and was set to be 9.84%. One of the parameters defining the WACC is the 'Unlevered Beta', which measures the market risk for a company based on the industry it operates in (NYU Stern, 2023). For this model, the chosen industry was 'Green & Renewable Energy'. However, as the model is used to study the feasibility of a full project, multiple companies (e.g. grid operators, wind farm operators, energy suppliers, constructors, etc.) are involved. Even though they operate in the 'Green & Renewable Energy' industry, they might have their own WACC based on their acceptable risk profile. If it turns out that for one of the stakeholders, the business case, using one WACC, is unfavourable, that stakeholder might withdraw from the project. It would therefore be more realistic to assume a different WACC for every stakeholder or stakeholder category. This comes with a challenge. As the WACC is used to calculate the NPV of the cash flows (see section 4.1), all cash flows should be allocated to the right stakeholder or stakeholder category to use the right WACC. This could be complicated. It was also assumed that the WACC is constant over the project's lifetime. However, the WACC is calculated with daily fluctuating parameters, such as the nominal risk-free rate (Bloomberg, 2023). It will therefore not stay the same value.

The escalation (inflation) rate was assumed to be 2%, based on the escalation target of the European Central Bank (ECB) (European Central Bank, 2021). But, in reality, this rate is not constant (Kuttner et al., 2022). As can be seen in Figure 6.2, this number fluctuates over time. However, the figure also shows that it is difficult to predict the escalation rate. For future model improvement, it could be considered to implement a dynamic escalation rate based on historical data. Even though it is unclear how big the added value would be to the accuracy of the model, it is important to be aware of the uncertainty of the results that come with this assumption.

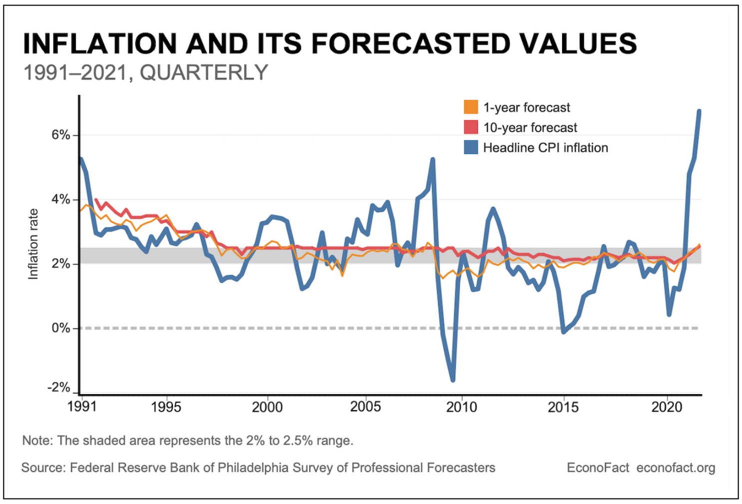

Figure 6.2: Visualisation of historical escalation data and its forecasted values in the United States (Kuttner et al., 2022)

Energy Production and Efficiency

The generated wind energy is assumed to be constant over the project's lifetime in this model. It is calculated by multiplying the wind park capacity by the number of operational hours (4380 hours), which assumes the wind park to be generating energy for 50% of the year. The constant wind speed was based on previous research, where the same was assumed (IRENA, 2019; Kopp et al., 2017; Lappalainen, 2019; Rezaei et al., 2020). However, this method does not take into account factors, such as air density, wind velocity, blade aerodynamic efficiency, and rotor swept area - which some research does (Yan et al., 2021). Other research used real historic wind speed data to calculate the NPV of an offshore wind park (McDonagh et al., 2020). The assumed formula in this model most probably overestimates the annual energy production of the wind parks. The global availability of wind energy is not uniform and fluctuates over time (Figure 6.3), both on a seasonal and daily basis. Not only does the wind speed, and thus the generated energy, fluctuate over time, but also does it fluctuate over space (Manwell et al., 2010). Figure 6.4 shows the dependency of wind speed on local topographical variations. The graph displays the mean wind speeds for two parks 21 km apart. The five-year average mean wind speeds differ by about 10%.

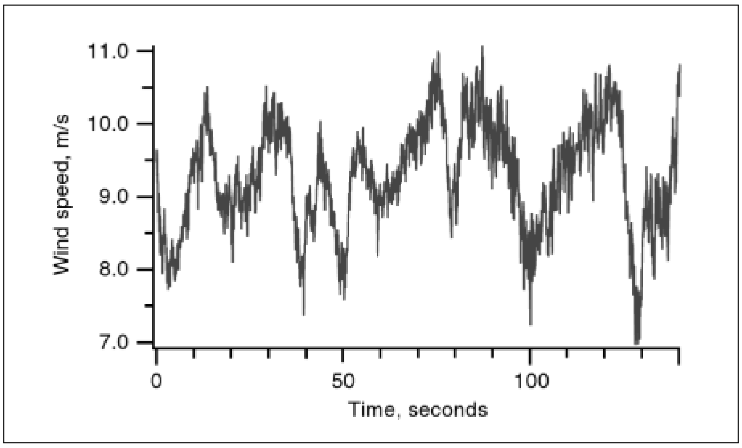

Figure 6.3: Typical plot of wind speed vs. time for a short period (Manwell et al., 2010)

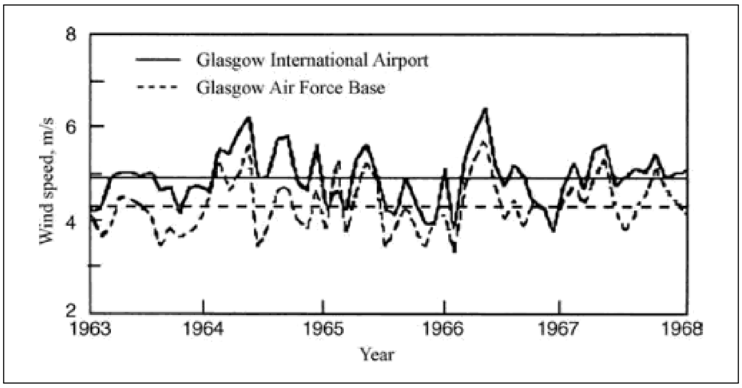

Figure 6.4: Time series of monthly wind speeds for two wind parks 21 km apart (Manwell et al., 2010)

The possible overestimation of energy production in this research could result in marked financial implications, as the predicted revenue cash flows might be too optimistic. For improvement of the model, wind speed data should be used. Using that data, the power production from a wind park can be predicted by three methods: (i) fundamental equations that calculate the available power in the wind, (ii) presumed power curves based on the wind turbine's design, or (iii) actual power curves provided by the manufacturer of the wind turbine (V. N. Dinh et al., 2021).

The produced or generated energy by the wind park does not equal the transport energy onshore. In the model, the produced wind energy is multiplied by a number of efficiency factors per element of the supply chain, such as the cables. These efficiencies are assumed to be constant percentages. Even though the efficiency of the HVDC cables is approximated with a formula where the efficiency is linear to the distance, there are more factors in play. The power loss also depends on the amount of power flowing through the cable and the temperature, among others (Eeckhout et al., 2009). Furthermore, technological developments and innovation are expected to have a positive effect on efficiency. This is not only the case for cables and pipelines, but also for other assets, such as the electrolyser and DCAC converter (Burton et al., 2021; Lee et al., 2012). For these two reasons, it is unrealistic to assume that this efficiency is constant over the project's lifetime. Similar to the asset price scenarios, a study could be done into potential developments of the supply chain efficiency and define certain scenarios that can be used in the model.

Finally, the assumed energy prices are a source of uncertainty. In Table 4.3 it was described how these prices were determined. As electricity is sold on the spot market and green hydrogen not (yet), the first might pose less uncertainty than the second. However, the assumption that both prices are constant over the project's lifetime is unrealistic (European Union, 2022). Energy prices do not only fluctuate due to supply and demand, but also due to geopolitical events, weather conditions, and government policies (Agnello et al., 2020; Jiang & Tan, 2013; Li et al., 2021; Saidur et al., 2010). Figure 6.5 displays this volatility.

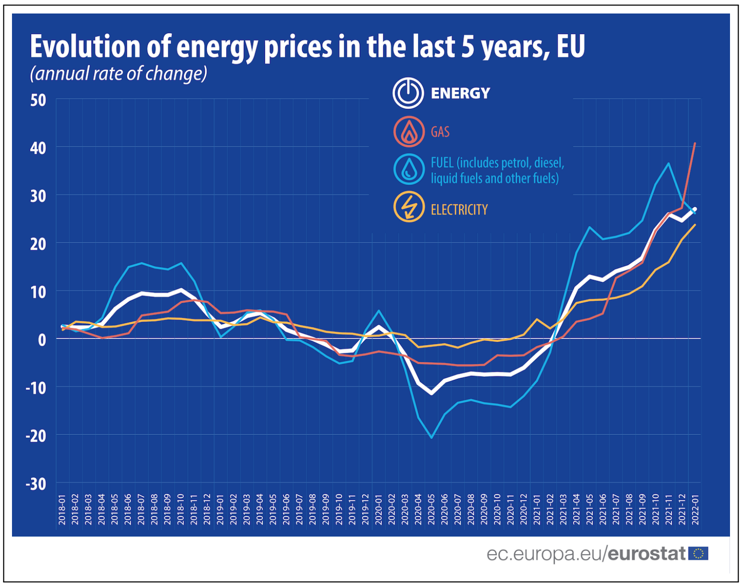

Figure 6.5: Annual rate of change of energy prices in the last 5 years in Europe (European Union, 2022)

Because of the uncertainty around energy prices, it is also difficult to forecast these. A study was performed into the use of machine learning to long-term forecast energy prices, which outperformed econometric methods (Herrera et al., 2019). For future improvement of the model, the implementation of dynamic prices should be considered. This is something that was also mentioned by stakeholders in the interviews. As described in section 4.3, Python offers useful tools for that (Dimitriosroussis, 2021; J. A. Rodrigo & Ortiz, 2021). However, as the green hydrogen market is immature, it will be difficult to forecast these dynamic prices. A simplified approach could be the definition of price scenarios, e.g. an optimistic one, a moderate one, and a pessimistic one.

Geospatial Data

The only geospatial parameters the current Python model considers are: distance wind park - HVDC converter, distance wind park - artificial island, distance HVDC converter - shore, and distance artificial island - shore. These distances are assumed to be a straight line. The model could be further improved by integrating actual geospatial data, which possibility Python offers (Prapas, n.d.). A geospatial analysis could be done, such as assessing the environmental and ecological impact of a project and determining the hydraulic and meteorological influence on a project. According to the EU Nature Directives, for a wind farm in or near Natura 2000 areas, developers are required to investigate whether there is a significant effect of the project on the ecology in that area (European Commission, 2020a). The governmental organisations that were interviewed also mentioned that the ecological impact of a project is a factor determining the winner of an offshore wind tender. The purpose of Natura 2000 is to establish a network of protected areas that will ensure the preservation of Europe's most valuable habitats and species. Data sets providing the exact locations of these areas can be found online, which could be integrated into the model (StraTopo, 2023). Hydraulic data could be integrated to assess the effect of water depth, currents, and waves on certain structures, which could require extra investments (e.g. breakwater reinforcement for artificial island). Finally, the meteorological impact on a project could be especially useful for obtaining more accurate estimations of the energy production. With the Meteostat package, it is possible to obtain historical weather and climate data, including wind speed and direction, for any geographical location (Lamprecht, 2021).

Supply Chain Scope

The scope of this thesis (section 1.4) described that the research would focus on establishing a model that can be used to compare greenfield offshore wind to hydrogen concepts that are feasible on the North Sea. Greenfield means that nothing has been built yet, and no existing assets or infrastructure can be used. Recently, studies have been commissioned or done by gas pipeline operators into the development of a European hydrogen pipeline network (GASCADE, 2023; Gasunie, 2022). If developed, the network could be ready by 2030. The model could be extended by adding the option of considering existing infrastructure in the calculations.

For the offshore energy hub, the only considered option was an artificial sandy island. However, other possibilities are the construction of a large offshore platform or a caisson island. Research into the comparison of these options has been done, but to improve the model the caisson island and platform could be added as an alternative to the artificial island (NSWPH, 2021). Further, the model now assumed the hydrogen to be transported onshore through a hydrogen pipeline, but adding other transportation options such as ships could also extend the model.

It was assumed that all wind energy used for electrolysis comes from offshore wind parks. Based on the financial analyses with the Python model, it became clear that the offshore wind park accounts for almost 50% of the total cost of a project. The model could be improved by integrating the option of using curtailed energy to produce hydrogen. When wind parks generate more energy than the electricity grid can handle, the operators must curtail that energy. Hydrogen is considered a means of capturing that lost energy. The price for the curtailed energy is assumed to be (close to) zero (Chandrasekar et al., 2021).

Model Validation

The model was validated by using input data from two research papers and comparing the calculated LCOH with that in the papers. Furthermore, it was validated using data provided by Van Oord about a real-life offshore wind park case. See section 4.8. These were simple cases, but serve the purpose of this research.
It was mentioned by multiple stakeholders in the interviews, that the reliability of the model could be increased if it would be validated by an external party. Therefore, to further improve the model's adoption, independent experts, companies, or consultancy firms should check and validate the model.

In addition, MTBS and Van Oord were involved with the supervision of the setup of the model. For further development, an independent research institute or governmental organisation should take over the supervision. This organisation will be the designated owner responsible for maintaining and updating the model on behalf of the industry. This party could also be responsible for maintaining unit tests during further development of the model.

7 Conclusion & Recommendations

This chapter presents the conclusion of the research by answering all research questions presented in section 1.5. Subsequently, recommendations for future research are shared.

7.1. Conclusion

This research aims at developing a standardised analytical model to compare alternative offshore wind to hydrogen concepts, which will be used and trusted by various stakeholders in the industry. The goal of such a model would be to improve cooperation between parties working on the energy transition. By systematically and transparently quantifying various offshore wind to hydrogen concepts and the influence of the components on the final energy price more insight could be provided, which currently seems to be lacking.
First, the sub-questions will be answered after which the main research question will be answered.

7.1.1. Understanding Desired Functionalities of Comparison Model

What critical aspects do stakeholders involved in the energy transition believe a comparison model could help to better understand, and how can the development of such a model facilitate discussions among these stakeholders towards identifying the most feasible solutions?

For the interviewed stakeholders, a comparison model would be most helpful to gain a better understanding of the technical and financial structure of future offshore wind to hydrogen concepts. As the green hydrogen market industry is still under development and only a number of pilots have been realised, both technical and financial knowledge are lacking about the possible supply chains to convert wind energy to hydrogen ("Pilots met waterstof", 2022). A comparison model could have an educational purpose here, as it presents the structure of various concepts and their total costs separated per supply chain component. This way, stakeholders could learn more about the effect of a component on the overall costs and feasibility of a project. Even though future prices are uncertain, which is a concern shared by all stakeholders, the model could help to increase the conceptual understanding of the most feasible options.

All stakeholders envision big opportunities for the Dutch hydrogen market, but this comes with competition. It can be concluded that the competitive level and lack of understanding of the market make stakeholders cautious to have an open discussion. Stakeholders use their own comparison models based on in-house assumptions. Chances are that these models all consider different components and financial assumptions to calculate the total costs and LCOH of projects. Even though the stakeholders are aware that cooperation is required to accelerate the energy transition, there is a mismatch in trust and used methodology. Furthermore, each stakeholder has distinct objectives and concerns. A comparison model could facilitate this cooperation by serving as a neutral tool to compare concepts together. The goal of this model is to bridge the different interests of the stakeholders. It could help stakeholders gain insight into their and others' roles in the larger energy system. Furthermore, a standardised model could serve as a benchmark for existing in-house comparison models.

To conclude, a comparison model could help stakeholders to better understand possible offshore wind to hydrogen concepts, and the effect of components' prices on the total cost of a project. Finally, it could serve as a standardised method, which allows stakeholders to compare supply chain options using an unbiased model. This will facilitate discussions towards identifying the most feasible solutions.

7.1.2. Incentivising Stakeholder Use and Contribution

How can the model be developed in a way that incentivises stakeholders to both use and contribute to the model? What are the key factors that influence stakeholder willingness to contribute, and what measures can be taken to address potential barriers to contribution?

Stakeholders desire a transparent model that helps them understand the financial impact of components on the total costs and LCOH of various supply chains. A standardised financial methodology is essential as it is currently lacking, which came across from the reviewed literature (Table 1.1). Further, the methodology for valuations and energy production calculations must be clear. Capex and Opex, as well as their associated cost items, must also be transparent. Assumed prices for all components of the supply chain must be defined and transparent. Stakeholders are less inclined to use the model when these underlying assumptions are hidden since they will perceive the results as biased. A ”standard” case is created by making the starting set of values clear and the same for everyone. Stakeholders can then change the prices they are responsible for, allowing them to see how much total cost increase or decrease they can achieve compared to ”the standard.” This facilitates an open and fair discussion. Further, it is crucial that the entered values are not visible to other users due to the competitive character of the market.

To increase the model's reliability, stakeholders require an independent model that is not created by a single company. Currently, the model is supervised by MTBS and Van Oord. Testing and validating the model by independent experts would be the suggested first step to increasing reliability. But for further development, an independent research institute or governmental organisation should take over the supervision. This organisation will be the designated owner responsible for maintaining and updating the model on behalf of the industry.

According to the interviews conducted, it may be challenging to get stakeholders to contribute to the model. Sharing of price data by suppliers is the main contribution required. Most stakeholders accept publicly available data, but more precise values would enhance the model's reliability. However, suppliers are not willing to share cost data due to the early stage of the technologies, making it difficult to provide accurate price predictions. There is also a fear of sharing knowledge with competitors. One way stakeholders can contribute is by setting up price ranges based on public sources and letting relevant stakeholders verify them. To conclude, at this stage, prioritising stakeholder adoption over contribution may be more valuable.

7.1.3. Developing the Comparison Model

What is the current method for assessing the financial feasibility of offshore energy supply chain elements, and how can these separate elements be effectively integrated into a cohesive system view?

The current method for assessing the financial feasibility of offshore energy supply chain elements involves techno-economic analyses using LCOH and NPV measures (section 1.3). However, there is no standardised calculation method (see Table 1.1), which poses a challenge for stakeholders in the industry. MTBS, a financial feasibility expert in the maritime sector, uses the discounted cash flow method to evaluate the Capex and Opex cashflows of separate elements in a supply chain and calculate the summed NPV. This method allows for the effective integration of separate supply chain elements' costs into a cohesive system view using Excel. Although assumptions are made (section 4.3), such as an equal discount rate for all cashflows, this approach offers a practical solution to analyse larger projects or supply chains.

7.1.4. Improving the Current Method

What are the limitations of the current method in answering the questions of parties involved in the energy transition, and how can the method be extended to address these limitations and provide a more comprehensive analysis?

Reliability of the comparison model is crucial for industry-wide adoption, and transparency is key to achieving it. However, the current method seems to be lacking here. Excel sheets can be large and complex, making it challenging for users to comprehend the underlying assumptions and calculations that generate the results.

In addition, comprehensive and informed decision-making is essential for the ongoing energy transition, which cannot rely solely on financial analysis. Stakeholder interviews revealed that decisions require various perspectives, including meteorological, ecological, and hydraulic circumstances. Furthermore, probabilistic analyses are necessary to understand the impact of project components on the project's feasibility. Excel's functionalities are limited in this regard.

To address these limitations, an improved model was created using Python. It should be noted that Python notebooks may not be easily understood by everyone, and coding can be complicated. Nonetheless, when people understand coding, the written code is clear. This results in a transparent model. Unit testing allowed for an iterative setup of the model, ensuring that it reproduced the Excel model's results. Additionally, Python offers tools for working with spatial data and performing probabilistic calculations, enabling users to conduct more complex analyses.

To improve the transparency of the model's results, a standard notation system was developed. The system clearly communicates underlying assumptions, such as financial considerations, energy conversion rate, and project duration, which were previously lacking and made it difficult to interpret LCOH studies (Table 1.1). The notation system facilitates comparisons between different concepts, enabling users to easily identify similarities and differences.

In what respect has extending the method improved our ability to better understand the financial feasibility of various offshore wind to hydrogen chains?

The improved model, which uses Python, has added significant value to our ability to better understand the financial feasibility of various offshore wind to hydrogen chains. It has allowed us to add supply chain elements more easily, resulting in the analysis of more complex supply chains, including those involving energy islands (section 5.3). This was a challenge with the previous Excel model which required more work to add new elements and increased the risk of errors. Python has offered a better overview and debugging, reducing the risk of errors and enhancing the reliability of the results. Furthermore, using Python, we were able to study other variables, such as time, with greater ease. Something which had not been done before in previous studies. This provided us with a clear analysis of the impact of planned construction delays on a project's feasibility.

The improved model also enabled us to handle large data sets and complex calculations more efficiently, making it easier to perform Monte Carlo simulations. This allowed us to conduct sensitivity analyses (section 5.3) that assessed the impact of specific component prices on the LCOH - a desire that was mentioned by stakeholders in the interviews. Through Monte Carlo simulations, we can now provide ranges and probabilities for the LCOH, LCOE, and total costs providing more reliable feasibility analyses than when a specific value is calculated.

Overall, our experience was that the added value of the improved model using Python is that it offers greater flexibility and analytical power, providing a more comprehensive understanding of the financial feasibility of various offshore wind to hydrogen chains.

7.1.5. Enhancing the Comparison Model and Facilitating Greater Cooperation

How can we further enhance the comparison model and facilitate greater cooperation between stakeholders within the offshore wind and hydrogen industry?

There are several ways to enhance the comparison method and promote greater cooperation among stakeholders in the offshore wind and hydrogen industries. First, to increase the model's accuracy and reliability, it is recommended to use verified price ranges. Additionally, implementing a WACC per stakeholder would provide a more realistic representation of the project's financial situation.

Second, incorporating geospatial data is necessary to provide an accurate and realistic approximation of the costs and revenues of a project, which can be achieved by considering hydraulic and meteorological data. Geospatial analysis can also help users evaluate the ecological impact of a project, which is important for the governmental bodies that judge project tender submissions. By building the model in Python, we have established a foundation for a model that is both scalable and easily expandable.

In addition, to help stakeholders anticipate potential changes in the industry and simulate different market conditions, it is essential to include price scenarios for energy and assets in the model. Finally, external validation of the model is necessary to increase its credibility and promote its adoption across the industry. This will enable stakeholders to make well-informed decisions based on the model's results.

By implementing these enhancements, the comparison method can become a more valuable tool for stakeholders in the offshore wind and hydrogen industries. This can lead to greater collaboration, more accurate financial assessments, and a more sustainable energy future.

7.1.6. Main Research Question

How can you develop a standardised comparison model to compare alternative offshore wind to hydrogen concepts to improve cooperation between parties working on the energy transition? And what is required to obtain industry validation and promote widespread adoption of the model among key stakeholders?

This research aims to develop a standardised comparison model for the comprehensive evaluation of offshore wind to hydrogen concepts using the LCOH method. The LCOH is the most common method used to compare hydrogen concepts, but discrepancies exist due to variations in assumptions. While some researchers attempted to develop models for the techno-economic evaluation of offshore wind to hydrogen concepts, these models did not consider stakeholder adoption and contribution (V. N. Dinh et al., 2021; Yan et al., 2021).

This study addressed these gaps by building an improved model using Python and focusing on developing an open-source software tool. The model's assumptions are clear, and it can be easily used by stakeholders. The research identified the stakeholders' desires for the model's reliability, transparency, and user-friendliness, which were addressed in the development process. A consistent and transparent methodology was adopted for calculating cost measures, and a standard notation system was implemented for increased transparency and standardisation. The model's limitations were addressed, and future improvements were suggested, such as using verified price ranges and incorporating geospatial data. Implementing these suggestions will promote adoption by key stakeholders.

The potential impact of this work is significant, as it addresses current challenges hindering the cooperation between parties working on the energy transition. Without cooperation, there is a risk of misusing substantial financial resources on inappropriate infrastructure in unsuitable locations. This would also result in the wasteful utilisation of an even scarcer resource: time. Industry validation and refinement through stakeholder feedback will help establish the model as a reliable and widely accepted tool for better decision-making in the green hydrogen industry.
It is time for the industry to come together and take action towards a sustainable future, and this research offers a crucial first step towards achieving that goal.

7.2. Research Recommendations

This research has established a model that allows users to compare the financial feasibility of offshore wind to hydrogen concepts. Furthermore, the requirements have been studied for industry-wide adoption and validation of the model. In chapter 6, the model's assumptions and uncertainty were discussed. This section summarises the recommendations for possible future research:

1. Investigating accurate price data and defining potential price scenarios
   - Approach: Conduct interviews with suppliers to gather more accurate data on price data. Price ranges can be suggested based on public research. Use the interviews to validate and refine these price ranges. According to the interviews conducted, most suppliers appeared to be comfortable contributing in this manner. Simultaneously, study the drivers of potential price developments, such as material scarcity and technological advancements. Based on this, price scenarios can be developed to understand their potential impact on the financial feasibility of a project.
2. Further research into more accurate wind data and its influence on the energy production
   - Approach: To retrieve more accurate wind estimates, factors such as air density, wind velocity, blade aerodynamic efficiency, and rotor swept area could be taken into account (Yan et al., 2021). A second option is using real historic wind speed data (McDonagh et al., 2020). Thirdly, the power production can be estimated using power curves, either presumed and based on the wind turbine's design or provided by the manufacturer of the wind turbine (V. N. Dinh et al., 2021). Finally, a study could be done to study the uncertainty of wind speed. By incorporating these findings into the model, more accurate estimates of the energy production can be made, resulting in a more accurate financial feasibility analysis.
3. Assessing the financial feasibility of offshore wind to hydrogen projects using existing infrastructure, including curtailed energy utilisation
   - Approach: Research has been done into the development of a hydrogen pipeline network and into the use of existing gas pipelines for hydrogen transport (GASCADE, 2023; Gasunie, 2022; Kanellopoulos et al., 2022). Further research should be done into the viability of using these, but also into the viability of reusing other elements such as existing platforms. It is valuable to analyse the influence on the financial feasibility and potential challenges associated with integrating offshore wind to hydrogen projects into the existing infrastructure. Additionally, the research should consider the utilisation of curtailed energy as ”existing infrastructure”. When wind parks generate more energy than the grid can handle, operators must curtail that energy. Hydrogen is a means of capturing that lost energy. As the price for curtailed energy is assumed to be close to zero and no wind parks will have to be built, this could result in an optimistic business case (Chandrasekar et al., 2021). The use of vessels for transporting hydrogen onshore can also be explored as part of the existing infrastructure, as it may provide more financial feasibility and easier access to areas with higher demand.
4. Investigating trade-offs between using hydrogen as a storage medium for electricity generation and selling hydrogen directly to customers
   - Approach: study the energy efficiency and financial feasibility of both hydrogen business cases, using the Python model by extending the supply chain scope. When hydrogen is used as a storage medium and is converted back to electricity, it loses around 50% of its energy due to the efficiency of the conversion process (Energy Storage Association, 2021). This should then be considered. When hydrogen is sold directly sold to customers, the clients are mostly industrial players using the hydrogen as a feedstock in their existing production process. The market potential of this should be investigated to determine the financial feasibility of this business case. By comparing both, the best business case for hydrogen can be studied.
5. Further research into the implementation of next steps for industry-wide adoption of the developed model

- Approach: First, new stakeholder interviews should be conducted to gather feedback on the current version of the model. Then, the stakeholders' desires that were not realised in the current version should be studied. For example, explore the inclusion of geospatial data to evaluate the environmental impact of projects. Additionally, consider stakeholders' suggestions to have the model tested and validated by independent experts. Investigate potential improvements to enhance the usability of the current model based on stakeholder feedback. This could include enhancing user interfaces. Regularly assess the progress of implementation, monitor user feedback, and make iterative improvements to enhance user experience and maximise the model's value.

References

Adan, I., & Resing, J. (2002). Queueing theory. https://wwwhome.ewi.utwente.nl/~scheinhardtwrw/queueingdictaat.pdf

Agnello, L., Castro, V., Hammoudeh, S., & Sousa, R. M. (2020). Global factors, uncertainty, weather conditions and energy prices: On the drivers of the duration of commodity price cycle phases. *Energy Economics*, *90*, 104862. https://doi.org/https://doi.org/10.1016/j.eneco.2020.104862

Anciaux, S. (2019). Premium tariff (sde+). http://www.res-legal.eu/search-by-country/netherlands/single/s/res-e/t/promotion/aid/premium-tariff-sde/lastp/171/

Anderson, T. P., & Cherwonik, J. S. (1997). *Cost estimating risk and cost estimating uncertainty guidelines* (tech. rep.). NAVAL POSTGRADUATE SCHOOL MONTEREY CA DEPT OF OPERATIONS RESEARCH.

Barton, J. P., & Infield, D. G. (2004). Energy storage and its use with intermittent renewable energy. *IEEE transactions on energy conversion*, *19*(2), 441–448.

Beaudin, M., Zareipour, H., Schellenberglabe, A., & Rosehart, W. (2010). Energy storage for mitigating the variability of renewable electricity sources. *Energy for Sustainable Development*, *14*, 302–314. https://doi.org/10.1016/j.esd.2010.09.007

BEIS, U. (2021). Hydrogen production costs 2021 - gov.uk. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011506/Hydrogen_Production_Costs_2021.pdf

Belessiotis, V., Kalogirou, S., & Delyannis, E. (2016). Chapter one - desalination methods and technologies—water and energy. In V. Belessiotis, S. Kalogirou, & E. Delyannis (Eds.), *Thermal solar desalination* (pp. 1–19). Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-809656-7.00001-5

Benalcazar, P., & Komorowska, A. (2022). Prospects of green hydrogen in poland: A techno-economic analysis using a monte carlo approach. *International Journal of Hydrogen Energy*, *47*(9), 5779–5796. https://doi.org/https://doi.org/10.1016/j.ijhydene.2021.12.001

Berkeley Lab. (2020). New data compilation illustrates the maturity and declining cost of wind energy. https://emp.lbl.gov/news/new-data-compilation-illustrates-maturity-and

Bettoli, A., Heineke, F., Janecke, N., Nyheim, T., Schlosser, A., Spitzer, S., Staudt, C., Winter, R., & Zivansky, J. (2023). Renewable-energy development in a net-zero world: Disrupted supply chains. https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/renewable-energy-development-in-a-net-zero-world-disrupted-supply-chains

Bhandari, R., & Shah, R. R. (2021). Hydrogen as energy carrier: Techno-economic assessment of decentralized hydrogen production in germany. *Renewable Energy*, *177*, 915–931. https://doi.org/https://doi.org/10.1016/j.renene.2021.05.149

Bilgili, M., Yasar, A., & Simsek, E. (2011). Offshore wind power development in europe and its comparison with onshore counterpart. *Renewable and Sustainable Energy Reviews*, *15*(2), 905–915. https://doi.org/https://doi.org/10.1016/j.rser.2010.11.006

Bloomberg. (2023). Rates & bonds. https://www.bloomberg.com/markets/rates-bonds

Blum, W. (1965). Depreciation and enterprise valuation - university of chicago. https://chicagounbound.uchicago.edu/cgi/viewcontent.cgi?article=3427&context=uclrev

Breunis, W. (2021). Hydrogen gas production from offshore wind: A cost-benefit analysis of optionality through grid connection. https://repository.tudelft.nl/islandora/object/uuid:592c4ab2-7ab1-428b-b54c-1c44afc5ba5a?collection=education

Buljan, A. (2023). Belgians to start building world's first artificial energy island next year (video). https://www.offshorewind.biz/2023/03/02/belgians-to-start-building-world-first-artificial-energy-island-video/

Burdack, A., Duarte-Herrera, L., López-Jiménez, G., Polklas, T., & Vasco-Echeverri, O. (2023). Techno-economic calculation of green hydrogen production and export from colombia. *International Journal of Hydrogen Energy*, *48*(5), 1685–1700. https://doi.org/https://doi.org/10.1016/j.ijhydene.2022.10.064

Burton, N., Padilla, R., Rose, A., & Habibullah, H. (2021). Increasing the efficiency of hydrogen production from solar powered water electrolysis. *Renewable and Sustainable Energy Reviews*, *135*, 110255. https://doi.org/https://doi.org/10.1016/j.rser.2020.110255

Caldera, U., & Breyer, C. (2017). Learning curve for seawater reverse osmosis desalination plants: Capital cost trend of the past, present, and future. *Water Resources Research*, *53*(12), 10523–10538.

Carey, J. W., Morgan, M., & Oxtoby, M. J. (1996). Intercoder agreement in analysis of responses to open-ended interview questions: Examples from tuberculosis research. *CAM Journal*, *8*(3), 1–5. https://doi.org/10.1177/1525822X960080030101

Chai, S., Phang, F., Yeo, L., Ngu, L., & Shen, H. (2022). Future era of techno-economic analysis: Insights from review. *Frontiers in Sustainability*, *3*, 924047. https://doi.org/10.3389/frsus.2022.924047

Chandrasekar, A., Flynn, D., & Syron, E. (2021). Operational challenges for low and high temperature electrolyzers exploiting curtailed wind energy for hydrogen production [HYDROGEN ENERGY SYSTEMS]. *International Journal of Hydrogen Energy*, *46*(57), 28900–28911. https://doi.org/https://doi.org/10.1016/j.ijhydene.2020.12.217

Christopher Frey, H., & Patil, S. R. (2002). Identification and review of sensitivity analysis methods. *Risk analysis*, *22*(3), 553–578.

Crabtree, G., Misewich, J., Ambrosio, R., Clay, K., DeMartini, P., James, R., Lauby, M., Mohta, V., Moura, J., Sauer, P., et al. (2011). Integrating renewable electricity on the grid. *AIP Conference proceedings*, *1401*(1), 387–405.

Crown Estate. (2019). Guide to an offshore windfarm. https://guidetoanoffshorewindfarm.com/

DePamphilis, D. M. (2022). Chapter 7 - mergers and acquisitions cash flow valuation basics. In D. M. DePamphilis (Ed.), *Mergers, acquisitions, and other restructuring activities (eleventh edition)* (Eleventh Edition, pp. 175–202). Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-819782-0.00007-1

Designing Buildings. (2021). *Capital expenditure for construction*. Retrieved December 13, 2022, from https://www.designingbuildings.co.uk/wiki/Capital_expenditure_for_construction

Di Lullo, G., Giwa, T., Okunlola, A., Davis, M., Mehedi, T., Oni, A., & Kumar, A. (2022). Large-scale long-distance land-based hydrogen transportation systems: A comparative techno-economic and greenhouse gas emission assessment. *International Journal of Hydrogen Energy*, *47*(83), 35293–35319. https://doi.org/https://doi.org/10.1016/j.ijhydene.2022.08.131

Dimitriosroussis. (2021). Electricity price forecasting with dnns (+ eda). https://www.kaggle.com/code/dimitriosroussis/electricity-price-forecasting-with-dnns-eda

Dinh, Q. V., Dinh, V. N., Mosadeghi, H., Todesco Pereira, P. H., & Leahy, P. G. (2023). A geospatial method for estimating the levelised cost of hydrogen production from offshore wind. *International Journal of Hydrogen Energy*. https://doi.org/https://doi.org/10.1016/j.ijhydene.2023.01.016

Dinh, V. N., Leahy, P., McKeogh, E., Murphy, J., & Cummins, V. (2021). Development of a viability assessment model for hydrogen production from dedicated offshore wind farms [Recent Trends in Hydrogen Production and Utilization]. *International Journal of Hydrogen Energy*, *46*(48), 24620–24631. https://doi.org/https://doi.org/10.1016/j.ijhydene.2020.04.232

Dupuy, A., & Leveson, N. (2000). An empirical evaluation of the mc/dc coverage criterion on the hete-2 satellite software. *19th DASC. 19th Digital Avionics Systems Conference. Proceedings (Cat. No.00CH37126)*, *1*, 1B6/1–1B6/7 vol.1. https://doi.org/10.1109/DASC.2000.886883

DW Insights. (2022). *Understanding operating expenses*. Retrieved December 13, 2022, from https://www.dwenergygroup.com/understanding-operating-expenses/

Eeckhout, B., Van Hertem, D., Reza, M., Srivastava, K., & Belmans, R. (2009). Economic comparison of vsc hvdc and hvac as transmission system for a 300 mw offshore wind farm. *European Transactions on Electrical Power*, *20*, 661–671. https://doi.org/10.1002/etep.359

Ellims, M., Bridges, J., & Ince, D. C. (2006). The economics of unit testing. *Empirical Software Engineering*, *11*(1), 5–31. https://doi.org/10.1007/s10664-006-5964-9

Energy Storage Association. (2021). Hydrogen energy storage. https://energystorage.org/why-energy-storage/technologies/hydrogen-energy-storage/#:~:text=Hydrogen%5C%20Re-Electrification,as%5C%20high%5C%20as%5C%2060%5C%25).

European Central Bank. (2021). Two per cent inflation target. https://www.ecb.europa.eu/mopo/strategy/pricestab/html/index.en.html

European Commission. (2020a). Guidance document on wind energy developments and eu nature legislation. https://op.europa.eu/en/publication-detail/-/publication/2b08de80-5ad4-11eb-b59f-01aa75ed71a1

European Commission. (2020b). *Paris agreement*. Retrieved October 11, 2022, from https://climate.ec.europa.eu/eu-action/international-action-climate-change/climate-negotiations/paris-agreement_en

European Commission. (2022). Repowereu: A plan to rapidly reduce dependence on russian fossil fuels and fast forward the green transition*. https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131

European Union. (2022). Energy inflation rate continues upward hike, hits 27%. https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20220225-2

EWEA. (2022). *Operation and maintenance costs of wind generated power*. Retrieved December 13, 2022, from https://www.wind-energy-the-facts.org/operation-and-maintenance-costs-of-wind-generated-power.html

Fazeres-Ferradosa, T., Chambel, J., Taveira-Pinto, F., Rosa-Santos, P., Taveira-Pinto, F. V., Giannini, G., & Haerens, P. (2021). Scour protections for offshore foundations of marine energy harvesting technologies: A review. *Journal of Marine Science and Engineering*, *9*(3), 297. https://doi.org/10.3390/jmse9030297

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

Galway, L. A. (2007). *Evaluating uncertainty in cost estimates: A practical guide to eliciting expert judgments*. RAND Corporation. https://doi.org/10.7249/RB216

GASCADE. (2023). Offshore hydrogen pipeline: Gascade and fluxys step up plans. https://www.gascade.de/en/press/press-releases/press-release/offshore-hydrogen-pipeline-gascade-and-fluxys-step-up-plans

Gasunie. (2022). Gasunie investigates hydrogen network in north sea. https://www.gasunie.nl/en/news/gasunie-investigates-hydrogen-network-in-north-sea

Geissmann, T., & Ponta, O. (2017). A probabilistic approach to the computation of the levelized cost of electricity. *Energy*, *124*, 372–381. https://doi.org/10.1016/j.energy.2017.02.078

Gerrits, S. (2017). Feasibility study of the hub and spoke concept in the north sea: Developing a site selection model to determine the optimal location. http://resolver.tudelft.nl/uuid:9de1680b-7c16-4c93-bf3e-2af5e198eee0

Giampietro, M., & Mayumi, K. (2018). Unraveling the complexity of the jevons paradox: The link between innovation, efficiency, and sustainability. *Frontiers in Energy Research*, *6*. https://www.frontiersin.org/articles/10.3389/fenrg.2018.00026

Goldsmith, L. J. (2021). Using framework analysis in applied qualitative research [Recent Trends in Hydrogen Production and Utilization]. *The Qualitative Report*, *26*(6), 2061–2076. https://doi.org/https://doi.org/10.1016/j.ijhydene.2020.04.232

Greenwood, M. (2023). Quantitative finance with python: A practical guide to investment management, trading and financial engineering. *Quantitative Finance*, *0*(0), 1–2. https://doi.org/10.1080/14697688.2023.2179939

Groenemans, H., Saur, G., Mittelsteadt, C., Lattimer, J., & Xu, H. (2022). Techno-economic analysis of offshore wind pem water electrolysis for h2 production. *Current Opinion in Chemical Engineering*, *37*, 100828. https://doi.org/https://doi.org/10.1016/j.coche.2022.100828

Guidehouse. (2022). *Policy options offshore wind 2040*. https://open.overheid.nl/repository/ronl-c6155c48c530c8d4fca0d38cf773145ae6ede845/1/pdf/eindrapport-policy-options-offshore-wind-2040.pdf

Gür, T. M. (2018). Correction: Review of electrical energy storage technologies, materials and systems: Challenges and prospects for large-scale grid storage. *Energy & Environmental Science*, *11*(10), 3055–3055. http://dx.doi.org/10.1039/C8EE90053A

Halden, U., Cali, U., Dynge, M. F., Stekli, J., & Bai, L. (2021). Dlt-based equity crowdfunding on the techno-economic feasibility of solar energy investments. *Solar Energy*, *227*, 137–150. https://doi.org/10.1016/j.solener.2021.08.067

Hansen, K. (2019). Decision-making based on energy costs: Comparing levelized cost of energy and energy system costs. *Energy Strategy Reviews*, *24*, 68–82. https://doi.org/10.1016/j.esr.2019.02.003

Hasanaj, P. S., & Kuqi, B. (2019). (pdf) analysis of financial statements - researchgate. https://www.researchgate.net/publication/333880039_Analysis_of_Financial_Statements

Heijungs, R. (2019). On the number of monte carlo runs in comparative probabilistic lca - the international journal of life cycle assessment. https://link.springer.com/article/10.1007/s11367-019-01698-4#citeas

Herrera, G. P., Constantino, M., Tabak, B. M., Pistori, H., Su, J.-J., & Naranpanawa, A. (2019). Long-term forecast of energy commodities price using machine learning. *Energy*, *179*, 214–221. https://doi.org/https://doi.org/10.1016/j.energy.2019.04.077

Hoffmann, C. (2020). Decarbonization challenge for steel - mckinsey & company. https://www.mckinsey.com/~/media/McKinsey/Industries/Metals%5C%20and%5C%20Mining/Our%5C%20Insights/Decarbonization%5C%20challenge%5C%20for%5C%20steel/Decarbonization-challenge-for-steel.pdf

Holmgren, W. F., Hansen, C. W., & Mikofski, M. A. (2018). Pvlib python: A python package for modeling solar energy systems. *Journal of Open Source Software*, *3*(29), 884. http://dx.doi.org/10.21105/joss.00884

IEA. (2019). *The future of hydrogen*. https://www.iea.org/reports/the-future-of-hydrogen

IEA. (2022). Energy island project in the north sea – policies. https://www.iea.org/policies/11562-energy-island-project-in-the-north-sea

Impram, S., Varbak Nese, S., & Oral, B. (2020). Challenges of renewable energy penetration on power system flexibility: A survey. *Energy Strategy Reviews*, *31*, 100539. https://doi.org/https://doi.org/10.1016/j.esr.2020.100539

IRENA. (2019). Hydrogen - a renewable energy perspective. https://www.irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective

ISPT. (2023). Gigawatt green hydrogen plant: Design and costs. https://ispt.eu/publications/public-report-gigawatt-green-hydrogen-plant/

Jalili, S., & Maheri, A. (2022). Cost modelling for offshore wind farm decommissioning. https://northsearegion.eu/

Jang, D., Kim, K., Kim, K.-H., & Kang, S. (2022). Techno-economic analysis and monte carlo simulation for green hydrogen production using offshore wind power plant. *Energy Conversion and Management*, *263*, 115695. https://doi.org/https://doi.org/10.1016/j.enconman.2022.115695

Janowitz, D., Groche, S., Yüce, S., Melin, T., & Wintgens, T. (2022). Can large-scale offshore membrane desalination cost-effectively and ecologically address water scarcity in the middle east? *Membranes*, *12*(3), 323. https://doi.org/10.3390/membranes12030323

Jansen, M., Duffy, C., Green, T. C., & Staffell, I. (2022). Island in the sea: The prospects and impacts of an offshore wind power hub in the north sea. *Advances in Applied Energy*, *6*, 100090. https://doi.org/https://doi.org/10.1016/j.adapen.2022.100090

Jiang, Z., & Tan, J. (2013). How the removal of energy subsidy affects general price in china: A study based on input–output model. *Energy Policy*, *63*, 599–606. https://doi.org/https://doi.org/10.1016/j.enpol.2013.08.059

Jin, R., Hou, P., Yang, G., Qi, Y., Chen, C., & Chen, Z. (2019). Cable routing optimization for offshore wind power plants via wind scenarios considering power loss cost model. *Applied Energy*, *254*, 113719. https://doi.org/https://doi.org/10.1016/j.apenergy.2019.113719

Kaldellis, J. K. (2022a). 2.17 - financial evaluation of wind parks. In T. M. Letcher (Ed.), *Comprehensive renewable energy (second edition)* (Second Edition, pp. 567–588). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-819727-1.00177-1

Kaldellis, J. K. (2022b). 2.17 - financial evaluation of wind parks. In T. M. Letcher (Ed.), *Comprehensive renewable energy (second edition)* (Second Edition, pp. 567–588). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-819727-1.00177-1

Kanellopoulos, K., Busch, S., De Felice, M., Giaccaria, S., & Costescu, A. (2022). *Blending hydrogen from electrolysis into the european gas grid*. Publications Office of the European Union. https://publications.jrc.ec.europa.eu/repository/handle/JRC126763

Kiran, D. (Ed.). (2022). Chapter twenty-two - machinery replacement analysis. In *Principles of economics and management for manufacturing engineering* (pp. 259–267). Butterworth-Heinemann. https://doi.org/https://doi.org/10.1016/B978-0-323-99862-8.00002-9

Kopp, M., Coleman, D., Stiller, C., Scheffer, K., Aichinger, J., & Scheppat, B. (2017). Energiepark mainz: Technical and economic analysis of the worldwide largest power-to-gas plant with pem electrolysis [Special Issue on The 21st World Hydrogen Energy Conference (WHEC 2016), 13-16 June 2016, Zaragoza, Spain]. *International Journal of Hydrogen Energy*, *42*(19), 13311–13320. https://doi.org/https://doi.org/10.1016/j.ijhydene.2016.12.145

Krien, U., Schönfeldt, P., Launer, J., Hilpert, S., Kaldemeyer, C., & Pleßmann, G. (2020). Oemof.solph—a model generator for linear and mixed-integer linear optimisation of energy systems. *Software Impacts*, *6*, 100028. https://doi.org/https://doi.org/10.1016/j.simpa.2020.100028

Kusiak, A. (2016). Renewables: Share data on wind energy. *Nature*, *529*(7584), 19–21. https://doi.org/10.1038/529019a

Kuttner, K., Kuttner, K., Zaiour, G. P., Reem, Peri, G., & Zaiour, R. (2022). Thinking can make it so: The important role of inflation expectations. https://econofact.org/thinking-can-make-it-so-the-important-role-of-inflation-expectations

Lamprecht, C. (2021). Obtain weather data for any location with python. https://meteostat.net/en/blog/obtain-weather-data-any-location-python

Lappalainen, M. (2019). Techno-economic feasibility of hydrogen production via polymer membrane electrolyte electrolysis for future power-to-x systems. https://trepo.tuni.fi/handle/123456789/27224

Lavidas, G., & Polinder, H. (2019). North sea wave database (nswd) and the need for reliable resource data: A 38 year database for metocean and wave energy assessments. *Atmosphere*, *10*(9). https://doi.org/10.3390/atmos10090551

Lazard. (2021). Lazard's levelized cost of hydrogen analysis. https://lazard.com/media/12qcxl1j/lazards-levelized-cost-of-hydrogen-analysis-vf.pdf

Lee, C.-T., Chen, Y.-M., Chen, L.-C., & Cheng, P.-T. (2012). Efficiency improvement of a dc/ac converter with the power decoupling capability. *2012 Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, 1462–1468. https://doi.org/10.1109/APEC.2012.6166013

Letcher, T. M. (2017). *Wind energy engineering: A handbook for onshore and offshore wind turbines*. Academic Press. https://www.sciencedirect.com/book/9780128094518/wind-energy-engineering

Lewinson, E. (2020). *Python for finance cookbook: Over 50 recipes for applying modern python libraries to financial data analysis*. Packt Publishing Ltd. https://www.packtpub.com/product/python-for-finance-cookbook-second-edition/9781803243191

Li, F., Yang, C., Li, Z., & Failler, P. (2021). Does geopolitics have an impact on energy trade? empirical research on emerging countries. https://www.mdpi.com/2071-1050/13/9/5199

Lira, A. (2014). Uncertainties in the estimate of wind energy production - ufrj. https://www.gesel.ie.ufrj.br/app/webroot/files/publications/20_lira.pdf

Lorenczik, S., Kim, S., Wanner, B., Bermudez Menendez, J. M., Remme, U., Hasegawa, T., Keppler, J. H., Mir, L., Sousa, G., Berthelemy, M., et al. (2020). *Projected costs of generating electricity-2020 edition* (tech. rep.). Organisation for Economic Co-Operation and Development. https://www.iea.org/reports/projected-costs-of-generating-electricity-2020

Lucas, T. R., Ferreira, A. F., Santos Pereira, R., & Alves, M. (2022). Hydrogen production from the windfloat atlantic offshore wind farm: A techno-economic analysis. *Applied Energy*, *310*, 118481. https://doi.org/https://doi.org/10.1016/j.apenergy.2021.118481

Makridis, S. (2016). Hydrogen storage and compression. In *Methane and hydrogen for energy storage*. Institution of Engineering; Technology. https://digital-library.theiet.org/content/books/10.1049/pbpo101e_ch1

Makridis, S. (2017). Hydrogen storage and compression. *arXiv preprint arXiv:1702.06015*. https://doi.org/10.48550/arXiv.1702.06015

Manwell, J. F., McGowan, J. G., & Rogers, A. L. (2010). *Wind energy explained: Theory, design and application*. John Wiley & Sons.

Matutano, C., Negro, V., López-Gutiérrez, J.-S., & Esteban, M. D. (2013). Scour prediction and scour protections in offshore wind farms. *Renewable Energy*, *57*, 358–365. https://doi.org/https://doi.org/10.1016/j.renene.2013.01.048

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*, 114732. https://doi.org/https://doi.org/10.1016/j.apenergy.2020.114732

McIntosh, M. J., & Morse, J. M. (2015). Situating and constructing diversity in semi-structured interviews. *Global qualitative nursing research*, *2*, 2333393615597674.

Moser, M., Trieb, F., Fichter, T., Kern, J., & Hess, D. (2015). A flexible techno-economic model for the assessment of desalination plants driven by renewable energies. *Desalination and Water Treatment*, *55*(11), 3091–3105.

Neuwirth, M., Fleiter, T., Manz, P., & Hofmann, R. (2022). The future potential hydrogen demand in energy-intensive industries - a site-specific approach applied to germany. *Energy Conversion and Management*, *252*, 115052. https://doi.org/https://doi.org/10.1016/j.enconman.2021.115052

Nieuwe Stroom. (2023). Energieprijzen inkoopprijs dagmarkt. https://nieuwestroom.nl/energieprijzen/

NSWPH. (2018). Project 335 - north sea wind power hub. https://tyndp.entsoe.eu/tyndp2018/projects/projects/335

NSWPH. (2019). Modular hub-and-spoke concept to facilitate large scale offshore wind. https://northseawindpowerhub.eu/sites/northseawindpowerhub.eu/files/media/document/Concept_Paper_3-Specific-solution-options.pdf

NSWPH. (2021). Towards the first hub-and-spoke project. https://northseawindpowerhub.eu/files/media/document/NSWPH_Concept%5C%20Paper_05_2021_v2.pdf

NYU Stern. (2023). Betas by sector (us). https://pages.stern.nyu.edu/~adamodar/New_Home_Page/datafile/Betas.html

O'Connor, M., & Dalton, G. (2012). Operational expenditure costs for wave energy projects and impacts on financial returns. *Renewable Energy*, *50*, 1119–1131. https://doi.org/10.1016/j.renene.2012.08.059

Offshore Technology. (2022). *Project management services for the offshore industry*. Retrieved December 13, 2022, from https://www.offshore-technology.com/buyers-guide/project-management-services/

Ohlsen, G. (2019). Positioning of danish offshore wind farms until 2030 - using levelized ... https://backend.orbit.dtu.dk/ws/portalfiles/portal/170361654/MScThesisDefense_GydeOhlsen_revised_03_2019.pdf

Olan, M. (2003). Unit testing: Test early, test often. *Journal of Computing Sciences in Colleges - JCSC*, *19*. https://www.researchgate.net/publication/255673967_Unit_testing_Test_early_test_often

Onnen, H. (2021). Python scenario analysis: Modeling expert estimates with the beta-pert distribution. https://towardsdatascience.com/python-scenario-analysis-modeling-expert-estimates-with-the-beta-pert-distribution-22a5e90cfa79

Opus Kinetic. (2022). *Understanding commissioning of offshore oil and gas projects*. Retrieved December 13, 2022, from https://www.opuskinetic.com/2019/01/commissioning-offshore-oil-and-gas-projects/

Ortiz-Cebolla, R., Dolci, F., & Weidner, E. (2022). Assessment of hydrogen delivery options - eu science hub. https://joint-research-centre.ec.europa.eu/system/files/2021-06/jrc124206_assessment_of_hydrogen_delivery_options.pdf

Oughton, E. J., Katsaros, K., Entezami, F., Kaleshi, D., & Crowcroft, J. (2019). An open-source techno-economic assessment framework for 5g deployment. *IEEE Access*, *7*, 155930–155940. https://doi.org/10.1109/ACCESS.2019.2949460

Pagabo. (2022). *The complete guide to construction procurement*. Retrieved December 13, 2022, from https://www.pagabo.co.uk/guide-to-construction-procurement#

PetroWiki. (2022). *Offshore decommissioning*. Retrieved December 13, 2022, from https://petrowiki.spe.org/Offshore_decommissioning

Pilots met waterstof. (2022). https://www.alliander.com/nl/energietransitie/pilots-met-waterstof-2/

Port of Rotterdam. (2019). Port of rotterdam - port vision. https://www.portofrotterdam.com/sites/default/files/2021-06/port%5C%20vision.pdf

Povacz, L., & Bhandari, R. (2023). Analysis of the levelized cost of renewable hydrogen in austria. *Sustainability*, *15*(5). https://doi.org/10.3390/su15054575

Prapas, I. (n.d.). Analyze geospatial data in python: Geopandas and shapely. https://www.learndatasci.com/tutorials/geospatial-data-python-geopandas-shapely/

Raychaudhuri, S. (2008). Introduction to monte carlo simulation. *2008 Winter Simulation Conference*, 91–100. https://doi.org/10.1109/WSC.2008.4736059

Rezaei, M., Naghdi-Khozani, N., & Jafari, N. (2020). Wind energy utilization for hydrogen production in an underdeveloped country: An economic investigation. *Renewable Energy*, *147*, 1044–1057. https://doi.org/https://doi.org/10.1016/j.renene.2019.09.079

Rodrigo, J. A., & Ortiz, J. E. (2021). Skforecast: Time series forecasting with python and scikit-learn. https://www.cienciadedatos.net/documentos/py27-time-series-forecasting-python-scikitlearn.html

Rodrigo, S., Gunasekera, D., Mahajan, J. P., & Luo, L. (2021). Alternating current electrolysis for organic synthesis. *Current Opinion in Electrochemistry*, *28*, 100712. https://doi.org/https://doi.org/10.1016/j.coelec.2021.100712

Roos, T. H. (2021). The cost of production and storage of renewable hydrogen in south africa and transport to japan and eu up to 2050 under different scenarios [Special Issue on HYPOTHESIS XV]. *International Journal of Hydrogen Energy*, *46*(72), 35814–35830. https://doi.org/https://doi.org/10.1016/j.ijhydene.2021.08.193

RVO. (2021). Plannen windenergie op zee 2030-2050. https://www.rvo.nl/onderwerpen/windenergie-op-zee/plannen-windenergie-op-zee

RVO. (2022a). Dutch offshore wind guide. https://www.rvo.nl/sites/default/files/2021/10/Dutch%5C%20Offshore%5C%20Wind%5C%20Guide%5C%202022.pdf

RVO. (2022b). Offshore wind energy roadmap - english.rvo.nl. https://english.rvo.nl/sites/default/files/2022/12/Routekaart-windenergieopzee-december-2022-ENG.pdf

Saidur, R., Islam, M., Rahim, N., & Solangi, K. (2010). A review on global wind energy policy. *Renewable and Sustainable Energy Reviews*, *14*(7), 1744–1762. https://doi.org/https://doi.org/10.1016/j.rser.2010.03.007

Sblendorio, D. (2021). Top 10 python packages for finance and financial modeling. https://www.activestate.com/blog/top-10-python-packages-for-finance-and-financial-modeling/

Siemens Energy. (2023). Proven, efficient hydrogen compressors. https://www.siemens-energy.com/global/en/offerings/industrial-applications/compression/hydrogen-compressors.html

Singlitico, A., Østergaard, 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*, 100005. https://doi.org/https://doi.org/10.1016/j.rset.2021.100005

S&P Global Platts. (n.d.). Platts hydrogen price wall. https://www.spglobal.com/commodityinsights/PlattsContent/_assets/_files/en/specialreports/energy-transition/platts-hydrogen-price-wall/index.html?utm_source=insight&utm_medium=plattsblog&utm_campaign=lef

Srinil, N. (2016). 13 - cabling to connect offshore wind turbines to onshore facilities. In C. Ng & L. Ran (Eds.), *Offshore wind farms* (pp. 419–440). Woodhead Publishing. https://doi.org/https://doi.org/10.1016/B978-0-08-100779-2.00013-1

StraTopo. (2023). Dataset natura 2000-gebieden. https://shop.stratopo.nl/products/natura-2000-gebieden

SUNY College. (2021). Guidance note on estimating the uncertainty of emission reductions using monte carlo simulation. https://www.forestcarbonpartnership.org/sites/fcp/files/fcpf_guidance_on_monte_carlo_analysis_2021.pdf

Taibi, E., Blanco, H., & Miranda, R. (2020). Irena – green hydrogen cost reduction. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

Tang, O., Rehme, J., & Cerin, P. (2022). Levelized cost of hydrogen for refueling stations with solar pv and wind in sweden: On-grid or off-grid? *Energy*, *241*, 122906. https://doi.org/https://doi.org/10.1016/j.energy.2021.122906

Tanvir, F. (2023). 7 best python libraries to make probabilistic programming easier. https://python.plainenglish.io/7-best-python-libraries-to-make-probabilistic-programming-easier-a3ad44bde1e1

Tashie-Lewis, B. C., & Nnabuife, S. G. (2021). Hydrogen production, distribution, storage and power conversion in a hydrogen economy - a technology review. *Chemical Engineering Journal Advances*, *8*, 100172. https://doi.org/https://doi.org/10.1016/j.ceja.2021.100172

Thakur, M. (2022). *Residual value*. Retrieved December 13, 2022, from https://www.educba.com/residual-value/

TNO. (2020a). Energy hubs & transport infrastructure. https://north-sea-energy.eu/static/2fd1407691ef2b058666b7f5e5c93d05/NSE-2020-2022-1.1-Energy-Hubs-and-Transport-Infrastructure-v2.pdf

TNO. (2020b). Ijvergas - cedelft.eu. https://cedelft.eu/wp-content/uploads/sites/2/2020/06/CE_Delft_180020_IJVERGAS_Def.pdf

UNFCC. (2022). *What is the paris agreement?* Retrieved October 11, 2022, from https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

Ursua, A., Gandia, L. M., & Sanchis, P. (2012). Hydrogen production from water electrolysis: Current status and future trends. *Proceedings of the IEEE*, *100*(2), 410–426. https://doi.org/10.1109/JPROC.2011.2156750

US Dep. of Energy. (2023). Hydrogen pipelines. https://www.energy.gov/eere/fuelcells/hydrogen-pipelines

van der Veer, E., Sweers, B., Kawale, D., & van Unen, M. (2020). https://north-sea-energy.eu/static/0856dd12a36d1f321aaf757706bd5913/8a.-FINAL-NSE3_D3.8-Final-report-on-the-techno-economic-environmental-and-legal-assessment-of-offshore-energy-islands.pdf van Algemene Zaken, M. (2022). Kamerbrief over de voortgang uitvoering routekaart windenergie op zee 2030. https://www.rijksoverheid.nl/documenten/kamerstukken/2019/04/05/kamerbrief-over-de-voortgang-uitvoering-routekaart-windenergie-op-zee-2030

Vestas. (2023). Offshore wind turbines. https://www.vestas.com/en/products/offshore

Warnock, J., Mcmillan, D., Pilgrim, J., & Shenton, S. (2019). Failure rates of offshore wind transmission systems. *Energies*, *12*, 2682. https://doi.org/10.3390/en12142682

WECC. (2019). Wecc - western electricity coordinating council. https://www.wecc.org/Administrative/TEPPC_TransCapCostCalculator_E3_2019_Update.xlsx

WindEurope. (2022). https://windeurope.org/newsroom/news/energy-islands-coming-to-europes-seas/

Wu, X., Hu, Y., Li, Y., Yang, J., Duan, L., Wang, T., Adcock, T., Jiang, Z., Gao, Z., Lin, Z., Borthwick, A., & Liao, S. (2019). Foundations of offshore wind turbines: A review. *Renewable and Sustainable Energy Reviews*, *104*, 379–393. https://doi.org/https://doi.org/10.1016/j.rser.2019.01.012

Yan, Y., Zhang, H., Liao, Q., Liang, Y., & Yan, J. (2021). Roadmap to hybrid offshore system with hydrogen and power co-generation. *Energy Conversion and Management*, *247*, 114690. https://doi.org/https://doi.org/10.1016/j.enconman.2021.114690

Yates, J., Daiyan, R., Patterson, R., Egan, R., Amal, R., Ho-Baille, A., & Chang, N. L. (2020). Techno-economic analysis of hydrogen electrolysis from off-grid stand-alone photovoltaics incorporating uncertainty analysis. *Cell Reports Physical Science*, *1*(10), 100209. https://doi.org/https://doi.org/10.1016/j.xcrp.2020.100209

Zhao, X., Liu, Y., Wu, J., Xiao, J., Hou, J., Gao, J., & Zhong, L. (2020). Technical and economic demands of hvdc submarine cable technology for global energy interconnection. *Global Energy Interconnection*, *3*(2), 120–127. https://doi.org/10.1016/j.gloei.2020.05.004

Zhou, Y., & Searle, S. (2022). Cost of renewable hydrogen produced onsite at hydrogen refueling stations in europe. https://theicct.org/publication/fuels-eu-onsite-hydro-cost-feb22/#:~:text=Regardless%5C%20of%5C%20these%5C%20cost%5C%20reduction,president%5C%20of%5C%20the%5C%20European%5C%20Commission

Zoulias, E., Varkaraki, E., Lymberopoulos, N., Christodoulou, C., & Karagiorgis, G. (2004). A review on water electrolysis. *TCJST*, *4*, 41–71. https://www.researchgate.net/publication/284618929_A_Review_on_Water_Electrolysis

A
Stakeholder Analysis

A.1. Stakeholder Overview

Below are the stakeholder categories and the parties defined who were identified as most important in the Dutch North Sea offshore wind to hydrogen market, according to Van Oord's expertise and literature research.

1. Energy infrastructure
    - *Gasunie*
    - *Vopak*
    - *Tennet*
2. Energy supplier
    - *Shell*
    - *Equinor*
    - *E.On*
    - *BP*
    - *Eneco*
3. Offshore dredging company
    - *Van Oord*
    - *Boskalis*
    - *Jan de Nul*
4. Offshore project developer
    - *Iberdrola*
    - *Shell*
    - *Eneco*
    - *Ørsted*
    - *Vattenfall*
5. Governmental organisation
    - *TKI Wind op Zee*
    - *Groenvermogen*
    - *Ministry of Infrastructure and Water Management (I&W) with executive body Rijkswaterstaat (RWS)*
    - *Ministry of Interior and Kingdom Relations (BZK)*
    - *Ministry of Economic Affars & Climate Policy (EZK)*
    - *Netherlands Enterprise Agency (RVO)*

6. Research institute
    - *ISPT*
    - *TNO*
    - *TU Delft*
    - *TU Twente*
    - *TU Eindhoven*
    - *Differ*
7. Electrolyser manufacturer
    - *Siemens Energy Gamesa*
    - *Hydron Energy*
    - *Bosal Group*
8. Wind turbine manufacturer
    - *Siemens Energy Gamesa*
    - *Vestas*
    - *General Electric*
9. Engineering consultant
    - *Witteveen & Bos*
    - *Royal Haskoning DHV*
    - *Guidehouse*
10. Port
    - *Port of Rotterdam*
    - *Port of Amsterdam*

A.2. Stakeholder Interviews

A.2.1. Interview Protocol

The following protocol will be followed in the interview:

1. Introduce myself and the purpose of the interview, which is to understand the stakeholders' objectives, incentives, and views on a comparison model to compare various offshore wind energy to hydrogen concepts using LCOE and LCOH.
2. Ask the stakeholder about their role and involvement in the Dutch offshore wind energy and hydrogen market. What are their main needs and concerns regarding North Sea offshore wind to hydrogen system integration?
3. Ask the stakeholder about their views on the current state of the Dutch offshore wind energy and hydrogen market, including the challenges and opportunities that they see in general. What are their views on hydrogen integration options?
4. Ask the stakeholder about their thoughts on the use of comparison models in the Dutch offshore wind energy and hydrogen market. Do they think such models are useful and necessary? If so, what kind of comparison models would be most valuable in this market?
5. Ask the stakeholder about their experiences with comparison models in the past, both in the Dutch offshore wind energy and hydrogen market and in other markets. What were their successes and challenges with these models?
6. Present the concept of the current comparison model to the stakeholder, including the work and cost breakdown. What's their view on the standardisation of a cost breakdown?
7. Ask the stakeholder about their expectations and requirements for a comparison model in the Dutch offshore wind energy and hydrogen market. What features and capabilities would they like to see in such a model?

8. Ask the stakeholder if they are comfortable with sharing data that could be used to develop and validate a comparison model for the Dutch offshore wind energy and hydrogen market. What kind of data would they be willing to share, and what are their concerns and limitations around data sharing?
9. Thank the stakeholder for their time and insights, and ask if they have any other thoughts or concerns that they would like to share.

A.2.2. Questionnaire

Below are the questions listed, which were asked during the stakeholder interviews. This is the updated version after the preliminary interviews.

1. What is Stakeholder's role in the Dutch offshore wind and hydrogen market?
2. What are Stakeholder's main needs and concerns regarding the integration of offshore wind to hydrogen systems in the North Sea?
3. What is Stakeholder's view on the current state of the Dutch offshore wind and hydrogen market, including the challenges and opportunities you see in general?
4. How does Stakeholder view the current integration options for green hydrogen?
5. What are Stakeholder's thoughts on the use of comparison models in the Dutch offshore wind energy and hydrogen market? Do you think such models are useful and necessary? If so, what type of comparison models would be most valuable in the market?
6. What are Stakeholder's experiences with comparison models in the past, both for the offshore wind and hydrogen market and in other markets? What went well, and what went less well with these models?
7. If Stakeholder were to use the model, for what purpose would this be?
8. If not, why i that? Under what conditions would STAKEHOLDER do use the model?
9. What are Stakeholder's expectations and requirements for a comparison model for the offshore wind and hydrogen market? What functions and capabilities would you like to see in such a model?
10. Does Stakeholder feel comfortable sharing data that could be used to develop and validate a comparison model?
11. If not, why not? What are the threats? Under what conditions would you be willing to do so?

A.3. Validated Interview Summaries

In order to ensure the validity and reliability of the results obtained from the stakeholder interviews, a rigorous method was employed. Following each interview, the transcripts were carefully analysed, and key takeaways were documented. To enhance the accuracy of the analysis, the documented conclusions were shared with the respective interviewees to validate the accuracy of the researcher's findings. This approach served as a crucial quality control step to ensure the truth value of the analysis and to mitigate the risk of any misinterpretation or bias. As a result, the methodology applied in this research is highly replicable, and the outcomes generated are more robust, scientifically sound, and trustworthy. The interview takeaways are separated per stakeholder.

A.3.1. Energy Infrastructure

- Stakeholder is not willing to share specific cost data about pipelines. They use models to determine the costs of pipes and materials, which could possibly be shared.
- They would be willing to verify price ranges.

A.3.2. Energy Supplier and Offshore Project Developer

- It is important to be clear about the model's underlying assumptions and calculations. For example, are the costs NPV?

- The biggest challenges of the green hydrogen market according to Stakeholder are: regulations, capital uncertainty, technology change, supply chain uncertainty, TSO commitment, availability of electrons for H2, and the complexity of energy systems.
- The definition of the cost blocks of the model should be clearly defined and agreed on.
- Stakeholder feels comfortable in validating the model in terms of how it is defined. It feels less comfortable in directly sharing cost data.
- Through an anonymised industry group, Stakeholder might feel more comfortable in sharing cost data.
- Stakeholder would be willing to look at assumptions and help with commenting on the set-up of the model.
- The biggest threat around sharing cost data is the fact that suppliers don't know exact numbers yet.
- Reputational impact: statements/model results with Stakeholder's name on it could lead to disadvantageous interpretations by, for example, journalists.
- Antitrust: Stakeholder cannot share exact numbers due to antitrust regulations.
- If Stakeholder were to use the model, it would be to:
- Compare projects on a like-for-like basis
- See how other parties are looking at hydrogen value chains
- The model would be less relevant for Stakeholder's internal decision making. They'd use their own models for that.

A.3.3. Offshore Dredging Company

- Integration of offshore wind to hydrogen systems in the North Sea is still in the early stages, and there are many unknown factors, such as the location of conversion and when it is cheaper to produce offshore.
- Stakeholder believes that the Dutch offshore wind and hydrogen market is not yet fully established, but it has great potential for growth.
- Stakeholder thinks that comparison models are useful and necessary in the offshore wind and hydrogen market.
- Developing a comparison model for the offshore wind and hydrogen market requires accurate data inputs, including cost inputs from elements outside Stakeholder's scope, such as the cost of electrolysers.
- Stakeholder is open to sharing data that could be used to develop and validate a comparison model, but there are limits to the amount of data that can be shared due to competitiveness concerns.
- Stakeholder has concerns regarding the integration of offshore wind to hydrogen systems in the North Sea, such as the lack of laws and regulations, shortage of port capacity, and the technical footprint of such systems.
- Stakeholder sees a shortage of equipment, supply, and people in the Dutch offshore wind and hydrogen market, and the demand exceeds the supply.
- Stakeholder's view on integration options for green hydrogen depends on where they will be allowed to build and which options are available.
- Stakeholder expects a comparison model for the offshore wind and hydrogen market to be clear, transparent, and convincing to other parties, as they increasingly find themselves in the investment seat.
- Stakeholder is comfortable with sharing data that could be used to develop and validate a comparison model, as sharing data is necessary to move forward.

A.3.4. Governmental Organisation

Governmental organisation 1

- Stakeholder always commissions LCOE analyses for wind areas from independent experts/consultants to support the offshore wind roadmap and site decision process.
- Stakeholder considers more than the cost of energy, for example, environmental impact in their analyses.
- For Stakeholder, a comparison model must be independent and transparent. They will always outsource model work to independent experts/consultants, and don't do this in-house.

Governmental organisation 2

- According to Stakeholder, buyers of turbines are usually willing to release some information on prices. With that, you can set bandwidths to test with the manufacturers.
- Manufacturers are also happy with this because they get a better picture of prices in the market.
- Important to think about how you maintain the model.
- It is good if several models are developed by different parties. That way, one model can also be used as a benchmark for the other.
- Stakeholder does not expect PwC or Guidehouse to use my model.

Governmental organisation 3

- Stakeholder states the need for a baseline to see how choices affect the LCOH at this stage of the hydrogen industry
- The model needs to be open-source, or at least transparent. In particular, the starting set of values should be clear and the same for everyone, so that everyone calculates with the same assumptions.
- The model should be robust: if you, as a user, do something wrong, it should quickly become clear.
- You want a user to be able to change the starting values himself/herself for his/her part of the supply chain. This allows a user to see what kind of cost reduction they can achieve compared to the starting point ('the standard').
- According to Stakeholder, it is more important to have a model that parties want to use than to participate in building it.
- Stakeholder would use the model to understand which innovations trigger what cost impact. This can help in bringing focus to their innovation programme.
- Stakeholder would be interested in launching the model at a later stage with Governmental Organisation 2.

Governmental organisation 4

- Stakeholder proposes to include the following items in the model: dynamic energy prices, dynamic developments of infrastructure and technology (scenarios change over time and main scenario is still uncertain), price developments of assets.
- Stakeholder encourages open innovation for accelerating sustainability, sharing data helps tremendously in this regard.
- Stakeholder would possibly like to use the model under the following conditions
  - If the quality is good enough/matches the demand of the model
  - The model must be validated
  - Most important: depends on the wishes and requirements of partner they are currently working with. In collaboration with a partner, who has a particular issue. Stakeholder would never use it itself

A.3.5. Research Institute

- Stakeholder must know what the input of the model is and what the assumptions are.
- It is also important that parties themselves can play with it, understand the interactions and that the model's uncertainties are clear.
- Stakeholder is in favour of sharing data to accelerate the energy transition.
- Stakeholder is willing to verify price ranges.
- Stakeholder would like to use the model, but this depends on the quality, detail and flexibility versus the question they want to answer with it.

A.3.6. Electrolyser and Wind Turbine Manufacturer

- It would be useful if eventually a standard calculation method could be developed to compare different concepts.
- Now, it is still unclear how the market will develop as it is still in its conceptual phase. All concepts are currently inherently uncertain, because they are still concepts. Parties are careful to share their views because of commercial sensitivity, but also because of the uncertainty in basic assumptions. Nobody knows exactly how much this new technology will cost because it is all still conceptual.
- The experience with large energy and hydrogen projects is too limited so far: it is necessary to scale up quickly on land to gain experience.
- Stakeholder would be willing to share the 'direction of their thoughts', but assumptions and calculations are a step too far. However, they'd be willing to verify price ranges.
- A concern for Stakeholder is, that developments in electrolysis are so rapid that a model may not always deliver the right predictions.

A.3.7. Engineering Consultant

Engineering Consultant 1

- Stakeholder suggests that having a better understanding of the cost levels of hydrogen production onshore/offshore would make it easier for policymakers to make informed decisions about infrastructure planning and policies that may impact the industry.
- A model would be useful to see how alternative systems compare and where you need to innovate to reduce the costs.
- Stakeholder predicts that it will be difficult to obtain sensitive data from suppliers for an open source model.
- An alternative is to use public sources to define input data based on bandwidths/ranges and have the industry verify this.
- Stakeholder recommends designating an owner of the model who will keep it updated and maintained on behalf of the industry. An association could play this role (analogous to the FLOW/TKI-WOZ offshore wind cost model).

Engineering Consultant 2

- A standardised model would be valuable to Stakeholder, which could also serve as a benchmark for them
- The only problem is, that they won't be able to see the calculations/details/assumptions behind the modules with the current model set-up
- Stakeholder would prefer the input data to be public and transparent. In that case, they would be willing to contribute to setting up the model.

A.3.8. Port

- Stakeholder would only use the model to show that their location has a good business climate and thus positive impact on the final price of H2 for companies.
- The model is useful to understand the structure of LCOH, to better understand what a supply chain looks like and the effect of the type of supply chain on the final price.
- Stakeholder sees educational added value from the model. In this way, the port can better understand the LCOH and its construction. When they sit at the table with customers, they also want to be able to join in the discussion.
- The data on hydrogen is currently still quite unreliable and changing a lot. How the model works and how an LCOH is constructed tells the port more than which exact LCOH is extracted.

B

Model Data

In this Appendix, the data used in the model and their sources are clarified.

B.1. General Data

Parameter	Value	Unit	Source
Escalation	2	%	European Central Bank, 2021
WACC	9.84	%	MTBS
Electricity Sell Price	0.18	€/kWh	Nieuwe Stroom, 2023; Anciaux, 2019
Hydrogen Sell Price	6	€/kg	Ortiz-Cebolla et al., 2022; S&P Global Platts, n.d.; Zhou and Searle, 2022

Table B.1: Assumed values for general parameters with their sources

B.2. Financial Parameters per Element

B.2.1. Offshore wind park

Foundation & Cables

Parameter	Value	Unit	Source
Capex	1,000,000	€/MW	Crown Estate, 2019; Roos, 2021
Opex	1.5	% of Capex total	Van Oord, MTBS
Economic Lifetime	30	Years	Van Oord
Insurance Rate	0.5	% of Capex total	Van Oord, MTBS
Decommissioning Rate	35	% of Capex total	Van Oord; Jalili and Maheri, 2022

Table B.2: Assumed values for 'Foundation & Cables' parameters with their sources

Turbine

Parameter	Value	Unit	Source
Capex	1,200,000	€/MW	Crown Estate, 2019; McDonagh et al., 2020; Ohlsen, 2019
Opex	3	% of Capex total	Van Oord, MTBS
Economic Lifetime	30	Years	Van Oord
Insurance Rate	0.5	% of Capex total	Van Oord, MTBS
Decommissioning Rate	8	% of Capex total	Van Oord; Jalili and Maheri, 2022

Table B.3: Assumed values for 'Turbine' parameters with their sources

B.2.2. AC Substation & Transport

AC Substation

Parameter	Value	Unit	Source
Capex	185,000	€/MW	Crown Estate, 2019; WECC, 2019
Opex	3	% of Capex total	Van Oord, MTBS
Economic Lifetime	40	Years	Van Oord
Insurance Rate	0.5	% of Capex total	Van Oord, MTBS
Decommissioning Rate	2	% of Capex total	Van Oord

Table B.4: Assumed values for 'AC Substation' parameters with their sources

AC Collection Cable

Parameter	Value	Unit	Source
Capex	2,000	€/m	Crown Estate, 2019; PetroWiki, 2022
Opex	3	% of Capex total	Van Oord, MTBS
Economic Lifetime	40	Years	Van Oord
Insurance Rate	0.5	% of Capex total	Van Oord, MTBS
Decommissioning Rate	2	% of Capex total	Van Oord; Jalili and Maheri, 2022

Table B.5: Assumed values for 'AC Collection Cable' parameters with their sources

B.2.3. Converter & Transport

HVDC Converter

Parameter	Value	Unit	Source
Capex	470,000	€/MW	Crown Estate, 2019; WECC, 2019
Opex	2	% of Capex total	Van Oord, MTBS
Economic Lifetime	30	Years	Van Oord
Insurance Rate	0.5	% of Capex total	Van Oord, MTBS
Decommissioning Rate	2	% of Capex total	Van Oord

Table B.6: Assumed values for 'HVDC Converter' parameters with their sources

HVDC Cable

Parameter	Value	Unit	Source
Capex	3,800	€/m	Crown Estate, 2019; Jansen et al., 2022 Zhao et al., 2020
Opex	2	% of Capex total	Van Oord, MTBS
Economic Lifetime	30	Years	Van Oord
Insurance Rate	0.5	% of Capex total	Van Oord, MTBS
Decommissioning Rate	2	% of Capex total	Van Oord

Table B.7: Assumed values for 'HVDC Cable' parameters with their sources

B.2.4. Electrolysis, Electricity & Transport

Electrolyser

Parameter	Value	Unit	Source
Capex	500,000	€/MW	ISPT, 2023; BEIS, 2021; McDonagh et al., 2020; Roos, 2021; Taibi et al., 2020
Opex	2	% of Capex total	Van Oord, MTBS
Economic Lifetime	25	Years	Van Oord
Insurance Rate	0.5	% of Capex total	Van Oord, MTBS
Decommissioning Rate	2	% of Capex total	Van Oord

Table B.8: Assumed values for 'Electrolyser' parameters with their sources

Desalination Unit

Parameter	Value	Unit	Source
Capex	4,000	€/MW	Breunis, 2021; Caldera and Breyer, 2017; Janowitz et al., 2022; Moser et al., 2015
Opex	2	% of Capex total	Van Oord, MTBS
Economic Lifetime	15	Years	Van Oord
Insurance Rate	0.5	% of Capex total	Van Oord, MTBS
Decommissioning Rate	2	% of Capex total	Van Oord

Table B.9: Assumed values for 'Desalination Unit' parameters with their sources

Compressor Unit

Parameter	Value	Unit	Source
Capex	150,000	€/MW	Breunis, 2021; ISPT, 2023; BEIS, 2021; Lucas et al., 2022
Opex	2	% of Capex total	Van Oord, MTBS
Economic Lifetime	15	Years	Van Oord
Insurance Rate	0.5	% of Capex total	Van Oord, MTBS
Decommissioning Rate	2	% of Capex total	Van Oord

Table B.10: Assumed values for 'Compressor Unit' parameters with their sources

Storage Unit

Parameter	Value	Unit	Source
Capex	300,000	€/MW	ISPT, 2023; BEIS, 2021; Lucas et al., 2022
Opex	2	% of Capex total	Van Oord, MTBS
Economic Lifetime	15	Years	Van Oord
Insurance Rate	0.5	% of Capex total	Van Oord, MTBS
Decommissioning Rate	2	% of Capex total	Van Oord

Table B.11: Assumed values for 'Storage Unit' parameters with their sources

Compressor After Storage

Parameter	Value	Unit	Source
Capex	10,000	€/MW	ISPT, 2023; BEIS, 2021
Opex	2	% of Capex total	Van Oord, MTBS
Economic Lifetime	15	Years	Van Oord
Insurance Rate	0.5	% of Capex total	Van Oord, MTBS
Decommissioning Rate	2	% of Capex total	Van Oord

Table B.12: Assumed values for 'Compressor after Storage' parameters with their sources

DCAC Converter

Parameter	Value	Unit	Source
Capex	300,000	€/MW	Crown Estate, 2019; Breunis, 2021
Opex	3	% of Capex total	Van Oord, MTBS
Economic Lifetime	25	Years	Van Oord
Insurance Rate	0.5	% of Capex total	Van Oord, MTBS
Decommissioning Rate	2	% of Capex total	Van Oord

Table B.13: Assumed values for 'DCAC Converter' parameters with their sources

Artificial Island

Parameter	Value	Unit	Source
Capex	990,000 - 1.760,000,000 (5.2)	€	van der Veer et al., 2020
Opex	2	% of Capex total	Van Oord, MTBS
Economic Lifetime	80	Years	Van Oord
Insurance Rate	0.5	% of Capex total	Van Oord, MTBS
Decommissioning Rate	2	% of Capex total	Van Oord

Table B.14: Assumed values for 'Artificial Island' parameters with their sources

Mainland

Parameter	Value	Unit	Source
Capex	6,000	€/MW	MTBS
Opex	1	% of Capex total	Van Oord, MTBS
Economic Lifetime	30	Years	Van Oord
Insurance Rate	0.5	% of Capex total	Van Oord, MTBS
Decommissioning Rate	1	% of Capex total	Van Oord

Table B.15: Assumed values for 'Mainland' parameters with their sources

H2 Pipeline

Parameter	Value	Unit	Source
Capex	1,500	€/m	Breunis, 2021 Di Lullo et al., 2022
Opex	2	% of Capex total	Van Oord, MTBS
Economic Lifetime	30	Years	Van Oord
Insurance Rate	0.5	% of Capex total	Van Oord, MTBS
Decommissioning Rate	2	% of Capex total	Van Oord

Table B.16: Assumed values for 'H2 Pipeline' parameters with their sources

B.3. Efficiencies

Parameter	Value	Unit	Source
Inter-Array Cable Efficiency	99	%	Van Oord, Breunis, 2021 Lucas et al., 2022
AC Collection Cable Efficiency	95	%	Van Oord, Breunis, 2021
HVDC Cable Efficiency	100 - (0.00005*(x) + 4)	%	Eeckhout et al., 2009 (Fig B.1)
H2 Pipeline Efficiency	95	%	Breunis, 2021
DCAC Converter Efficiency	90	%	Breunis, 2021
Electrolysis Efficiency	50	kWh/kg	V. N. Dinh et al., 2021; Breunis, 2021

Table B.17: Assumed values for efficiencies with their sources

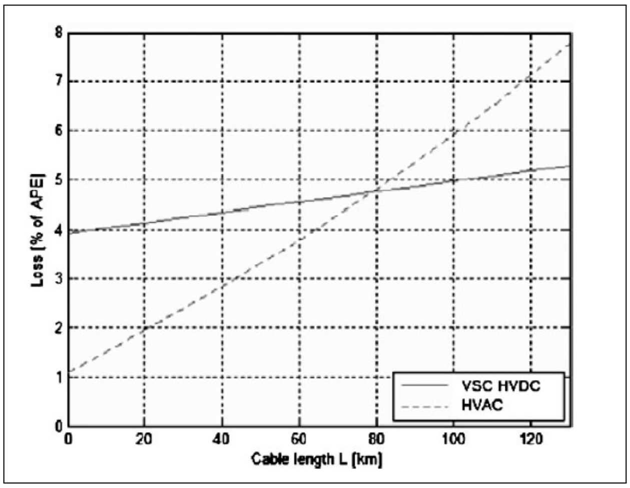

Figure B.1: Loss percentage $l_{\%}$ for VSC HVDC and HVAC cables as a function of cable length for a 300 MW wind farm Eeckhout et al., 2009

C
Results

C.1. Pie charts

C.1.1. Scenario 1

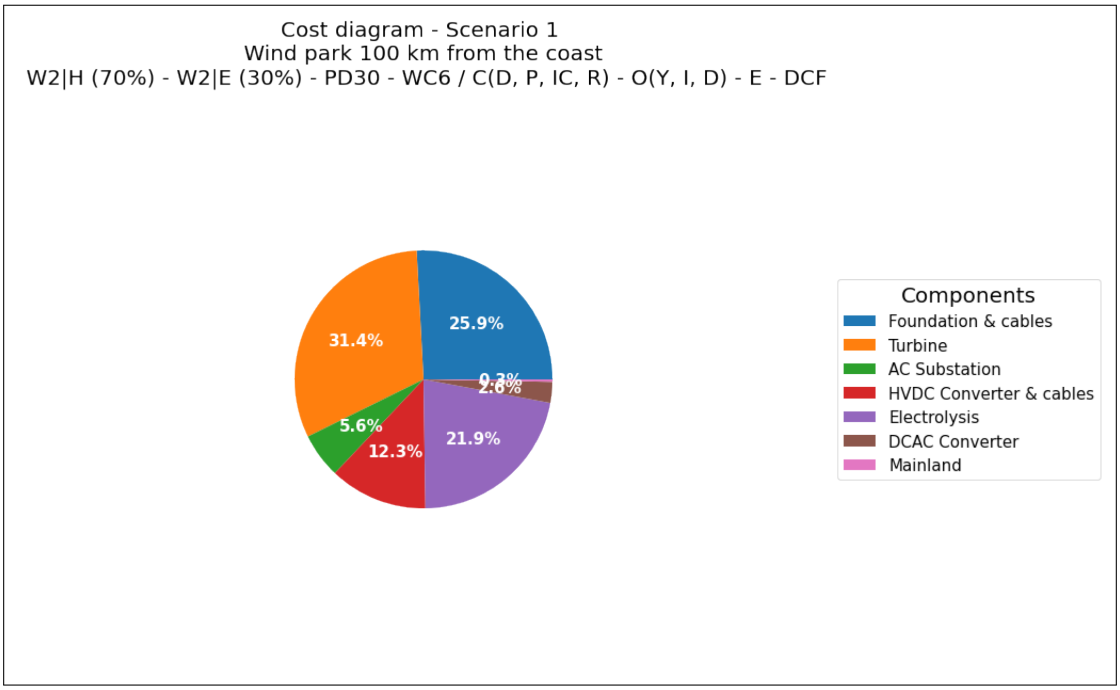

Figure C.1: Scenario 1 - cost breakdown for Case 1a

Total cost (NPV) = €27.9b

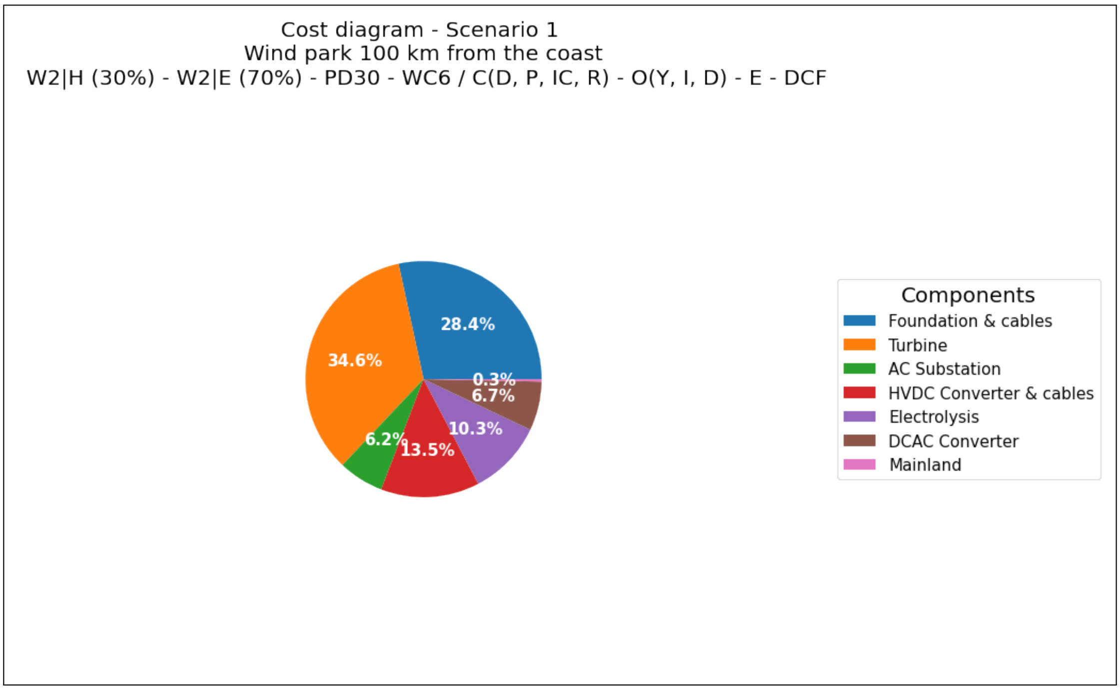

Figure C.2: Scenario 1 - cost breakdown for Case 1b

Total cost (NPV) = €25.6b

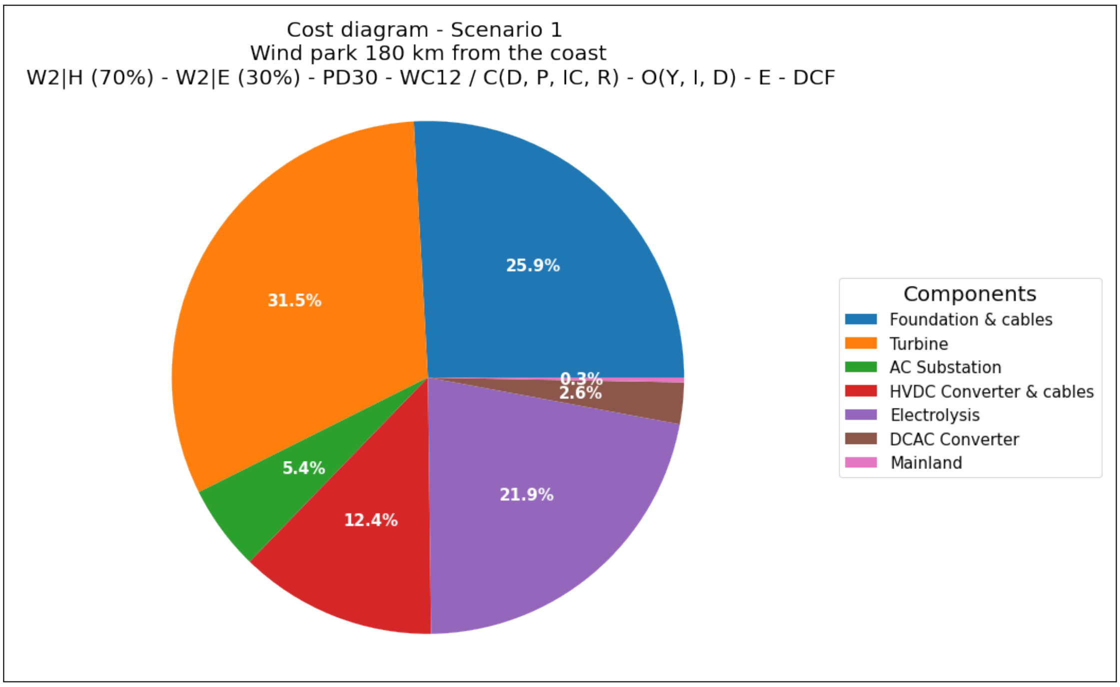

Figure C.3: Scenario 1 - cost breakdown for Case 2a

Total cost (NPV) = €55.7b

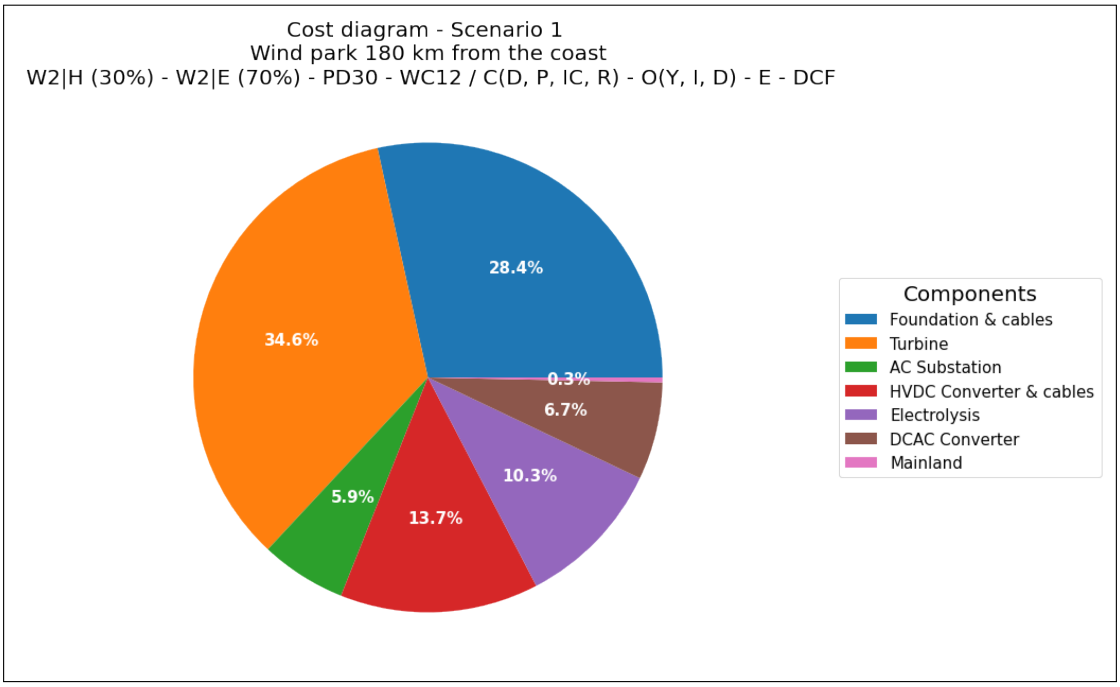

Figure C.4: Scenario 1 - cost breakdown for Case 2b

Total cost (NPV) = €51.1b

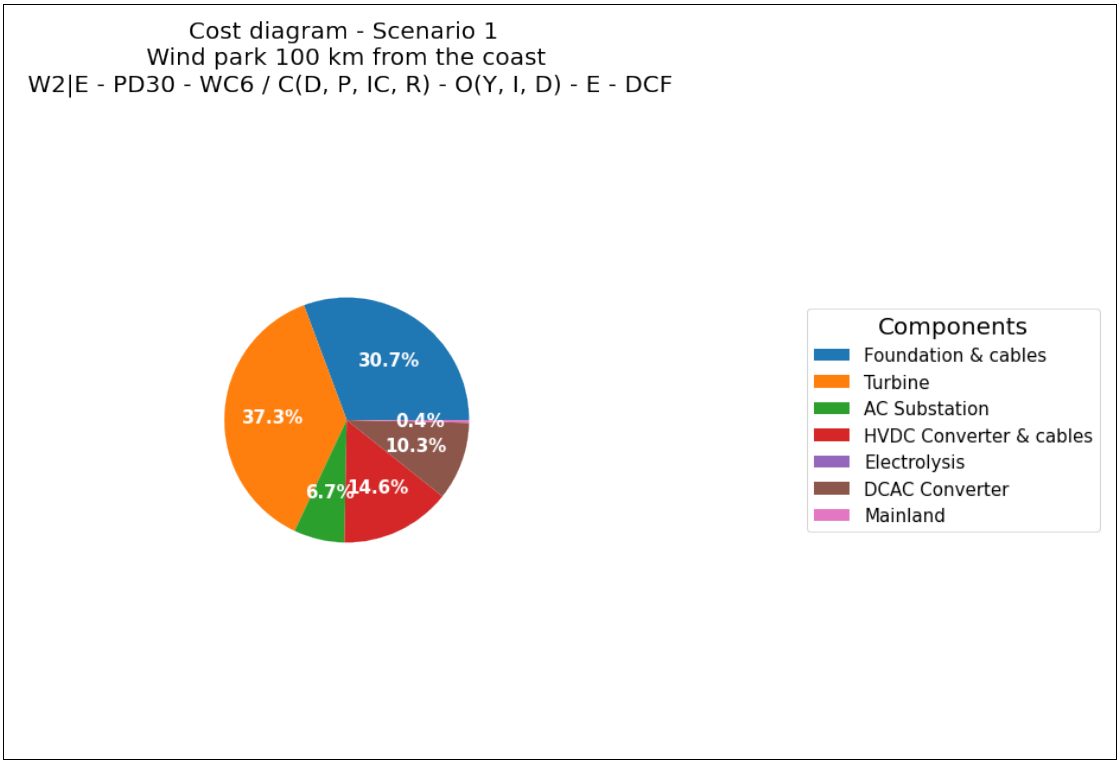

Figure C.5: Scenario 1 - cost breakdown for Case 1c (Reference Case)

Total cost (NPV) = €23.7b

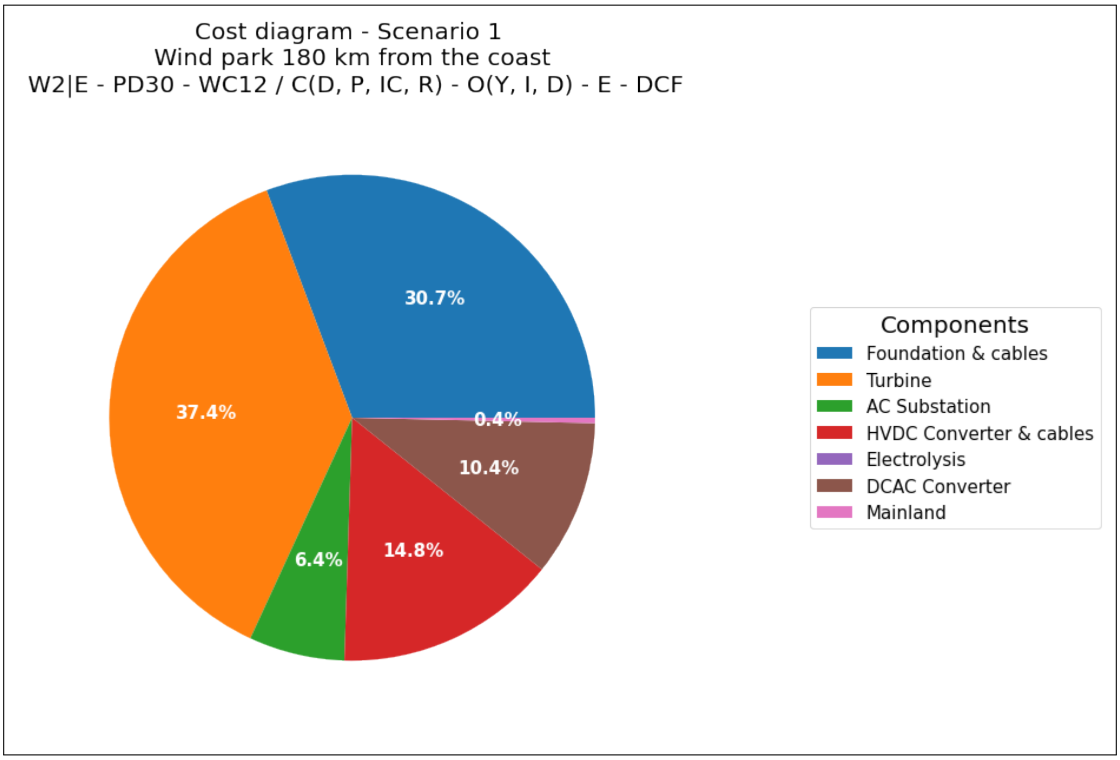

Figure C.6: Scenario 1 - cost breakdown for Case 2c (Reference Case)

Total cost (NPV) = €48.0b

C.1.2. Scenario 2

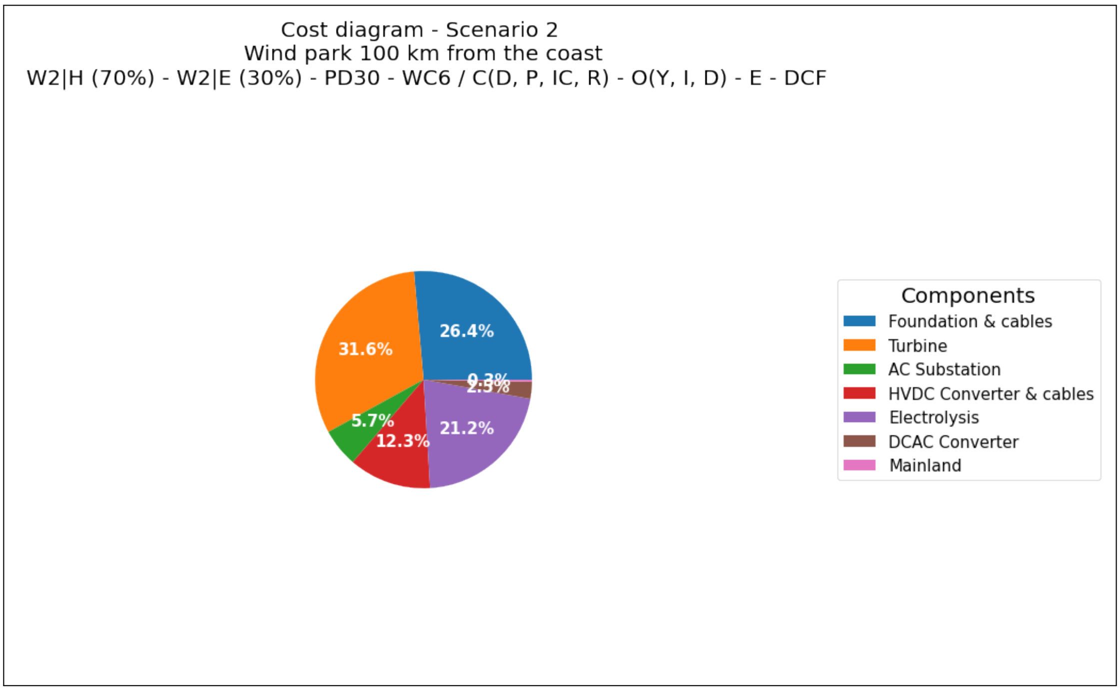

Figure C.7: Scenario 2 - cost breakdown for Case 1a

Total cost (NPV) = €23.4b

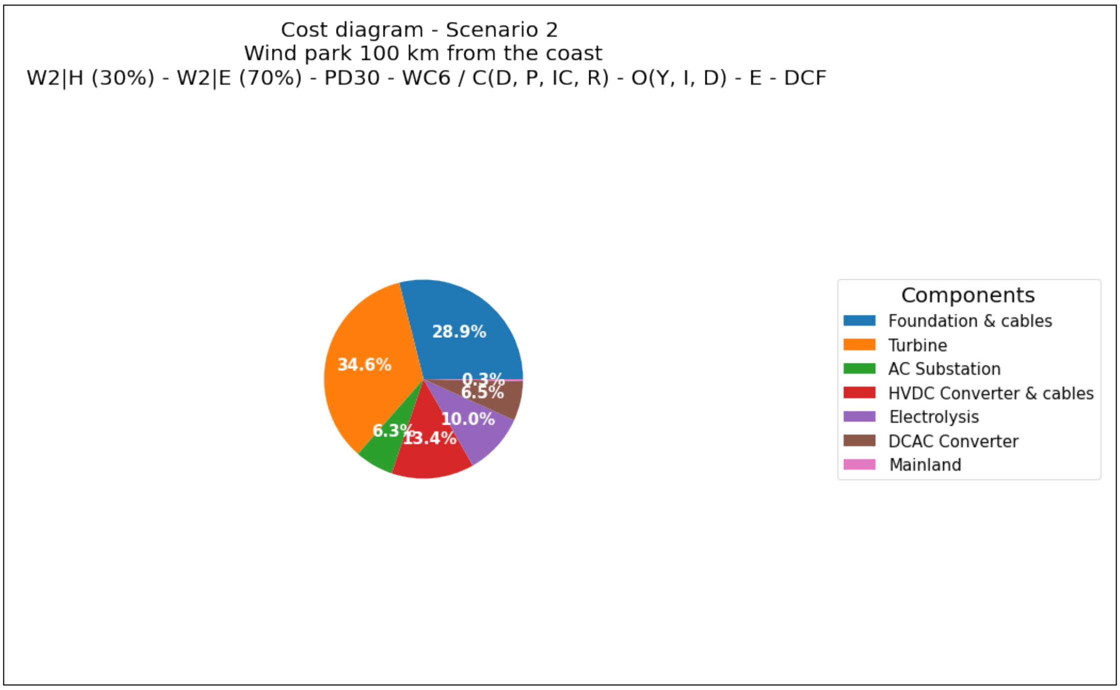

Figure C.8: Scenario 2 - cost breakdown for Case 1b

Total cost (NPV) = €21.5b

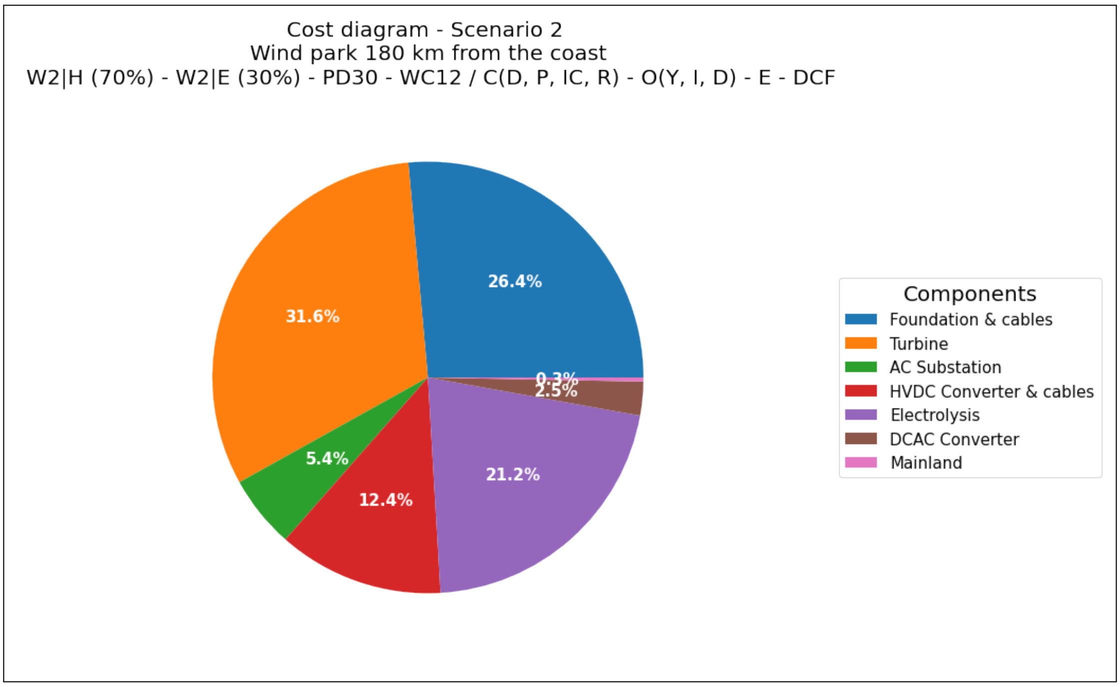

Figure C.9: Scenario 2 - cost breakdown for Case 2a

Total cost (NPV) = €46.8b

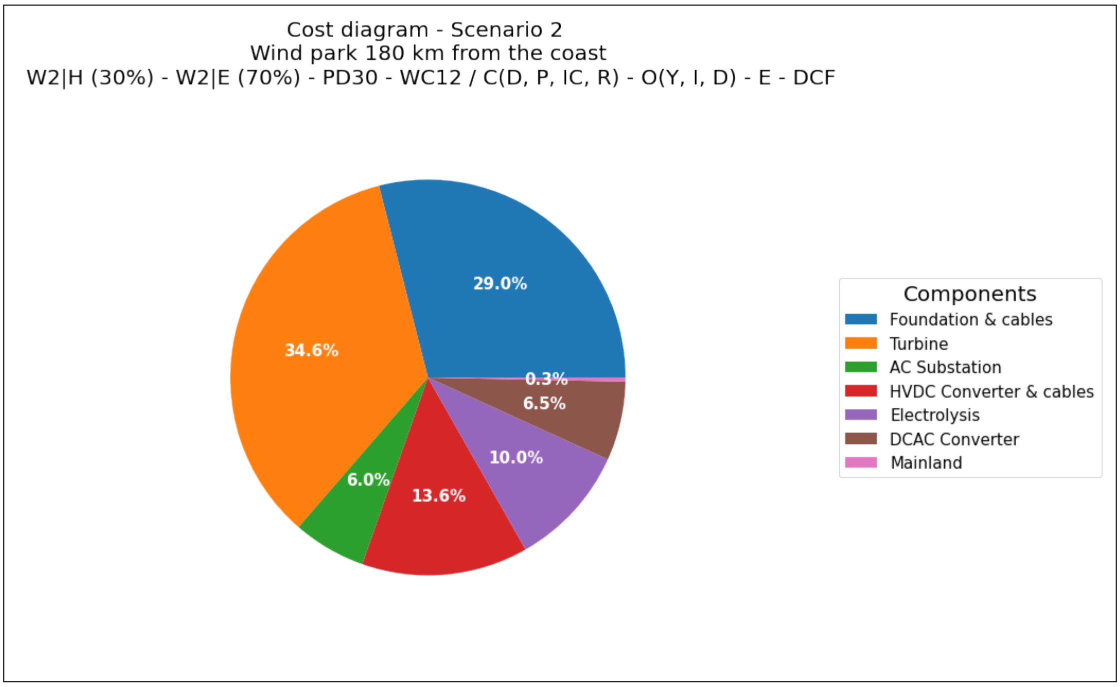

Figure C.10: Scenario 2 - cost breakdown for Case 2b

Total cost (NPV) = €43.0b

C.1.3. Scenario 3

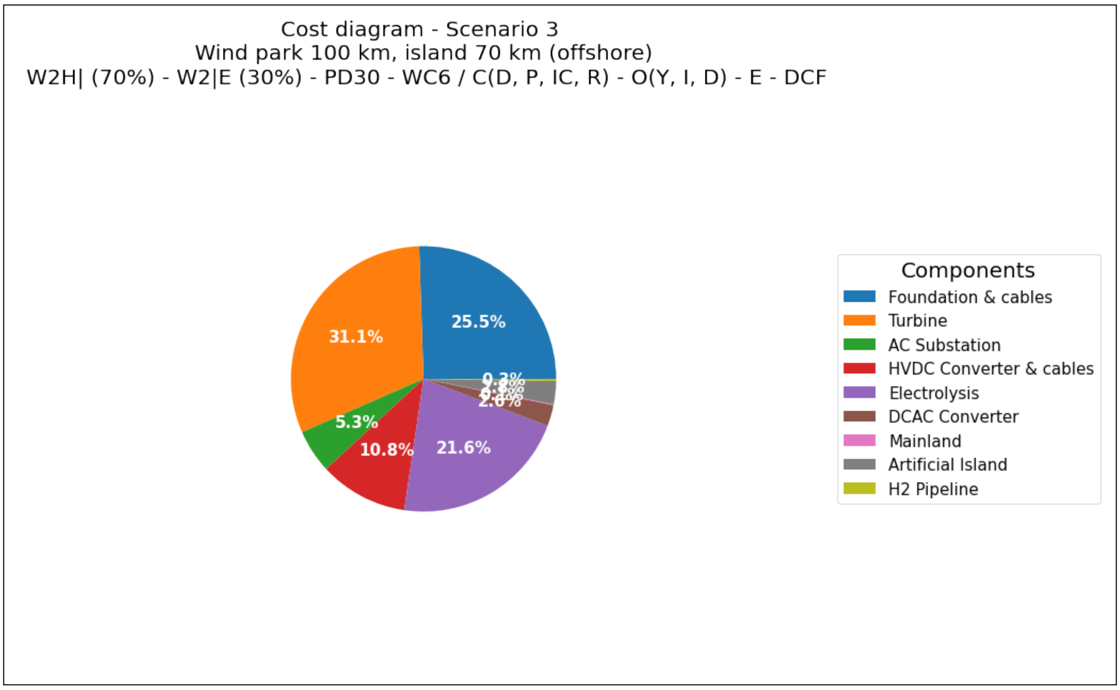

Figure C.11: Scenario 3 - cost breakdown for Case 1a

Total cost (NPV) = €28.6b

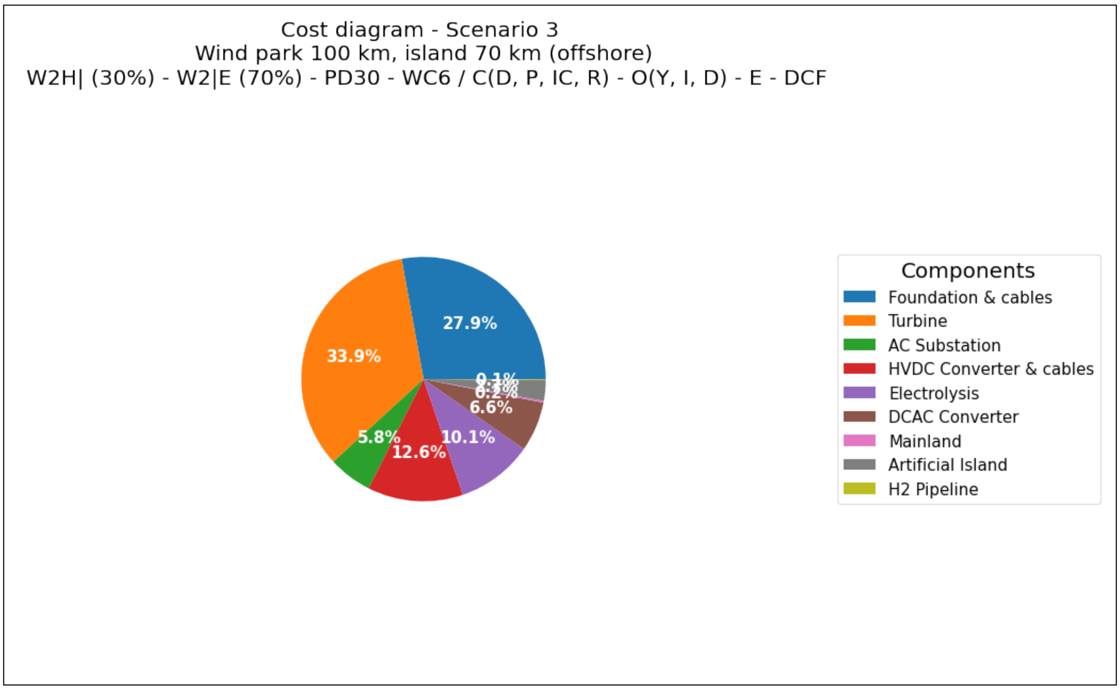

Figure C.12: Scenario 3 - cost breakdown for Case 1b

Total cost (NPV) = €26.5b

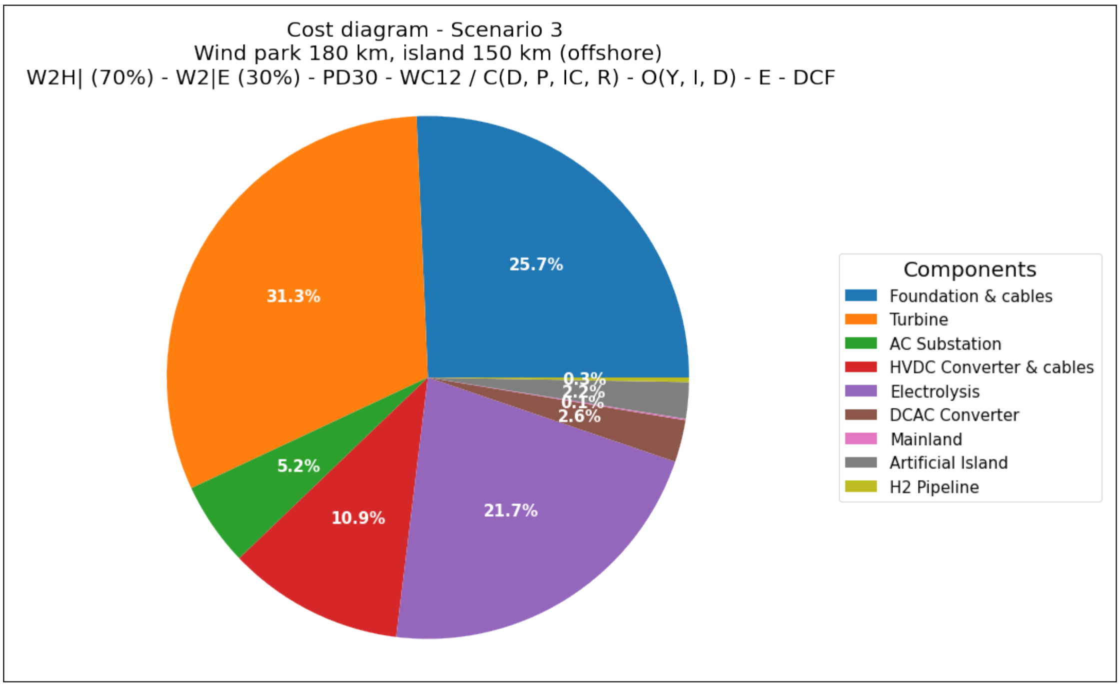

Figure C.13: Scenario 3 - cost breakdown for Case 2a

Total cost (NPV) = €56.8b

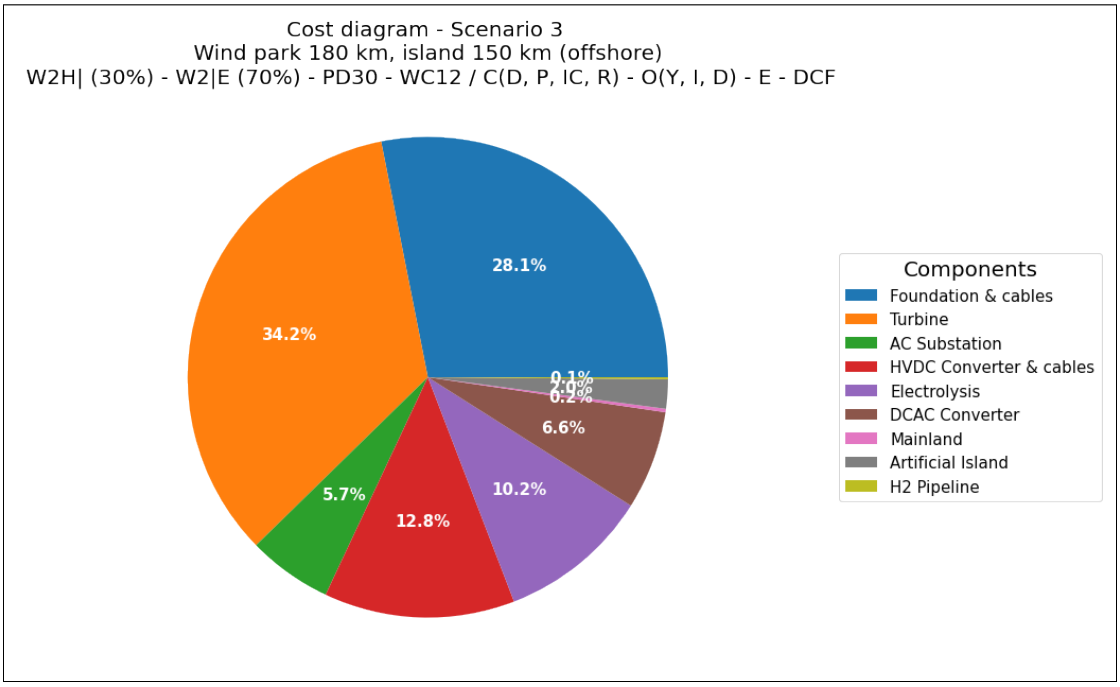

Figure C.14: Scenario 3 - cost breakdown for Case 2b

Total cost (NPV) = €52.3b

C.1.4. Scenario 4

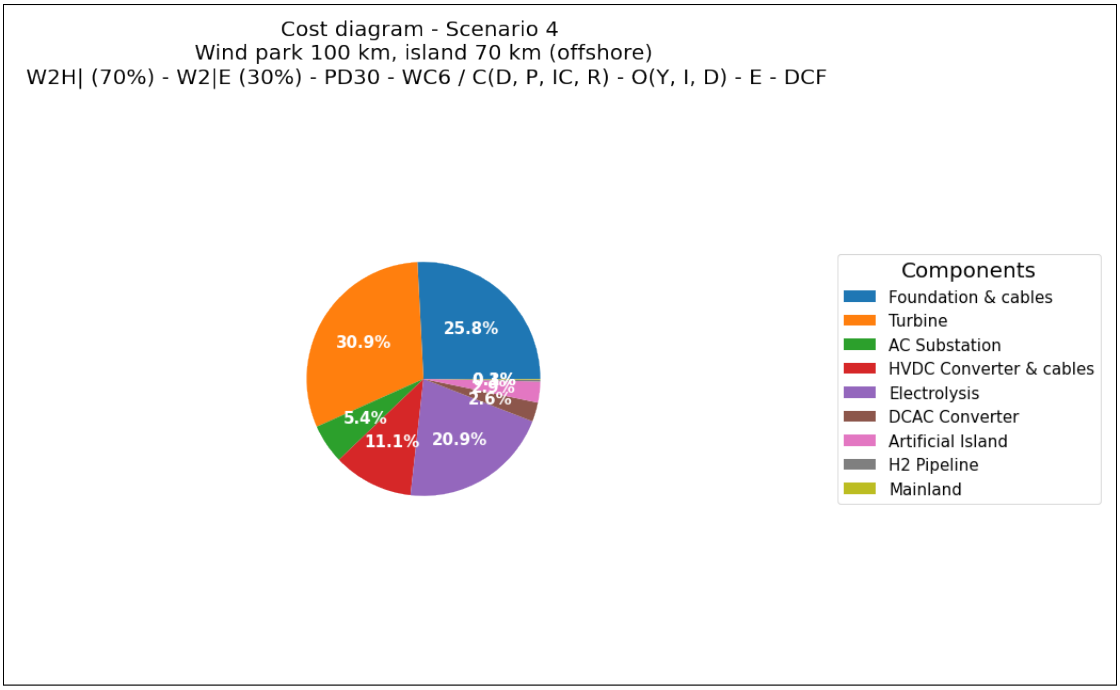

Figure C.15: Scenario 4 - cost breakdown for Case 1a

Total cost (NPV) = €25.3b

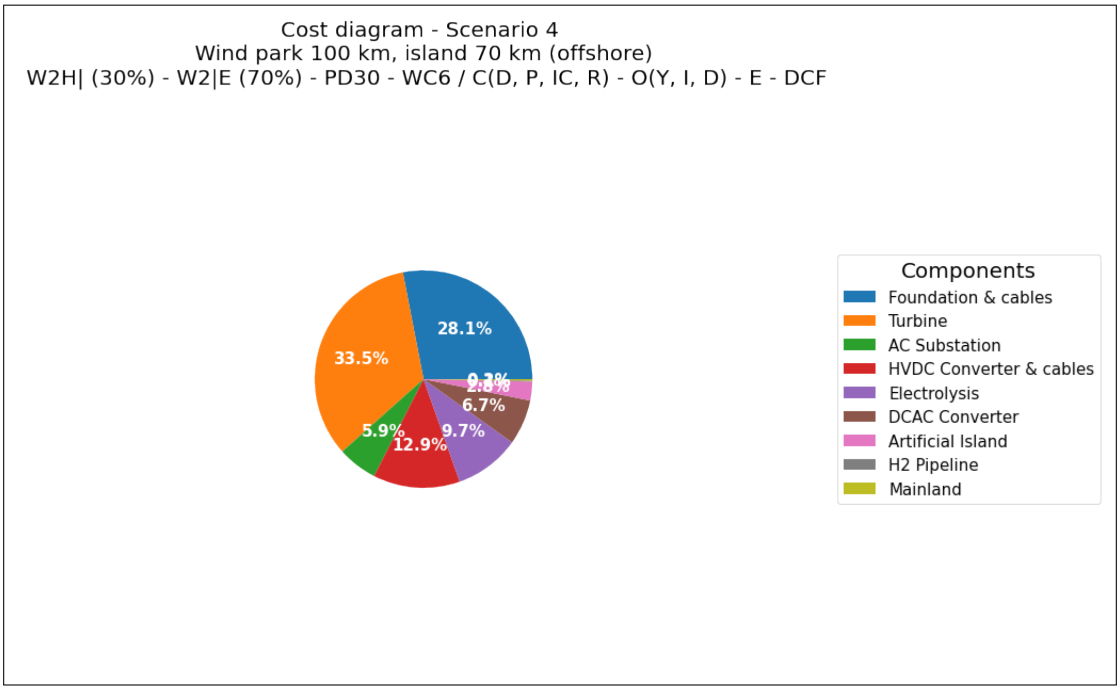

Figure C.16: Scenario 4 - cost breakdown for Case 1b

Total cost (NPV) = €23.6b

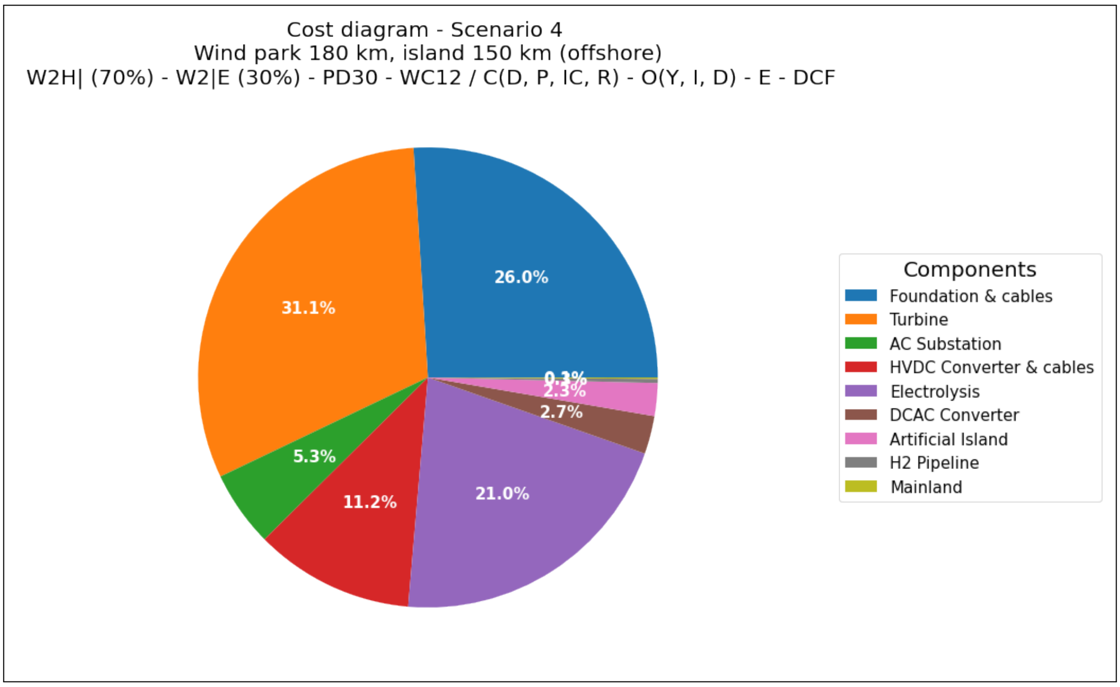

Figure C.17: Scenario 4 - cost breakdown for Case 2a

Total cost (NPV) = €50.0b

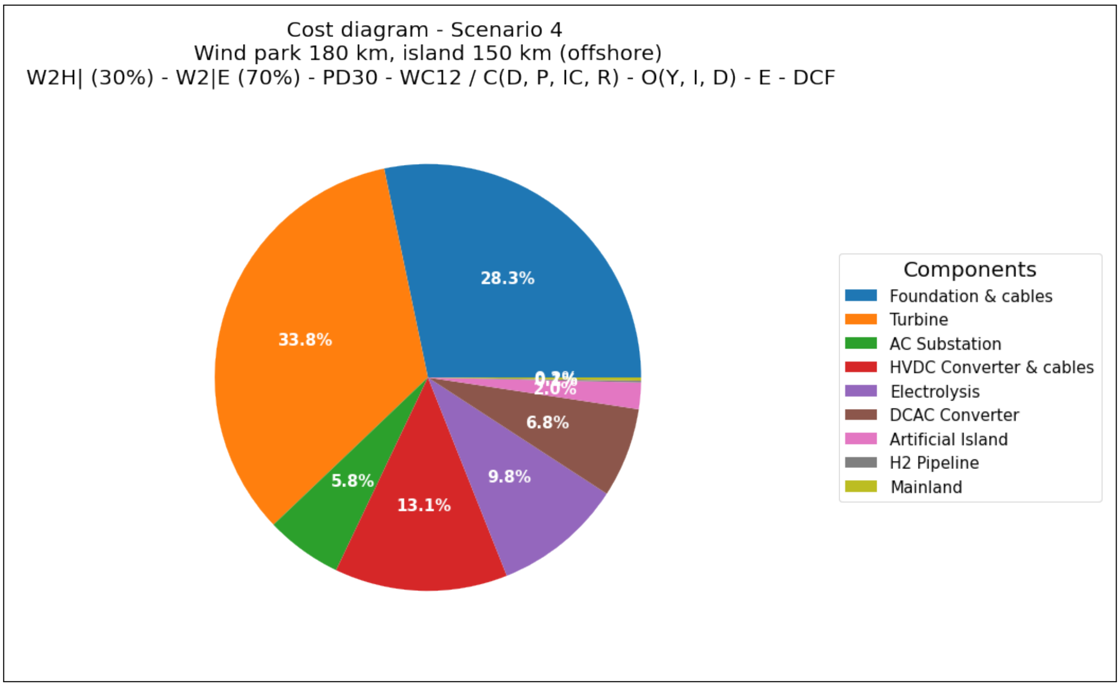

Figure C.18: Scenario 4 - cost breakdown for Case 2b

Total cost (NPV) = €46.5b

C.2. Cash flow charts

C.2.1. Scenario 1

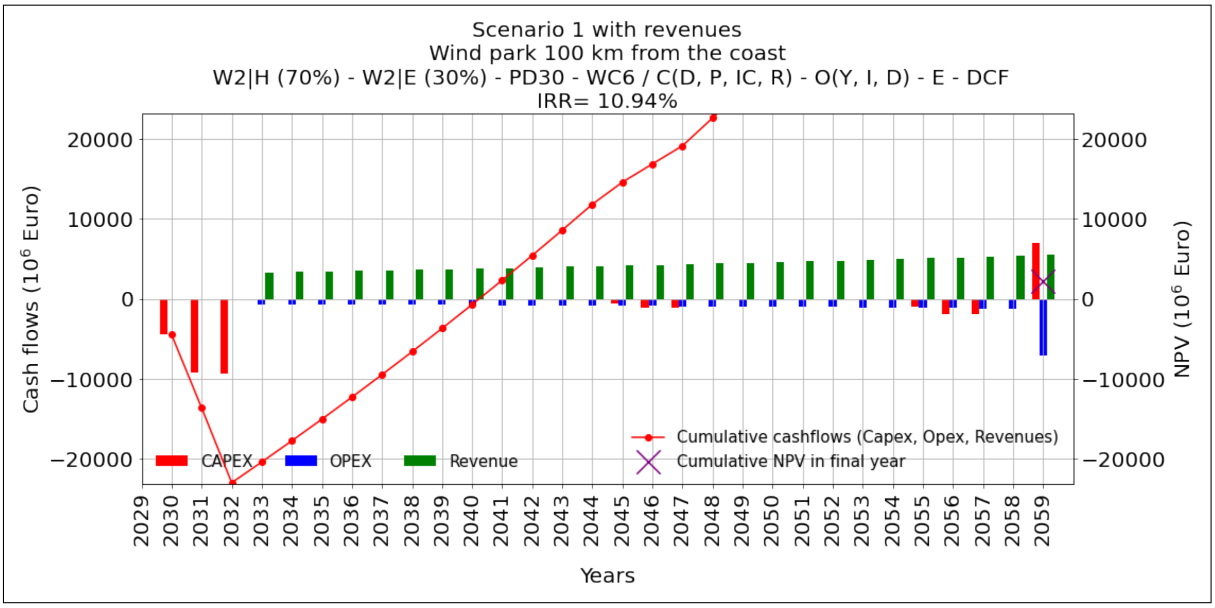

Figure C.19: Scenario 1 - cash flow chart for Case 1a

Final year cumulative NPV = €2.1b

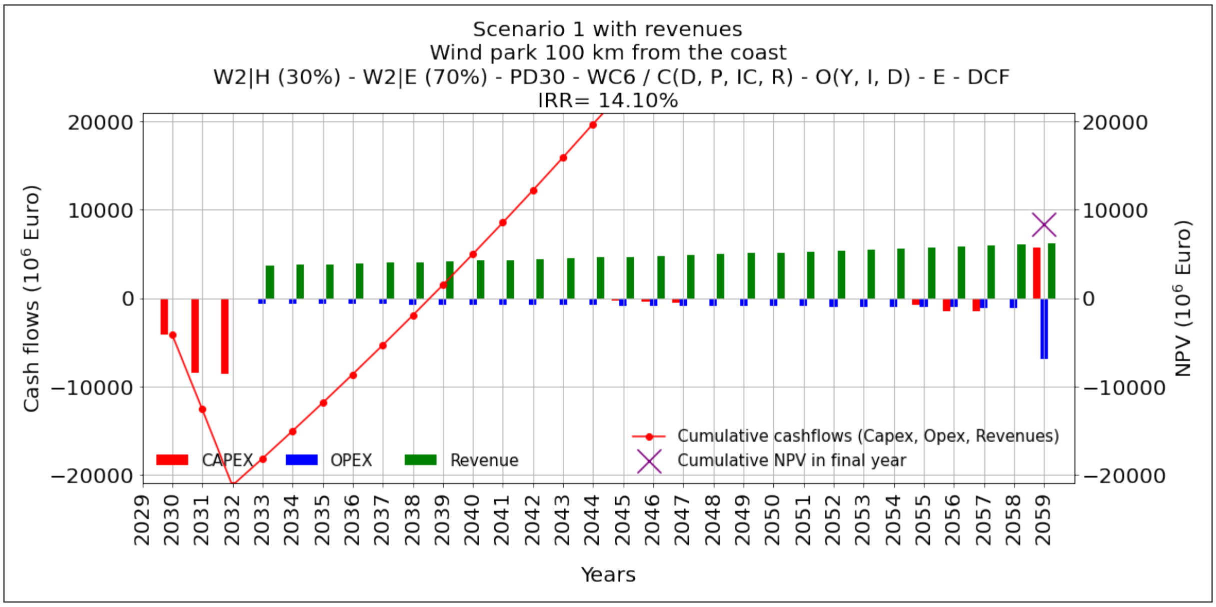

Figure C.20: Scenario 1 - cash flow chart for Case 1b

Final year cumulative NPV = €8.2b

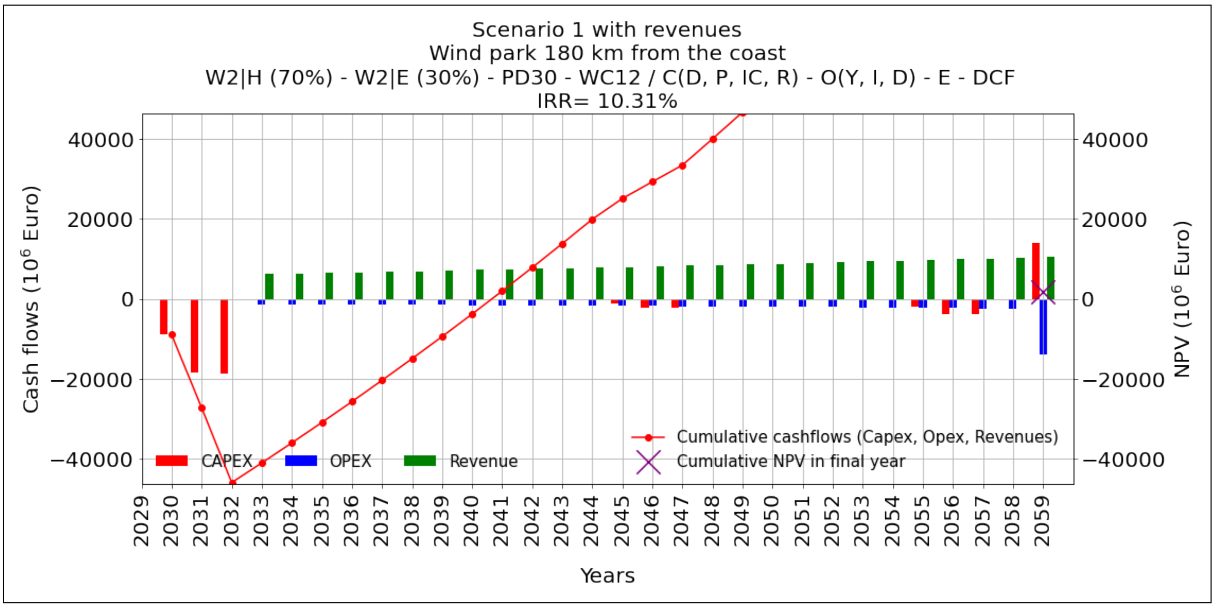

Figure C.21: Scenario 1 - cash flow chart for Case 2a

Final year cumulative NPV = €1.7b

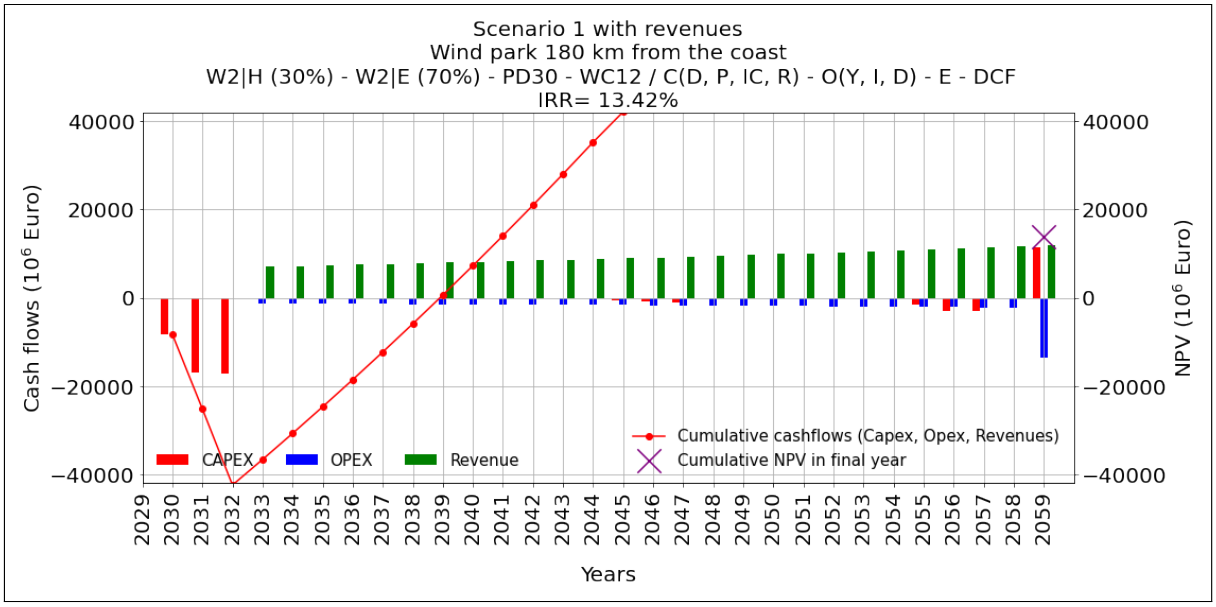

Figure C.22: Scenario 1 - cash flow chart for Case 2b

Final year cumulative NPV = €13.6b

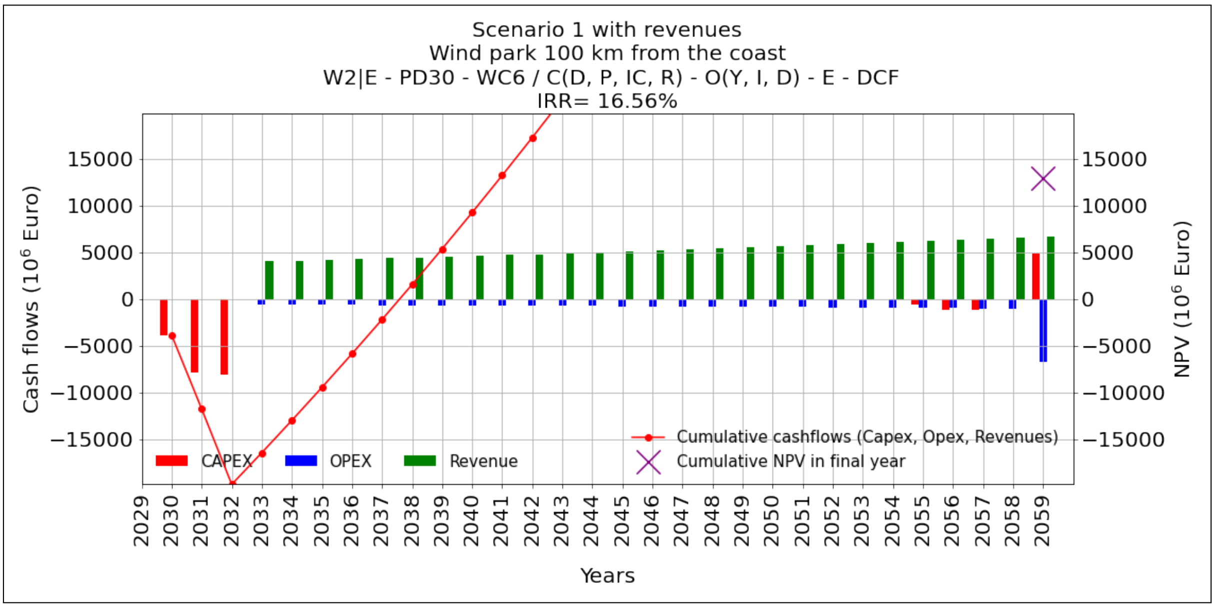

Figure C.23: Scenario 1 - cash flow chart for Case 1c (Reference Case)

Final year cumulative NPV = €12.8b

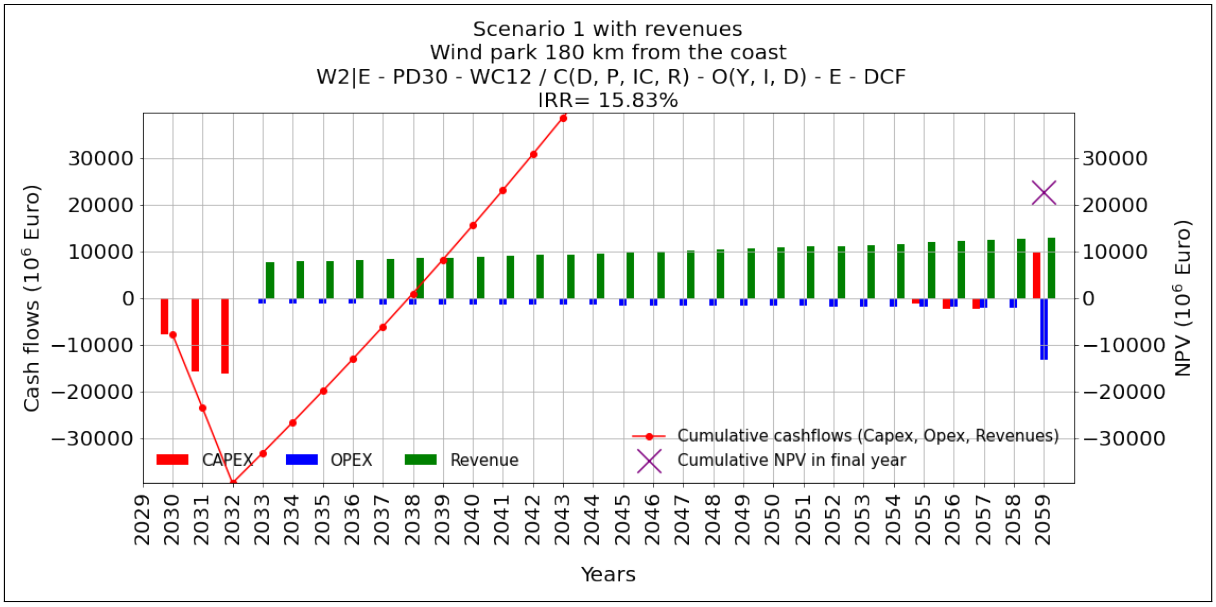

Figure C.24: Scenario 1 - cash flow chart for Case 2c (Reference Case)

Final year cumulative NPV = €22.4b

C.2.2. Scenario 2

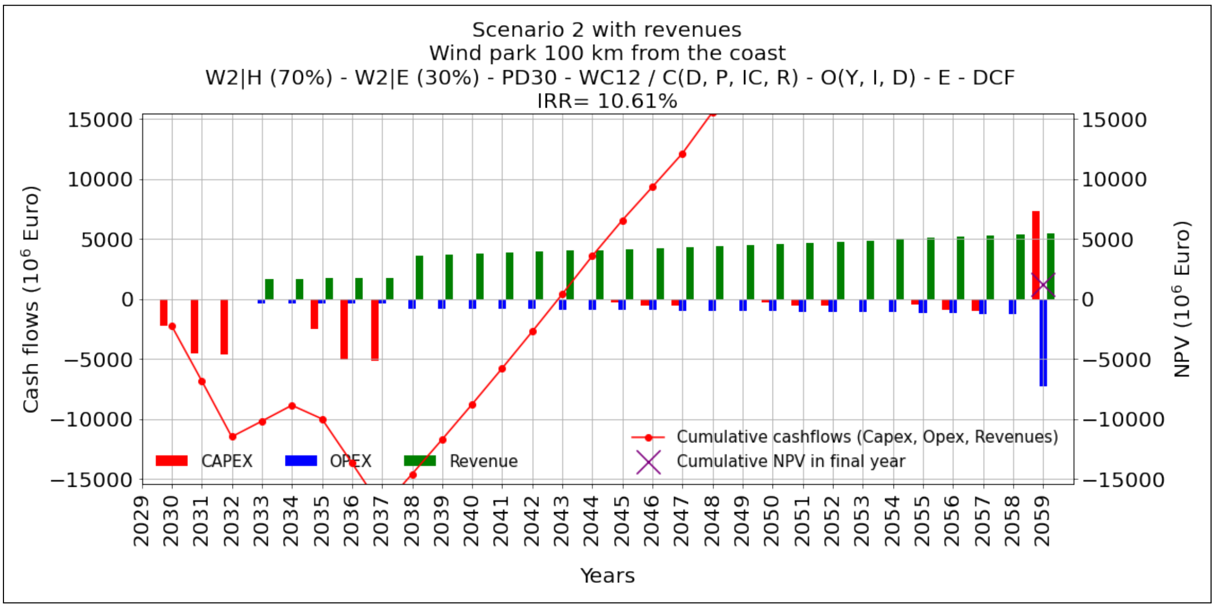

Figure C.25: Scenario 2 - cash flow chart for Case 1a

Final year cumulative NPV = €1.2b

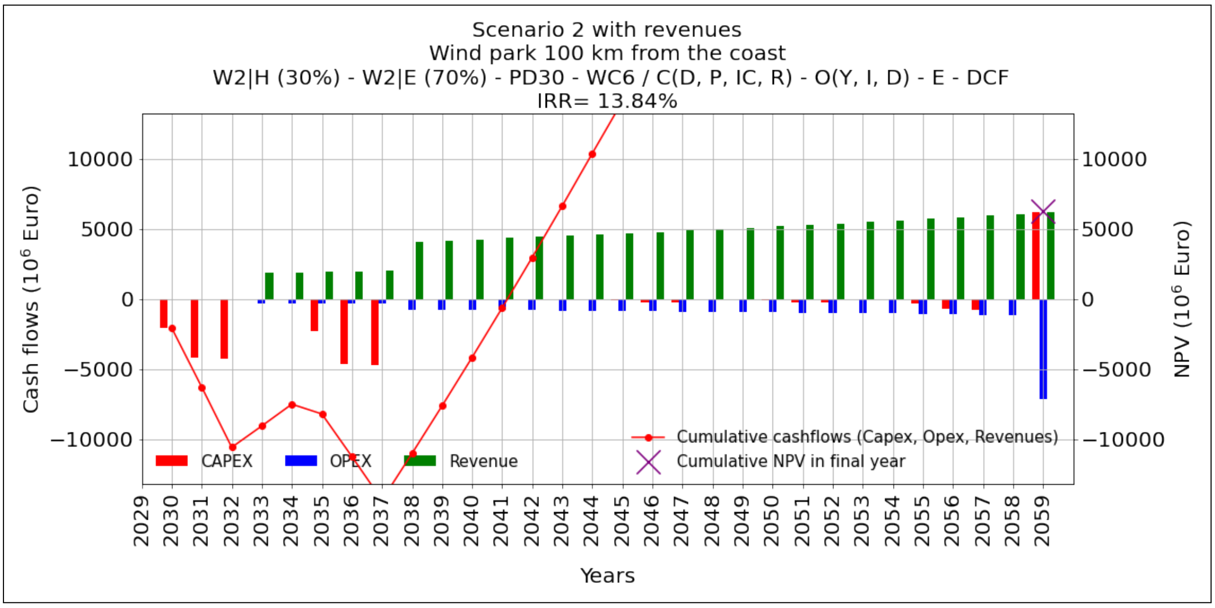

Figure C.26: Scenario 2 - cash flow chart for Case 1b

Final year cumulative NPV = €6.2b

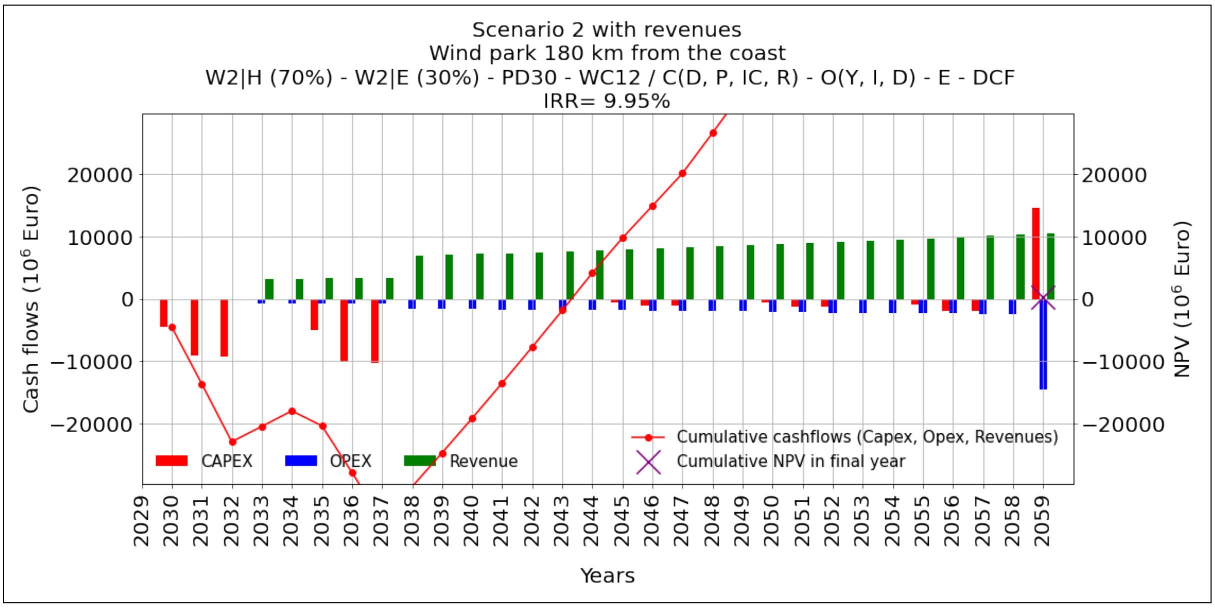

Figure C.27: Scenario 2 - cash flow chart for Case 2a

Final year cumulative NPV = €0.3b

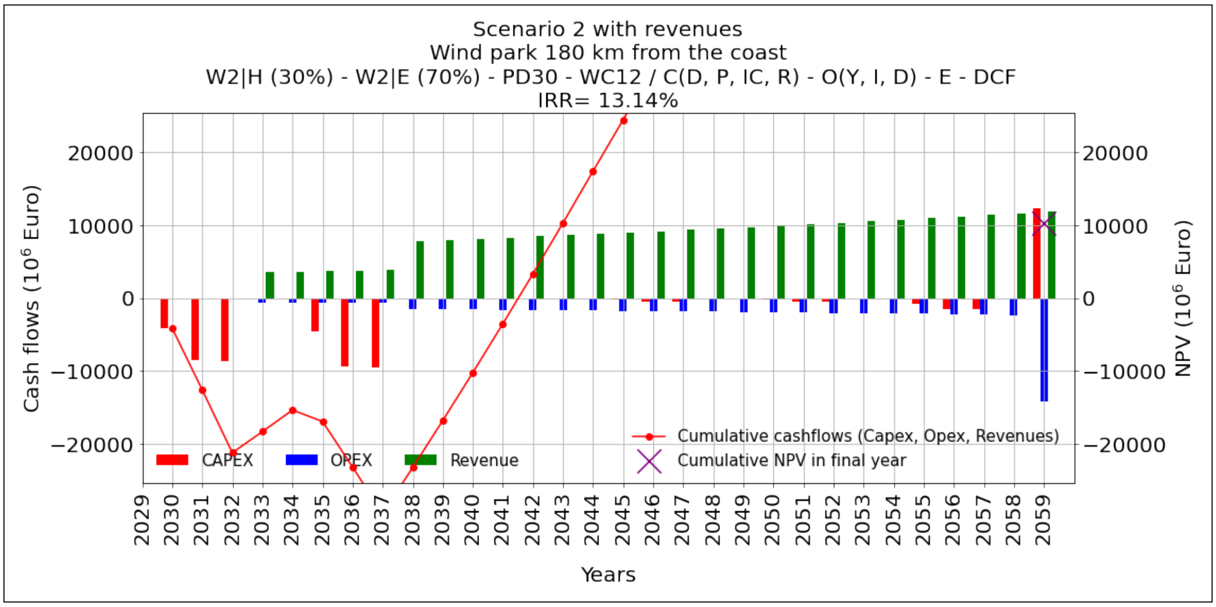

Figure C.28: Scenario 2 - cash flow chart for Case 2b

Final year cumulative NPV = €10.1b

C.2.3. Scenario 3

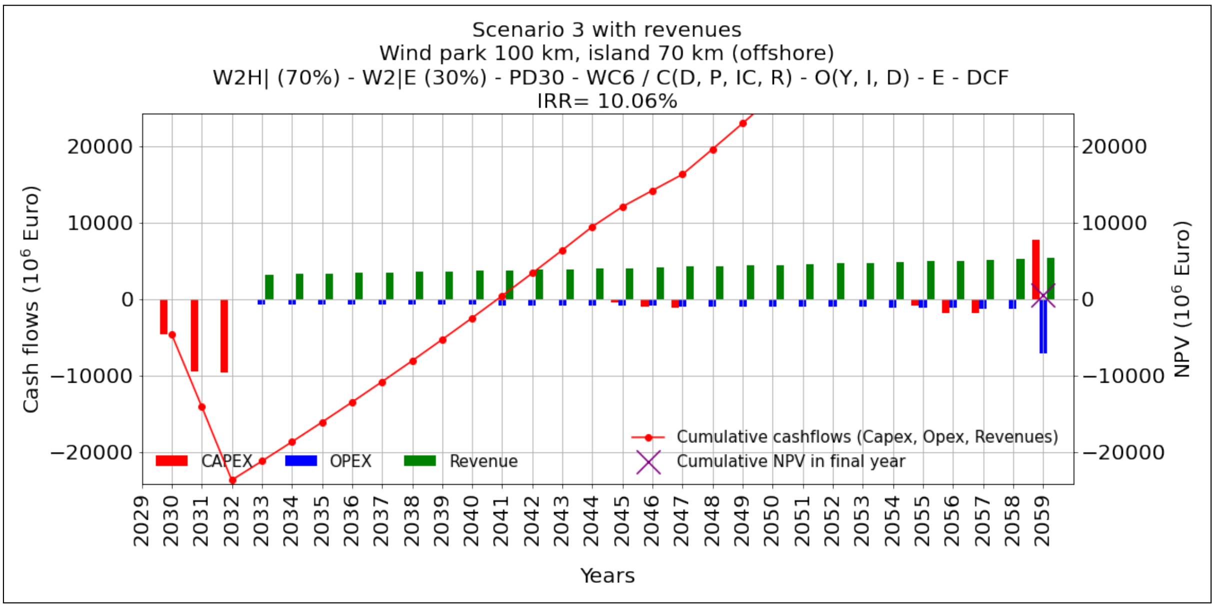

Figure C.29: Scenario 3 - cash flow chart for Case 1a

Final year cumulative NPV = €0.4b

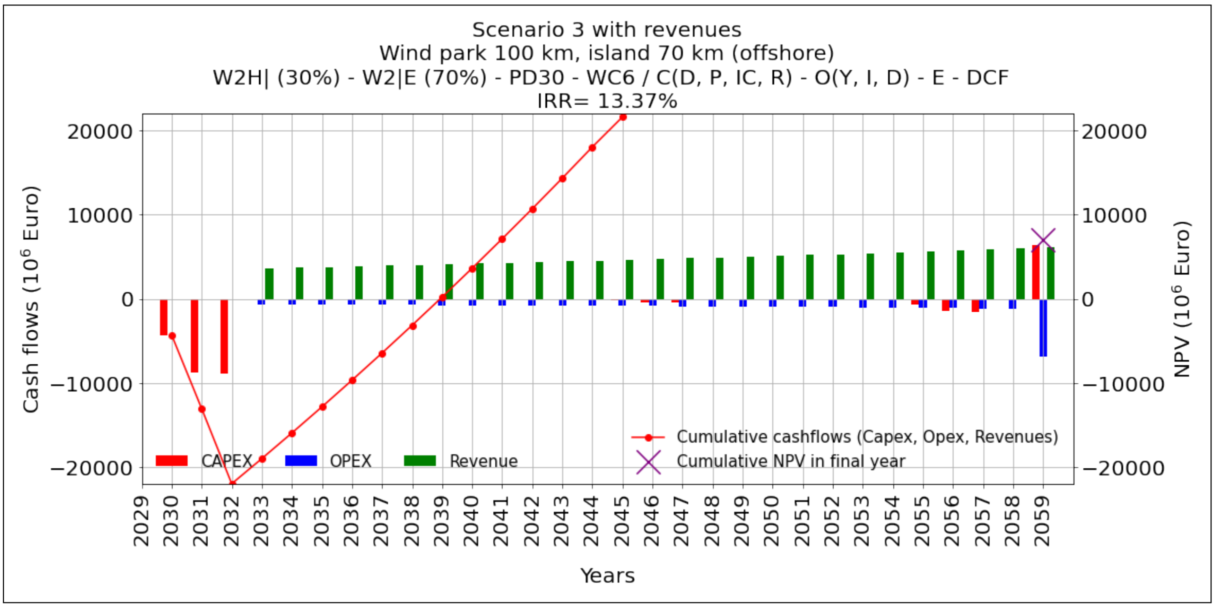

Figure C.30: Scenario 3 - cash flow chart for Case 1b

Final year cumulative NPV = €7.0b

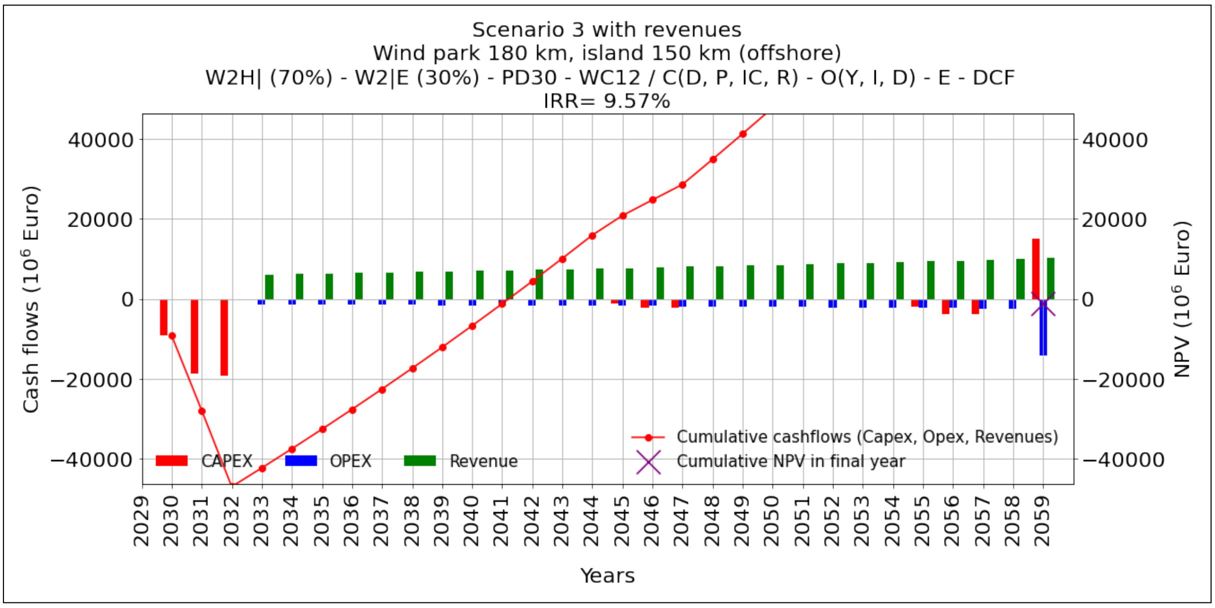

Figure C.31: Scenario 3 - cash flow chart for Case 2a

Final year cumulative NPV = €-1.1b

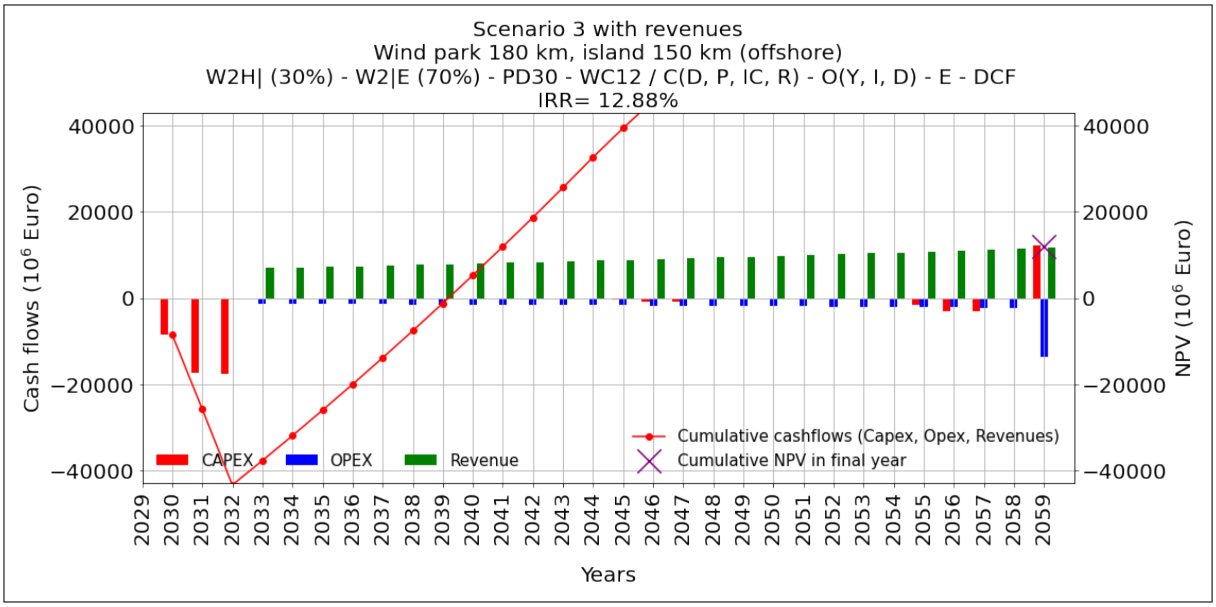

Figure C.32: Scenario 3 - cash flow chart for Case 2b

Final year cumulative NPV = €11.7b

C.2.4. Scenario 4

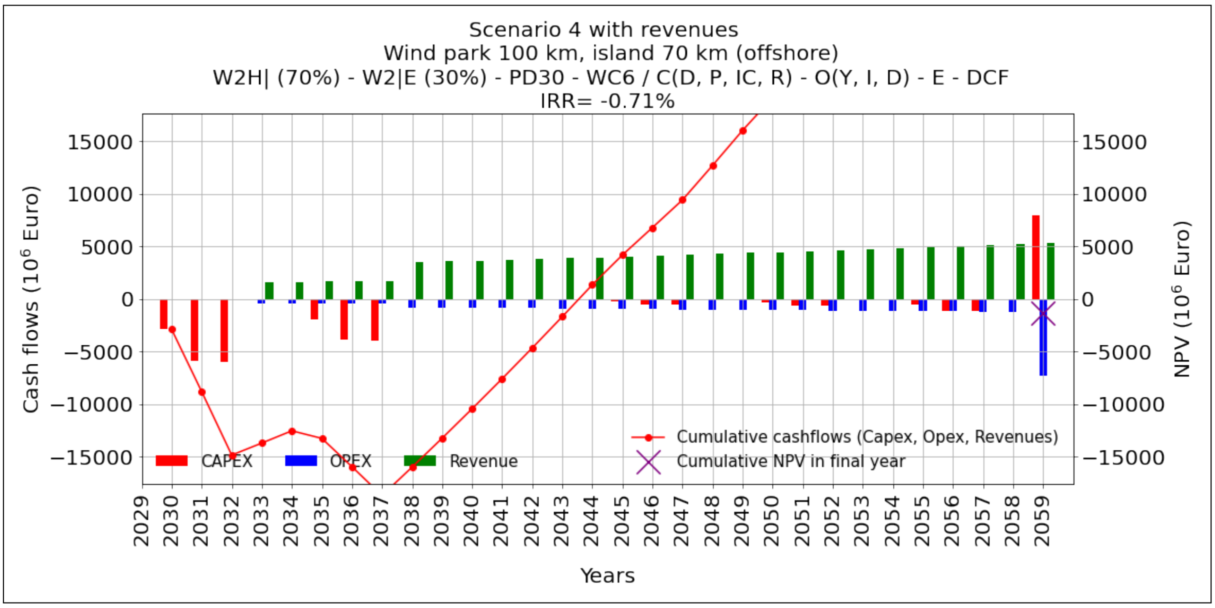

Figure C.33: Scenario 4 - cash flow chart for Case 1a

Final year cumulative NPV = €-1.4b

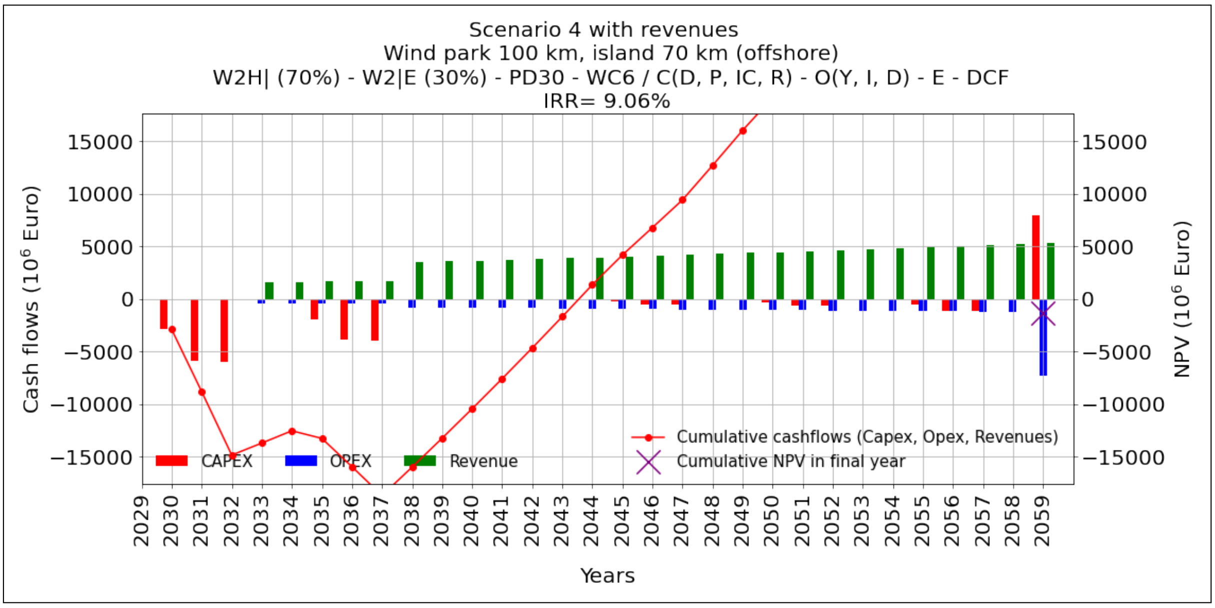

Figure C.34: Scenario 4 - cash flow chart for Case 1b

Final year cumulative NPV = €3.8b

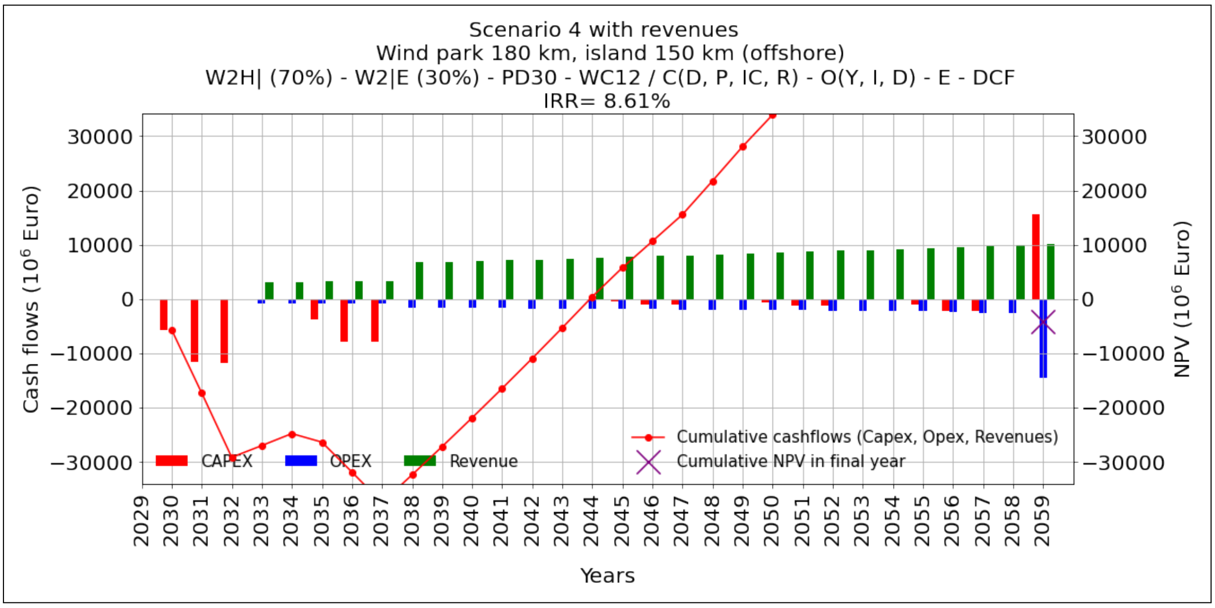

Figure C.35: Scenario 4 - cash flow chart for Case 2a

Final year cumulative NPV = €-4.3b

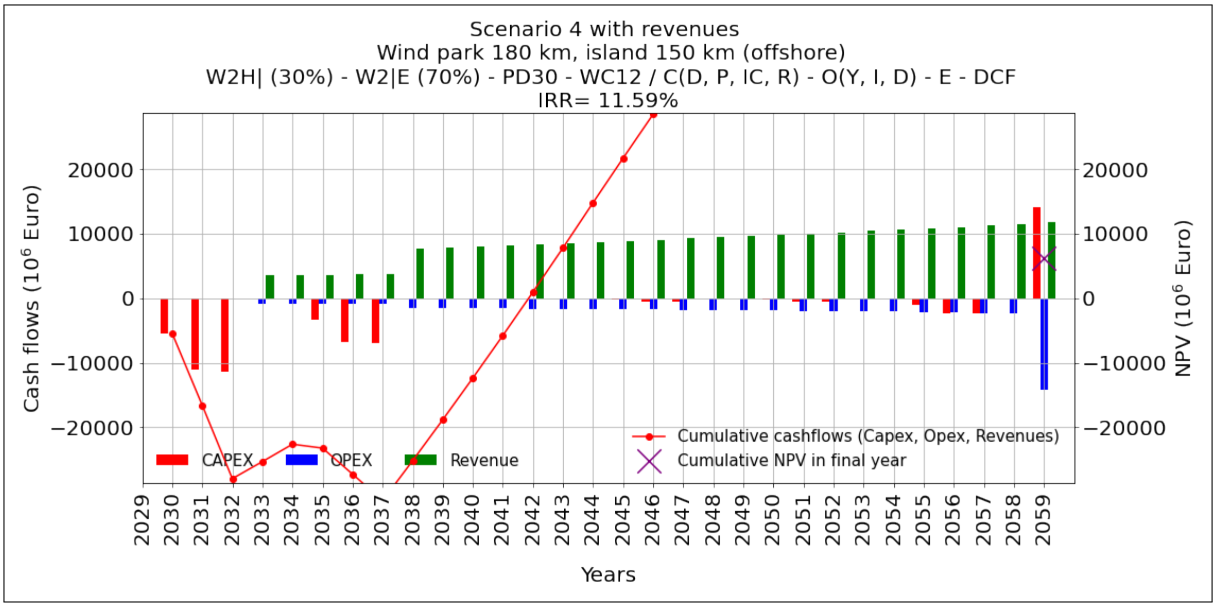

Figure C.36: Scenario 4 - cash flow chart for Case 2b

Final year cumulative NPV = €6.0b

C.3. Supply Chain Efficiency

C.3.1. Overview

	6 GW 100 km offshore 70% H2 / 30% E	**6 GW 100 km offshore 30% H2 / 70% E**	**12 GW 180 km offshore 70% H2 / 30% E**	**12 GW 180 km offshore 30% H2 / 70% E**
Scenario 1	71.5%	75.4%	68.4%	72.1%
Scenario 3	69.1%	74.3%	66.1%	71.1%

Table C.1: Supply Chain Efficiency for Scenario 1 and Scenario 3. As Scenario 2 and Scenario 4 only have different construction years, the efficiency is the same as Scenario 1 and 3 respectively.

C.3.2. Annual Energy Production after Losses

Scenario 1 (equal to Scenario 2)

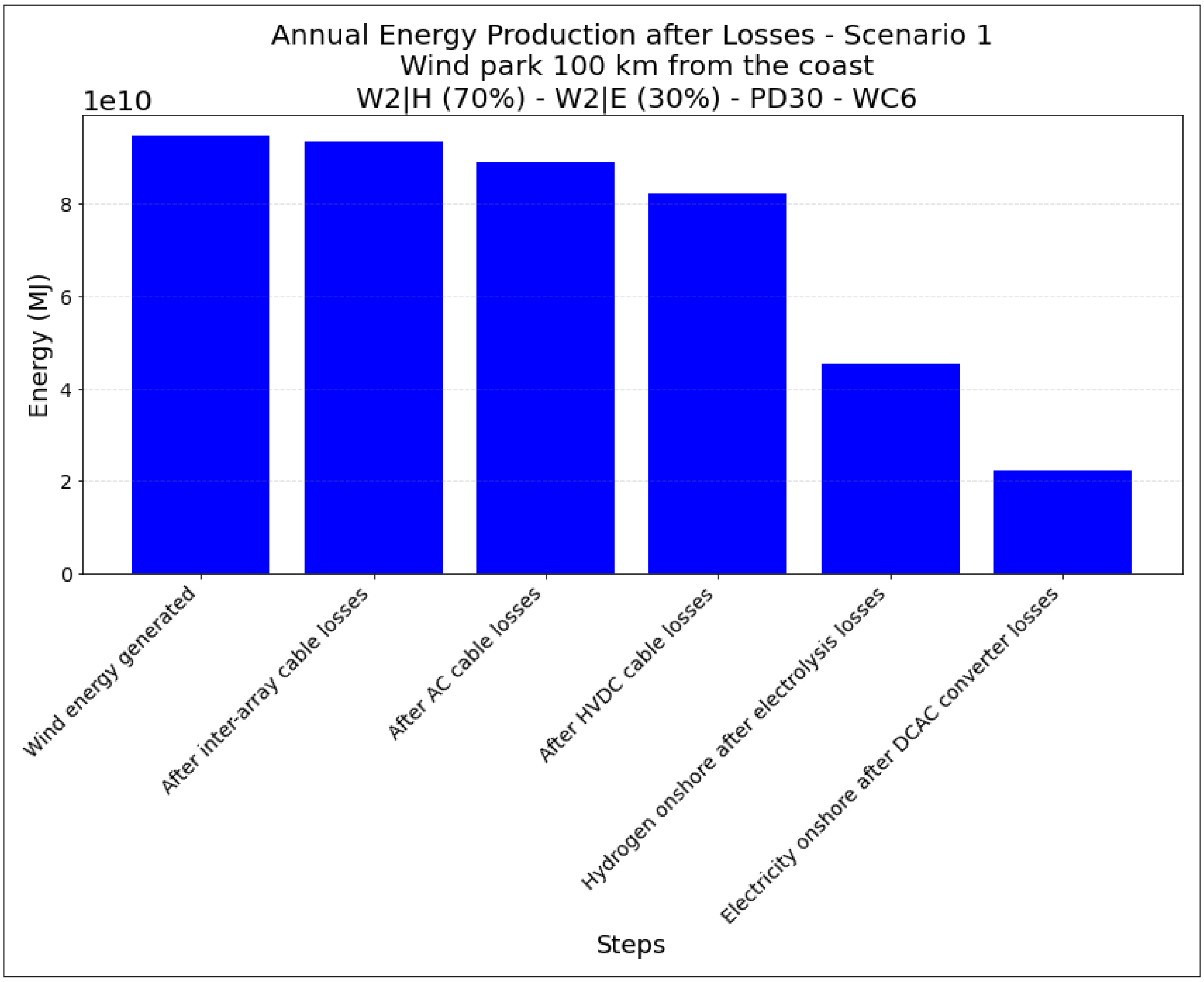

Figure C.37: Scenario 1 - Annual Energy Production per Supply Chain Step for Case 1a

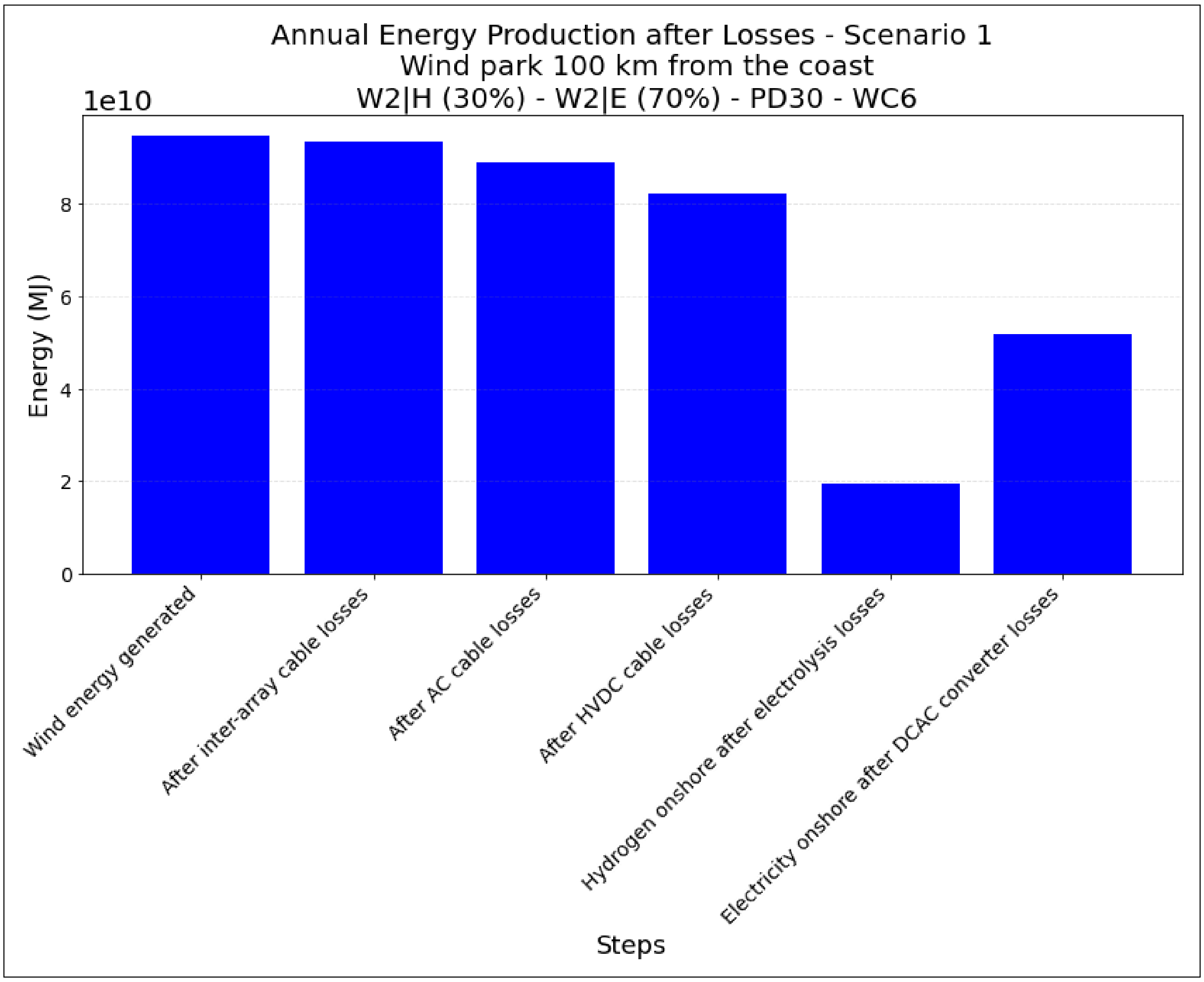

Figure C.38: Scenario 1 - Annual Energy Production per Supply Chain Step for Case 1b

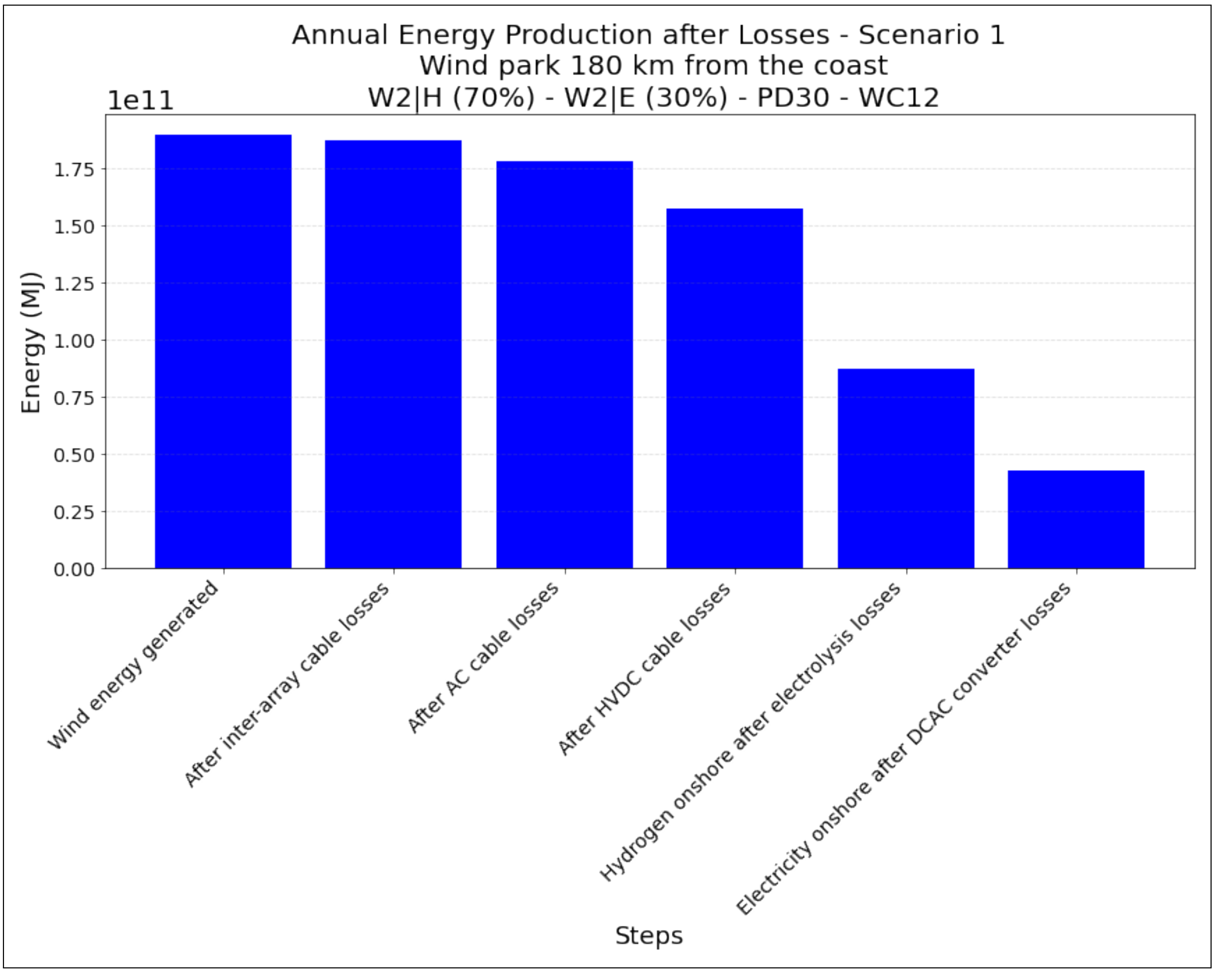

Figure C.39: Scenario 1 - Annual Energy Production per Supply Chain Step for Case 2a

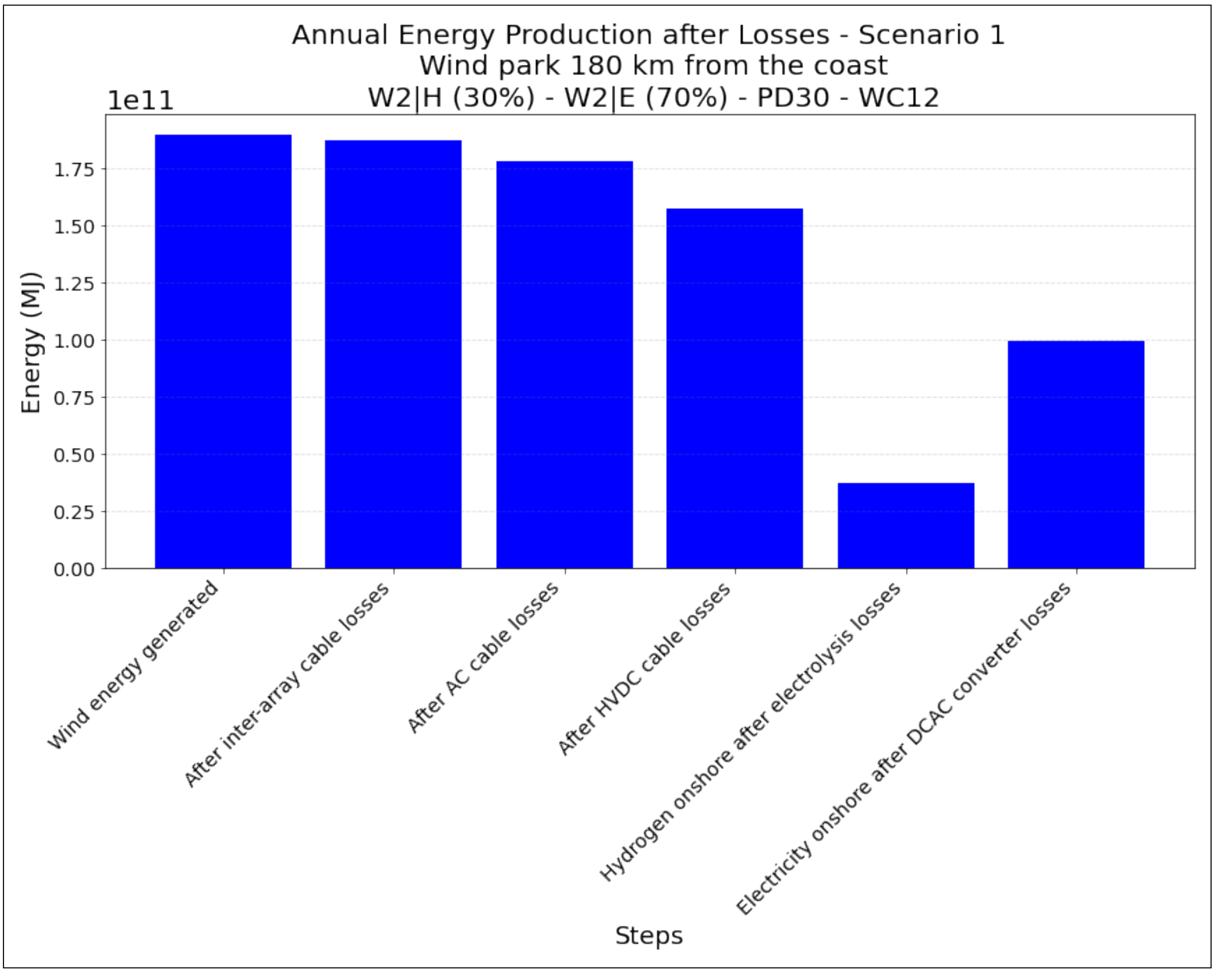

Figure C.40: Scenario 1 - Annual Energy Production per Supply Chain Step for Case 2b

Scenario 3 (equal to Scenario 4)

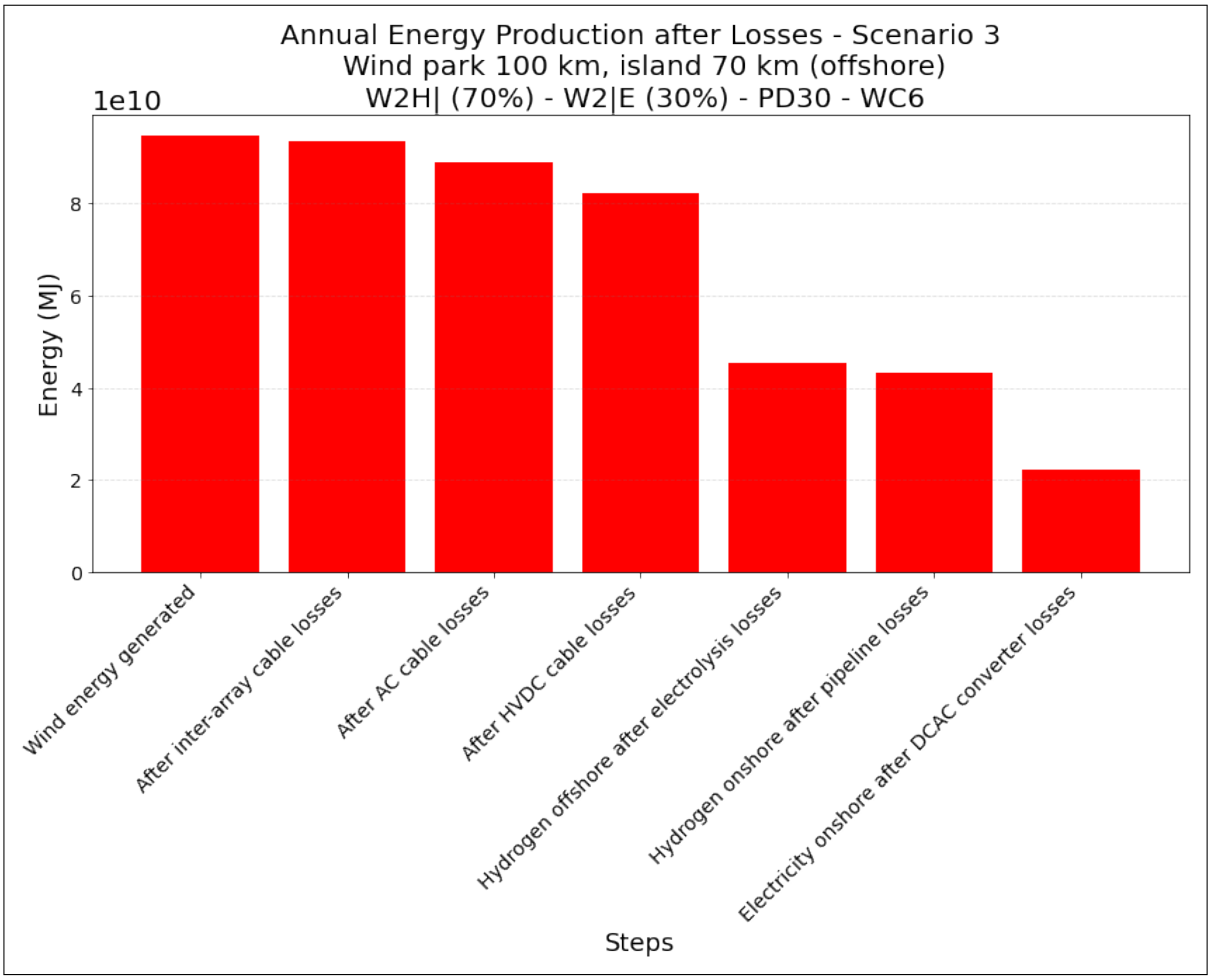

Figure C.41: Scenario 3 - Annual Energy Production per Supply Chain Step for Case 1a

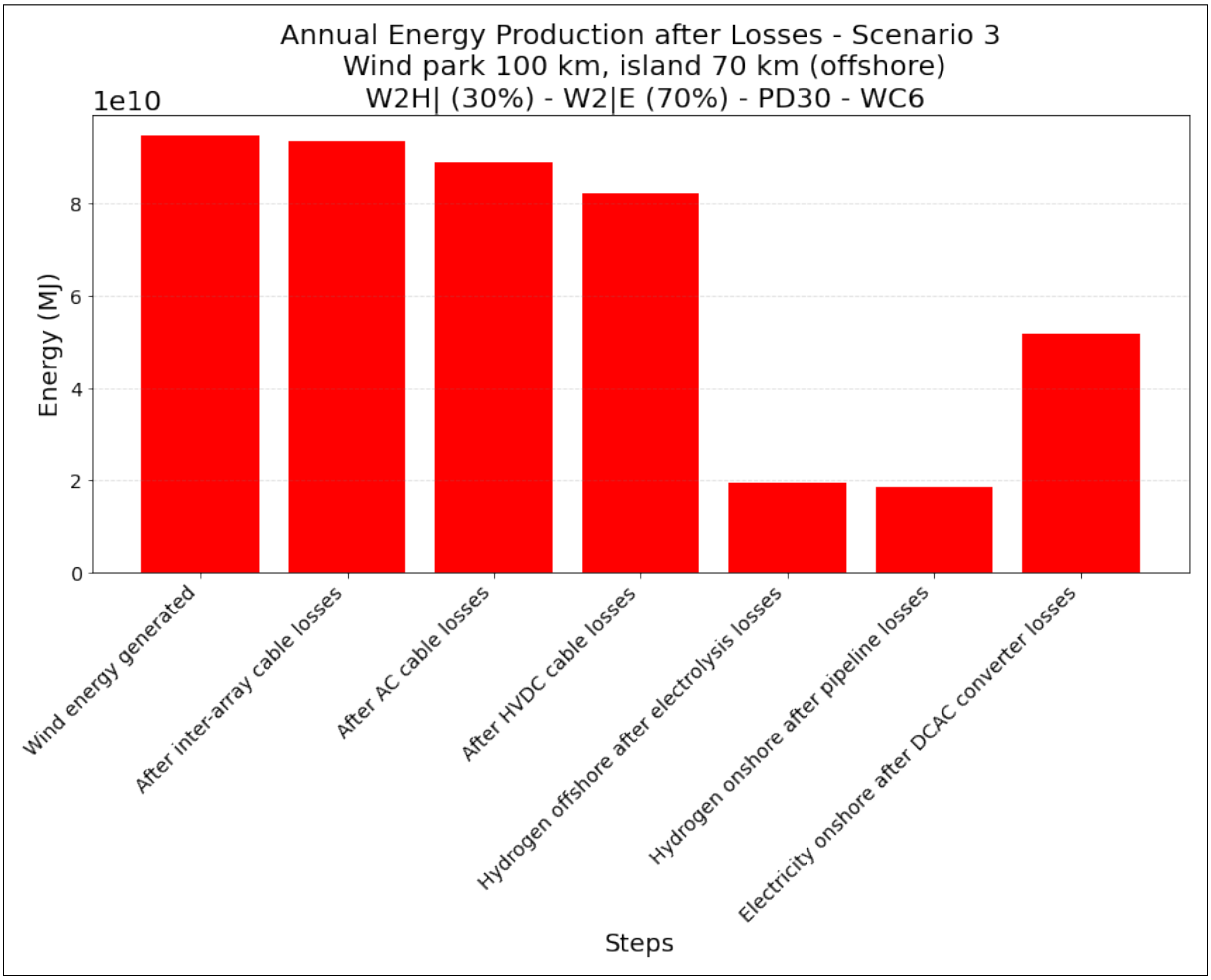

Figure C.42: Scenario 3 - Annual Energy Production per Supply Chain Step for Case 1b

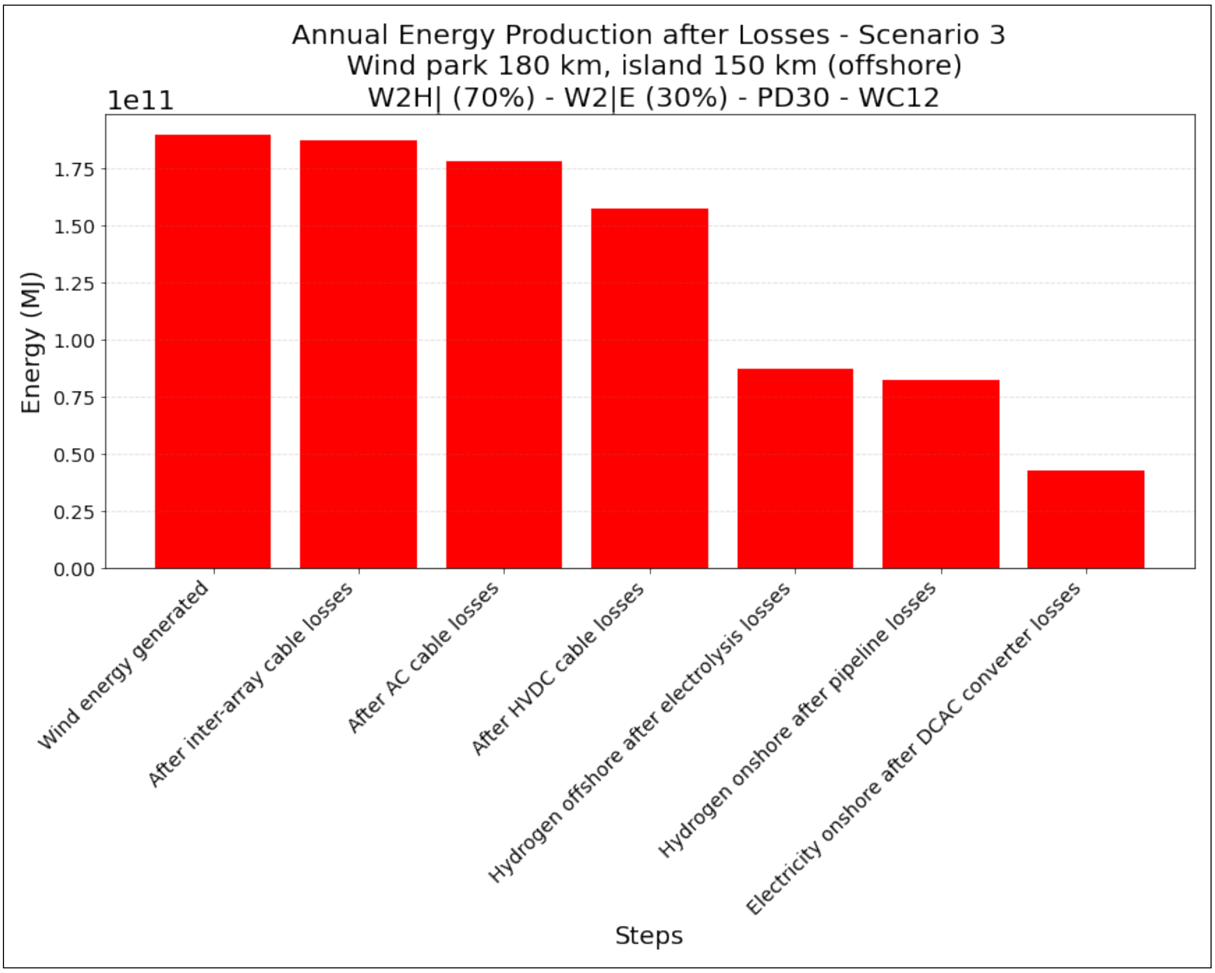

Figure C.43: Scenario 3 - Annual Energy Production per Supply Chain Step for Case 2a

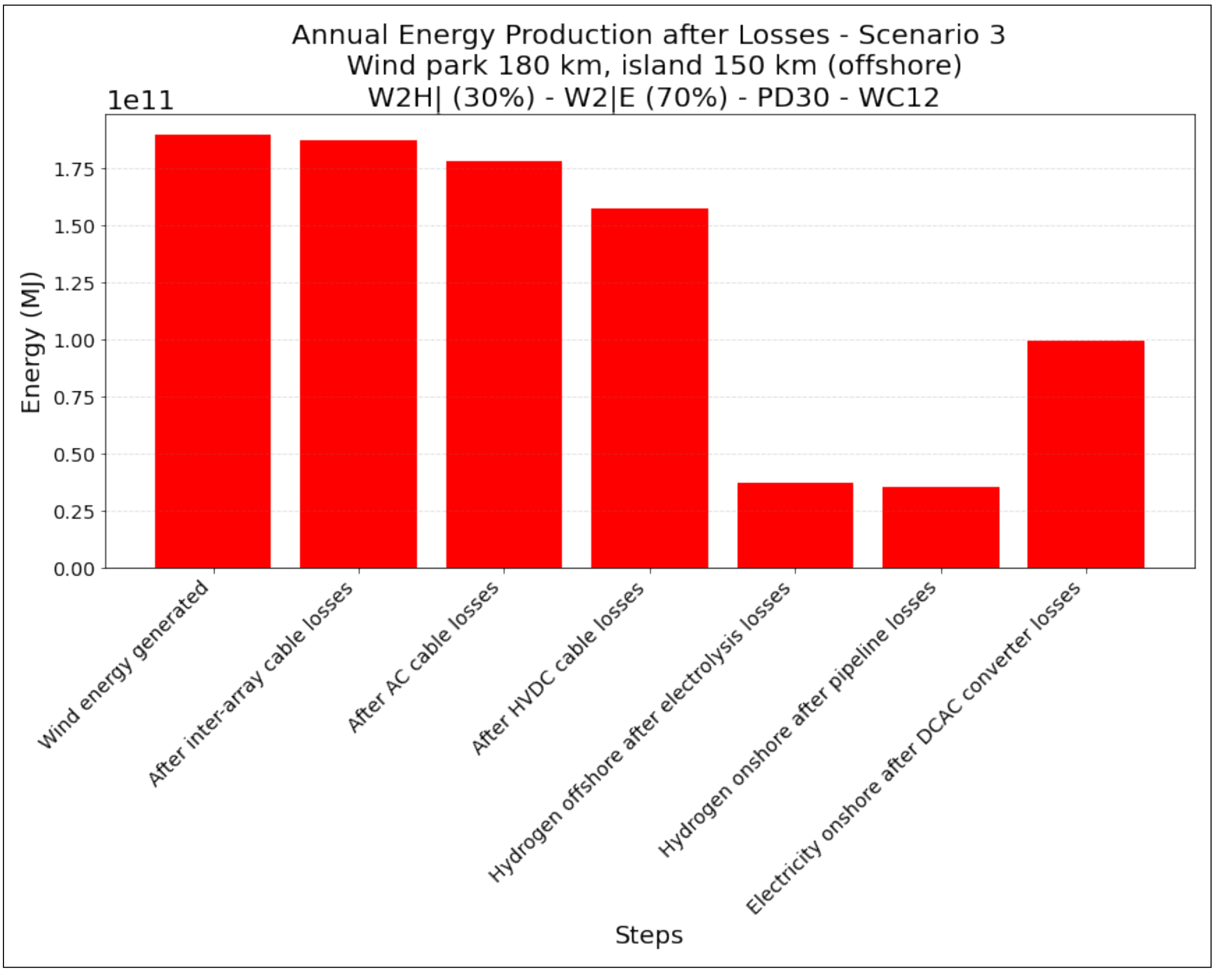

Figure C.44: Scenario 3 - Annual Energy Production per Supply Chain Step for Case 2b

C.3.3. Loss Percentages per Element

Scenario 1 (equal to Scenario 2)

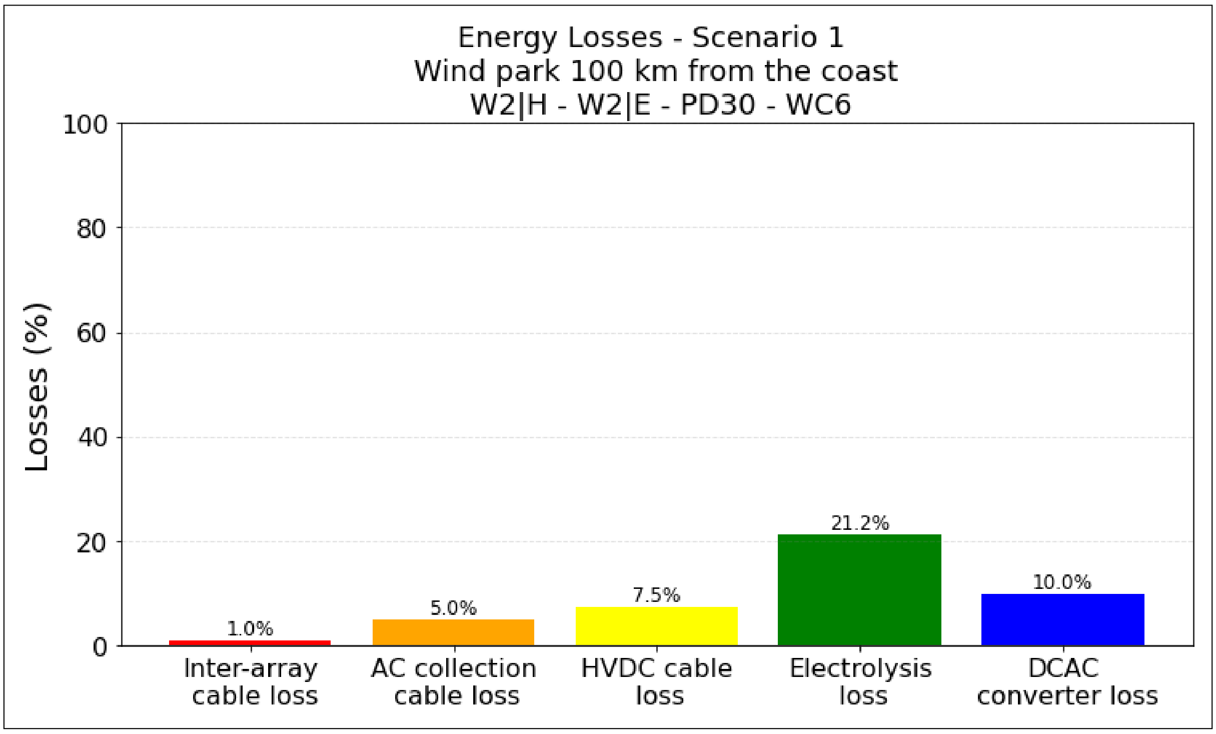

Figure C.45: Scenario 1 - Loss Percentages per Supply Chain Element for Case 1

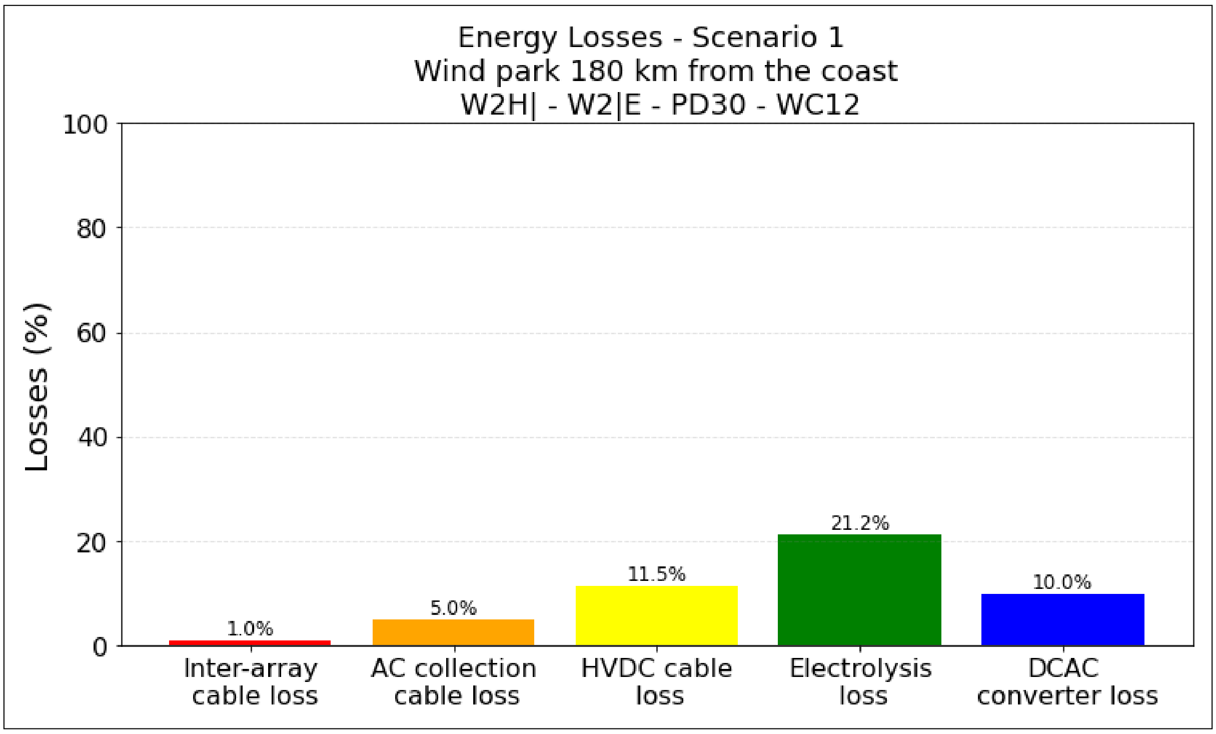

Figure C.46: Scenario 1 - Loss Percentages per Supply Chain Element for Case 2

Scenario 3 (equal to Scenario 4)

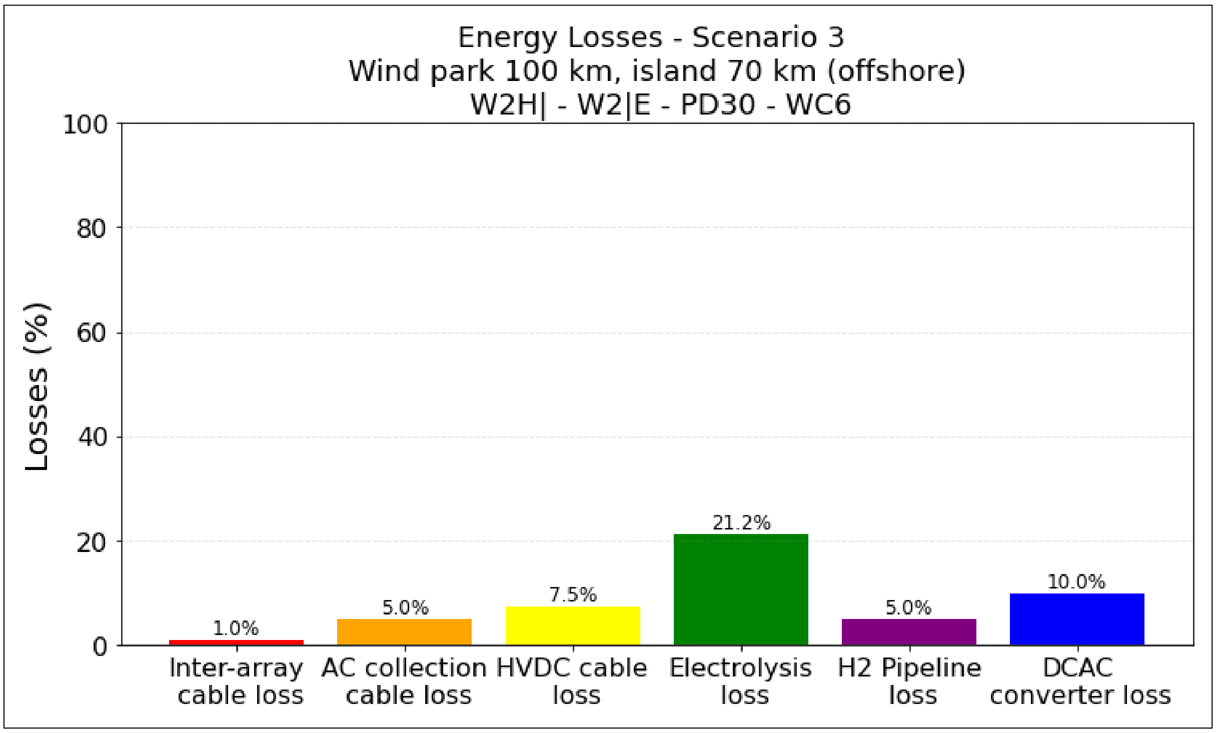

Figure C.47: Scenario 3 - Loss Percentages per Supply Chain Element for Case 1

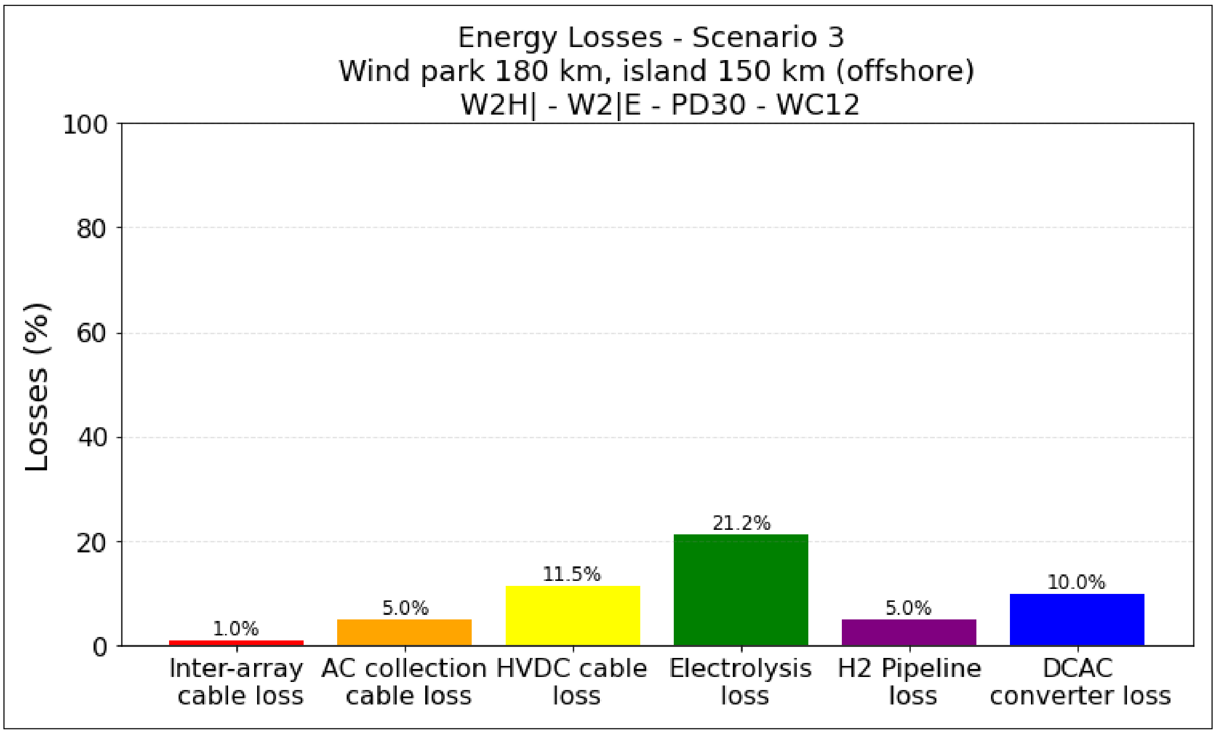

Figure C.48: Scenario 3 - Loss Percentages per Supply Chain Element for Case 2

C.4. Monte Carlo Simulations

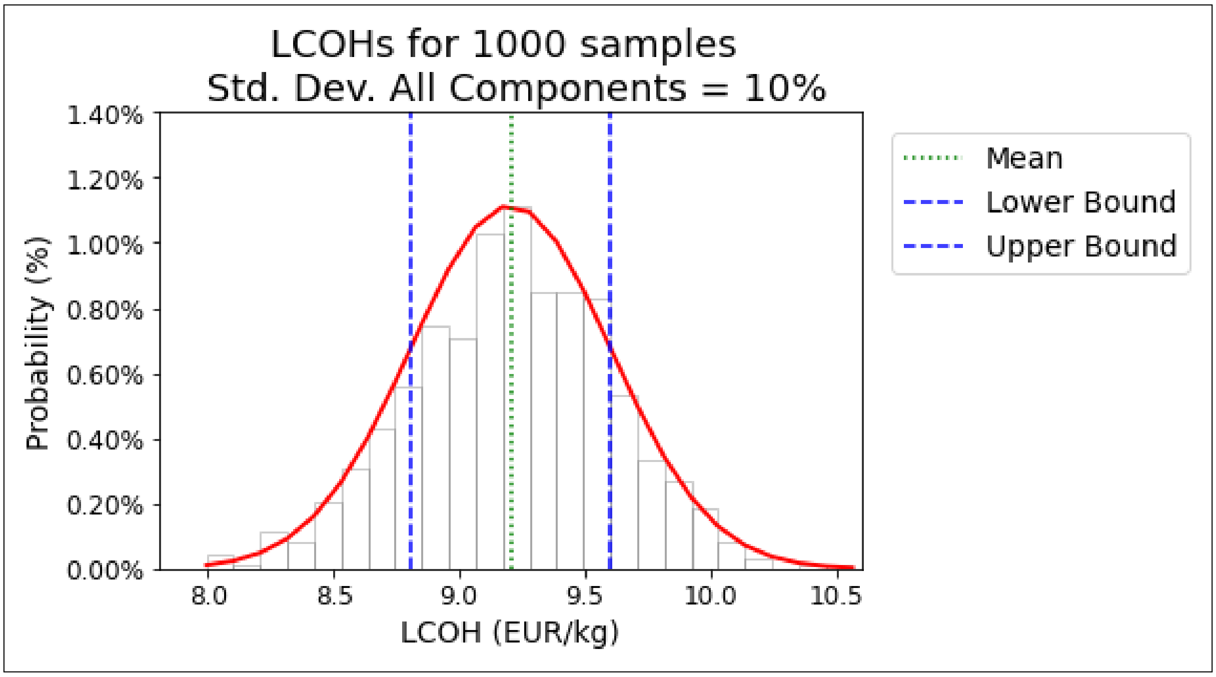

Figure C.49: PDF of Monte Carlo simulation for LCOH: all components 10% standard deviation

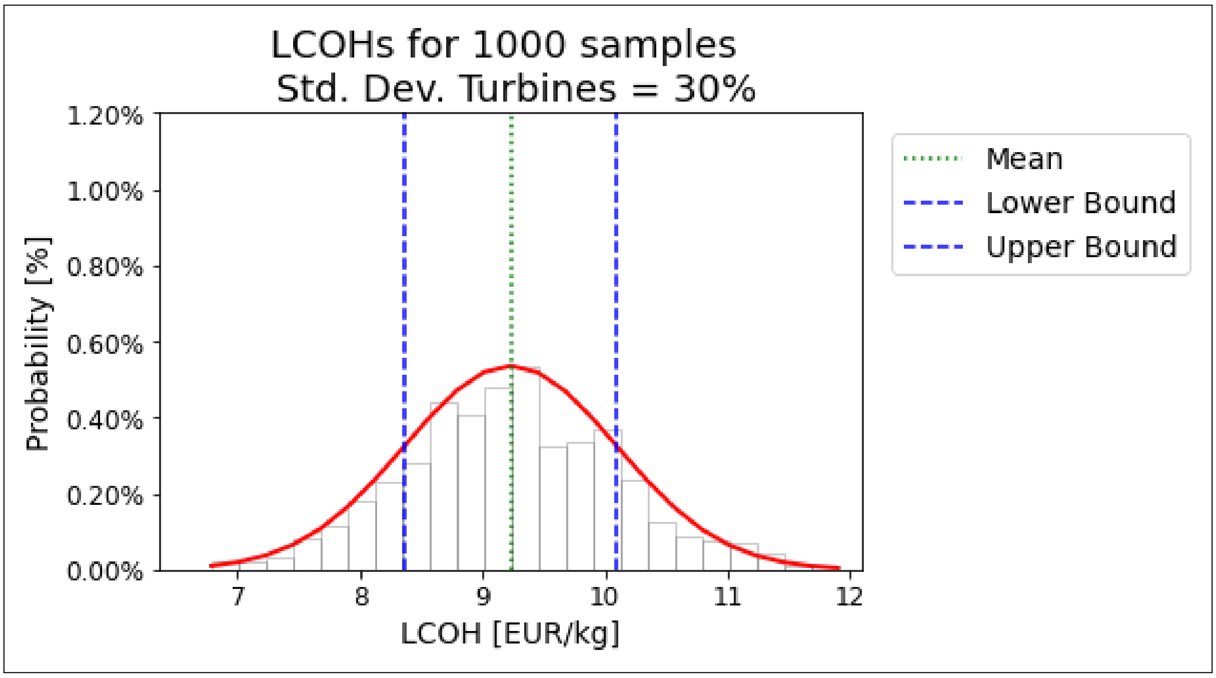

Figure C.50: PDF of Monte Carlo simulation for LCOH: turbines 30% standard deviation, all other components 10%

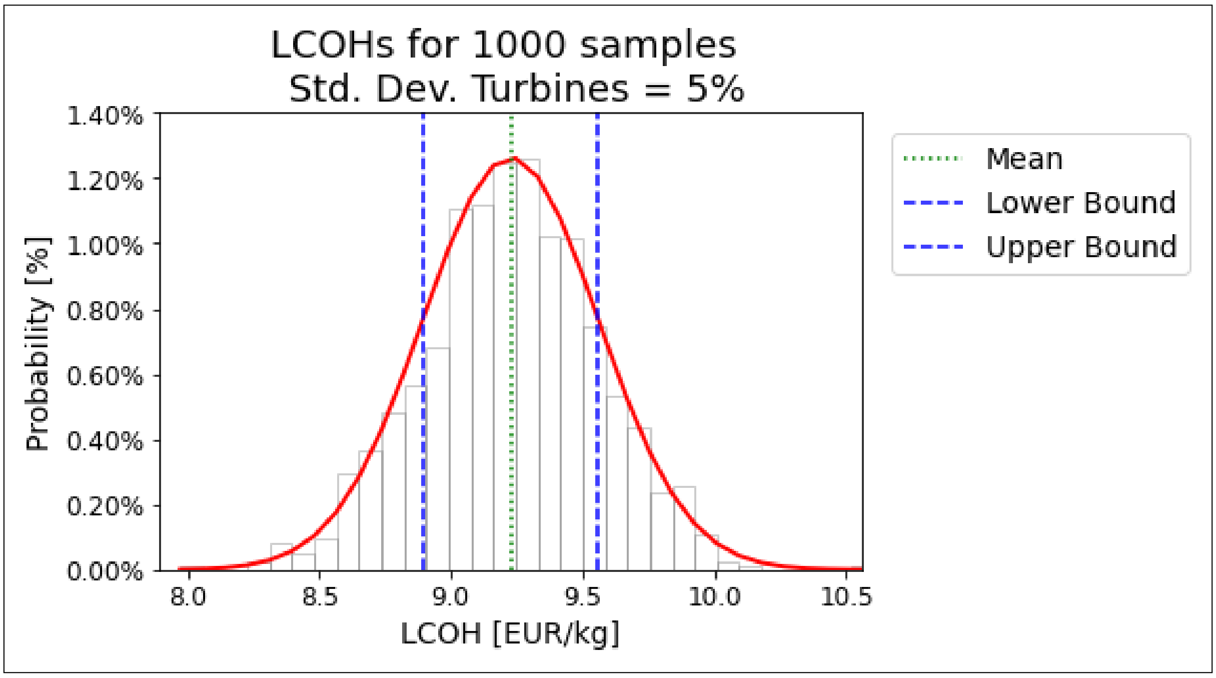

Figure C.51: PDF of Monte Carlo simulation for LCOH: turbines 5% standard deviation, all other components 10%

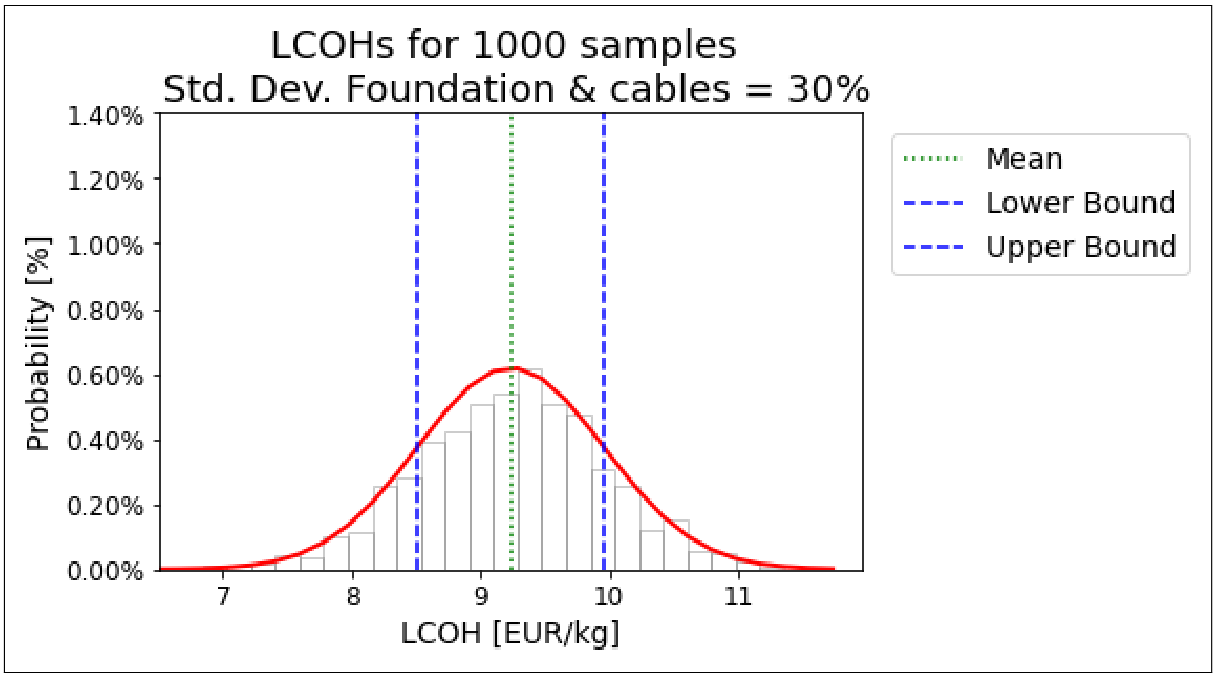

Figure C.52: PDF of Monte Carlo simulation for LCOH: foundation & cables 30% standard deviation, all other components 10%

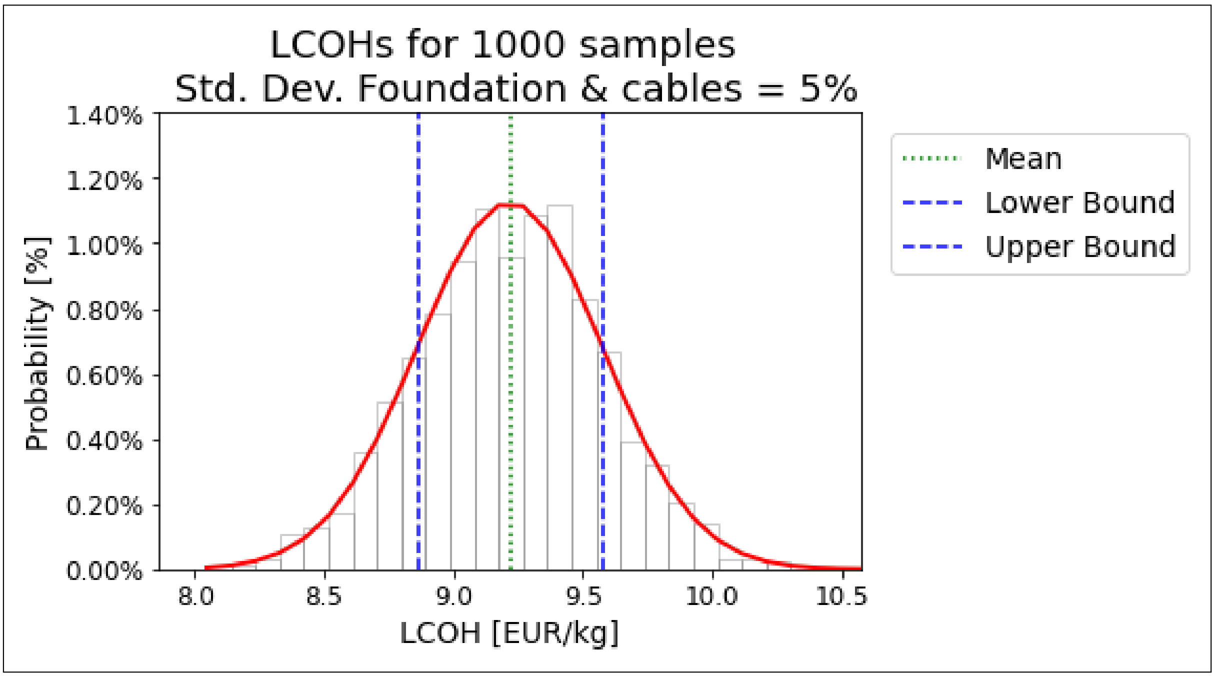

Figure C.53: PDF of Monte Carlo simulation for LCOH: foundation & cables 5% standard deviation, all other components 10%

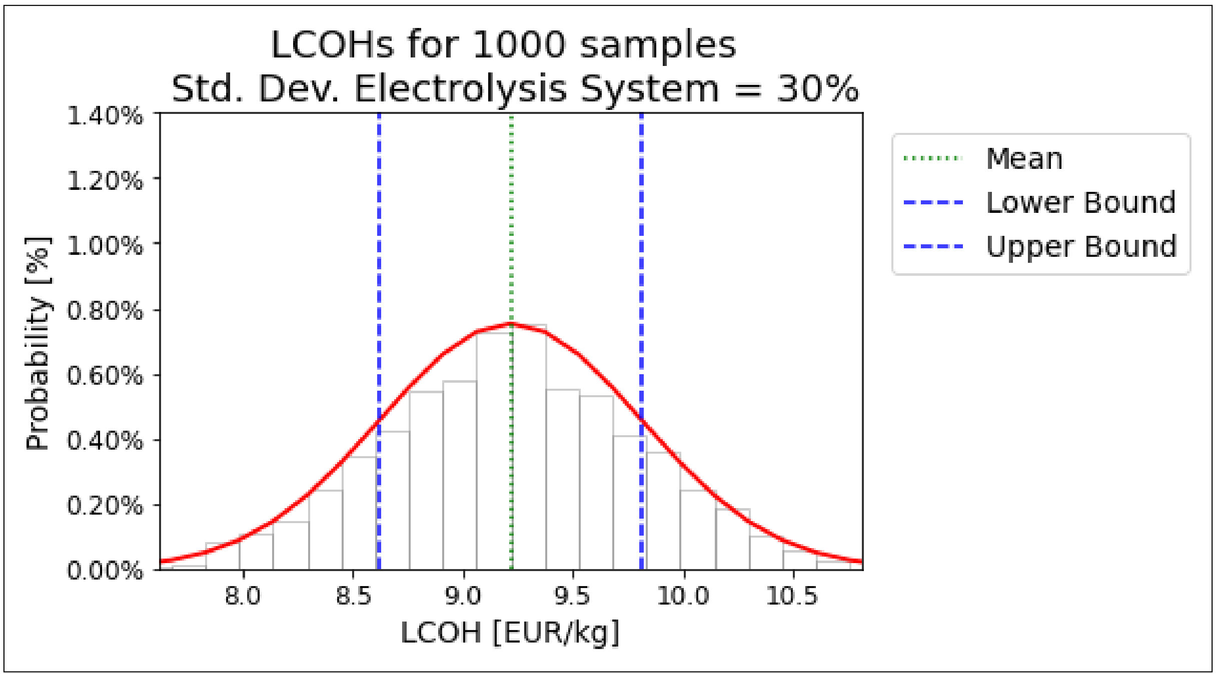

Figure C.54: PDF of Monte Carlo simulation for LCOH: electrolysis system 30% standard deviation, all other components 10%

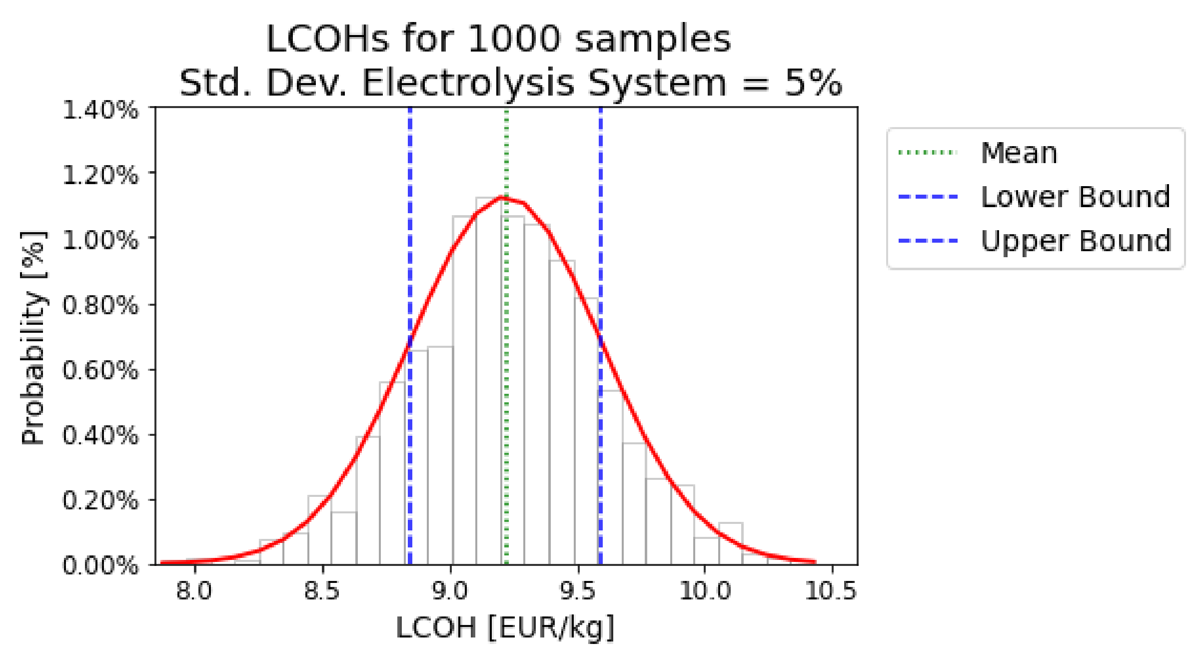

Figure C.55: PDF of Monte Carlo simulation for LCOH: electrolysis system 5% standard deviation, all other components 10%

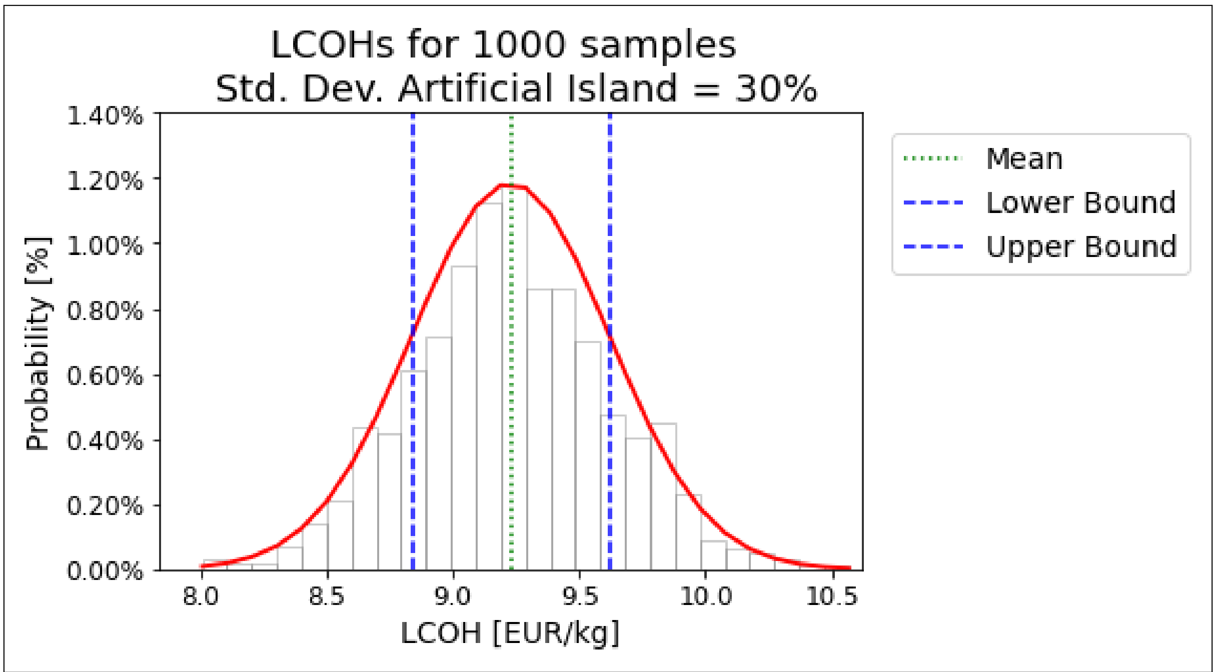

Figure C.56: PDF of Monte Carlo simulation for LCOH: artificial island 30% standard deviation, all other components 10%

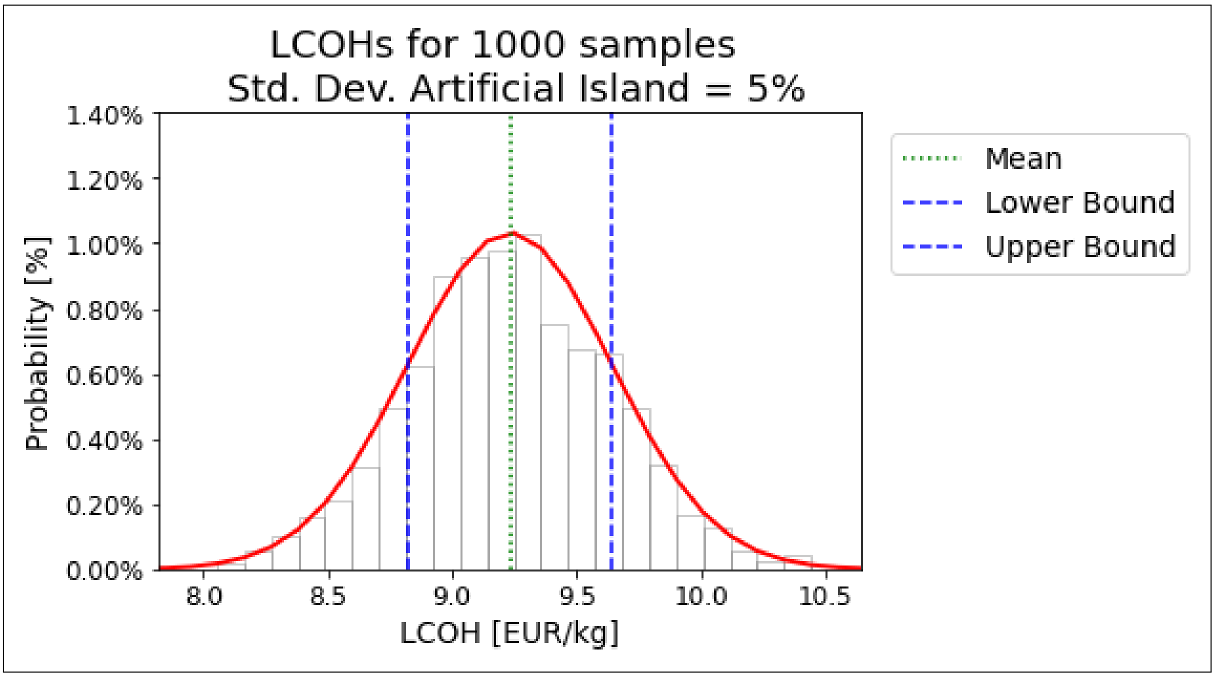

Figure C.57: PDF of Monte Carlo simulation for LCOH: artificial island 5% standard deviation, all other components 10%

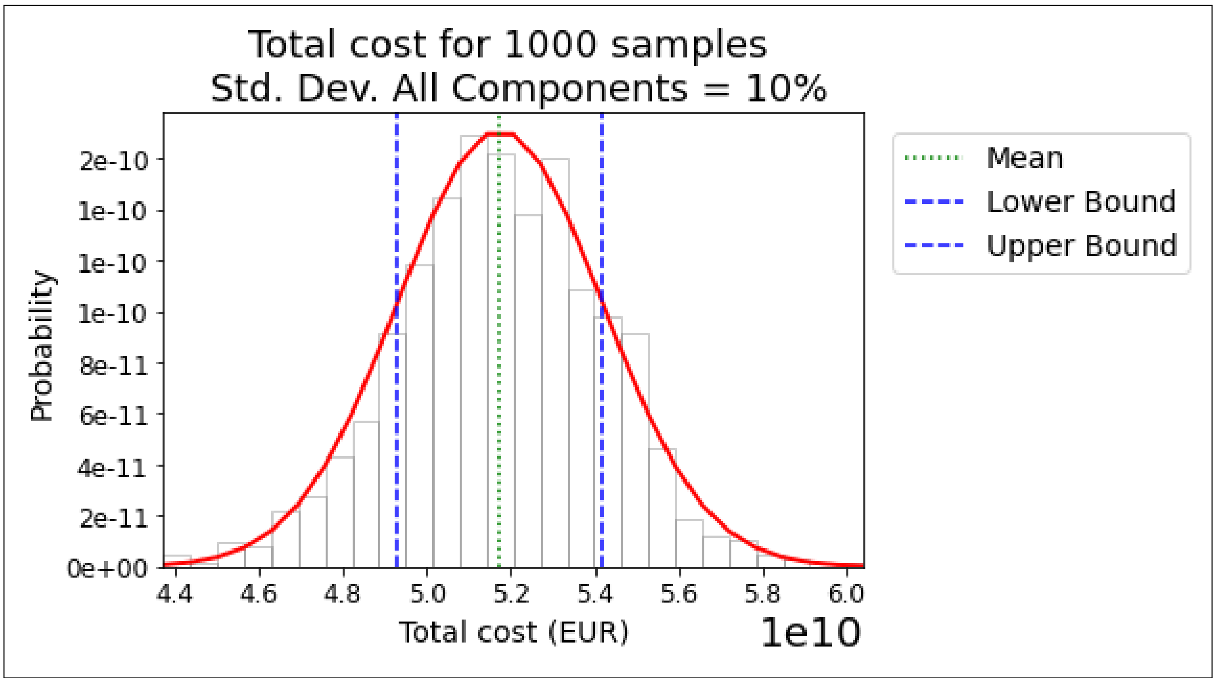

Figure C.58: PDF of Monte Carlo simulation for total cost: all components 10%

D
Python Source Code

The QR code in this Appendix redirects to the Github repository, where the Python codes used for this research can be found.

Figure D.1: QR Code redirecting to the Github repository

List of Figures

List of Tables