MASTER THESIS

The Future of the Green Hydrogen Production from Offshore Energy Systems in Accelerating the Energy Transition – Analysis in the Dutch Context

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ABSTRACT

For the realization of the 2050 energy-positive goals in the Netherlands, going deeper in the North Sea to harness wind energy is inevitable. This energy pursuit is due to the high competition on land and the sea's near-shore areas. Nevertheless, being in the first steps of development, producing energy from the deep marine environment is frequently viewed as troublesome and uneconomic. This perspective mainly includes the high costs of floating foundation technologies and grid connections. The current models for evaluating offshore energy costs are commonly misrepresented, prompting vulnerabilities that may hold investors back and hinder the market entrance of this renewable-energy market. Along these lines, an exact forecast of marine energy costs is essential to conclude the spectrum of its competitiveness. Accordingly, the study focused on technical and cost modeling of harnessing different energy resources as wave energy to maximize the system's output. More importantly, the study examined the possibility of utilizing green hydrogen as the energy carrier instead of exporting electricity through grid connections. For the most cost-effective green hydrogen transportation, the possibility of using the planned-to-be-decommissioned oil and gas platforms and pipelines by the Dutch government is considered. In other words, the ultimate goal was to find the most profitable way to invest in producing energy from the Dutch deep waters.

Keywords: LCOE, Green hydrogen, Floating wind turbines, Offshore, Costs, Energy.

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LIST OF ACRONYMS

LCOE	Levelized Cost of Energy
WEC	Wave Energy Converter
DNV GL	Det Norske Veritas and Germanischer Lloyd
IPCC	Intergovernmental Panel on Climate Change
GW	Gigawatt
KW	Kilowatt
KWh	Kilowatt per hour
MW	Megawatt
MWh	Megawatt per hour
TW	Terawatt
EX	Exajoule
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
USD	United States of America Dollar
O&M	Operation and Maintenance
VRE	Variable Renewable Energy
LCOH	Levelized Cost of Hydroge
SOEC	Solid Oxide Electrolyzer Cell
ALK	Alkaline
PEM	Polymer Electrolyte Membrane
IEA	International Energy Agency
NPV	Net Present Value
TLWT	Tension Leg Wind Turbine
TLB	Tension Leg Buoy
TLP	Tension Leg Platform
IDEAS	International Design, Engineering and Examination Service
IRR	Internal Rate of Return
EEZ	Exclusive Economic Zone
LCCA	Life Cycle Cost Analysis
CG	Cradle to Grave
kV	Kilovolt
DC	Direct Current
EWEA	European Wind Energy Association
NaCL	Sodium Chloride
KOH	Potassium Hydroxide

1 INTRODUCTION

1.1 BACKGROUND

The reduction of energy-related CO_2 emissions are at the core of the energy transition. Quickly moving the world away from the utilization of non-renewable energy sources that cause environmental problems and towards a cleaner, sustainable types of energy are critical if the world is to agree on the climate objectives (European Comission, 2019). The change of the worldwide energy systems needs to quicken considerably to meet the targets of the Paris Agreement, which plan to keep the ascent in average global temperatures to closer to 1.5 °C in the current century (European Comission, 2019).

In response to that, in 2019, the Dutch government completed the first Climate Act. This act contains the main features of climate policies for the next ten years (The Government of the Netherlands, 2019). Besides, the law examined the latest scientific findings on climate change, technological developments, international policy developments, and economic consequences. This agreement contains a package of measures, which have the active support of the involved parties to achieve the Green House Gas emissions reduction target of 49% by 2030 (The Government of the Netherlands, 2019).

The Climate Act specifies that the Netherlands has to reduce 95% greenhouse gas emissions by 2050 compared to the 1990's ones. The Netherlands, like most European countries, obliged by the EU to be climate neutral by 2050 (The Government of the Netherlands, 2020b). This goal is currently one of the world's most ambitious targets for 2050 laid down in legislation. For short-term goals, the Netherlands has set a challenging goal for 2020 to produce 14% of its total energy share from renewables. However, this goal seems to be impossible as, according to Energieakkord 2020, the contribution of renewable energy resources is only 10% in February 2020, as shown in Figure 1.1.

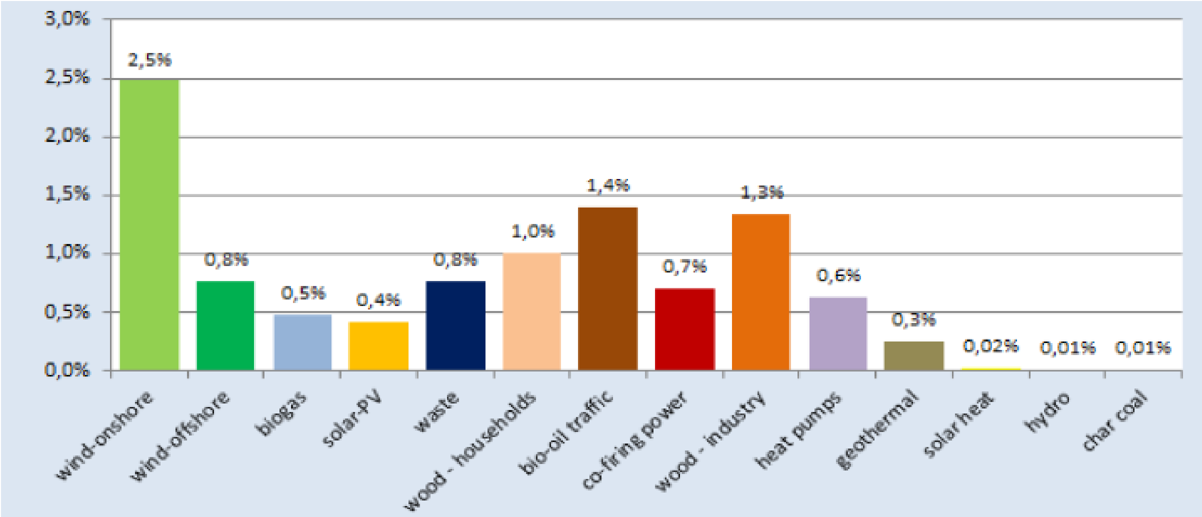

Figure 1.1 Contribution of renewable energy resources in the Netherlands in February 2020 (Energieakkord, 2020)

In the Dutch context, one of the proposed solutions currently in to accelerate the energy transition is to go deeper in the North Sea to install wind turbines. The offshore renewable energy industry has risen with power in a quest to look for alternatives to traditional energy resources. Be that as it may, some boundaries could impede its presentation into the energy mix, for example, the maturity level of the innovations, high costs included, and lack of knowledge in regards to environmental impacts (IRENA, 2019b). Moreover, the deep grid connections are technically challenging, with high installation costs (DNV GL, 2018).

In this regard, the study focused on the possibilities of using the green hydrogen as an alternative energy carrier. Transporting energy using green hydrogen instead of exporting electricity through grid connections could be an up-and-coming solution (IEA, 2019). On the one hand, the falling expenses of renewable energy have expanded the intrigue of these stationary applications; on the other hand, the earnestness of climate action has expanded and now establishes a key driver. Endeavors to increase green hydrogen use for the energy transition are growing in the Netherlands, with an accentuation for more significant scope, and more power system-friendly electrolysis (The Government of the Netherlands, 2020b)

Many synergies can result from the green hydrogen utilization as the North Sea is home to numerous oil and gas platforms and pipelines that have arrived at the end of their life span and should be decommissioned (Nextstep, 2018). These would now be able to be given another chance to live. As the development of offshore renewable energy projects proceeds at the current pace to move further away from the coast, it is critical to research the most practical and cheap approaches to get the power created there to land (Kemp, 2010).

1.2 RESEARCH OBJECTIVE

The objective of this research is to assess the contribution of the expected technological advancement in the offshore renewable energy industry in achieving the carbon-neutral goals in the Netherlands. The study analyzed the possibility of utilizing green hydrogen as an energy carrier to produced energy by floating wind turbines instead of using the grid connections. This possibility is addressed in both technical and financial terms by assessing the technologies' state of the art by 2020 and their associated costs. However, the study's main focus is to analyze the possibility by 2030, so the expected technological advancement and the cost reduction for the systems' components are researched to measure the technical and the financial feasibility for both approaches by 2030 with respect to the Dutch vision.

1.3 ETHICS STATEMENT

This research followed the ethical standards of the Ethic procedures from the University of Twente stated in the Research Ethics Policy (University of Twente, 2019). Moreover, the study is intended to be carried out to help in finding a solution to one of the most imminent global crises, with no bias to any scientific arguments or industrial interests.

1.4 THESIS LAYOUT

The thesis is structured in five chapters including this one. After the introduction, chapter two explains the research methodology and the selected criteria for the analysis. Going through the study's main body, chapter three shows the current technological status of the different offshore energy systems. On one hand, the chapter goes through the technical design selection of the wind turbines' model and foundation and their associated grid connections. On the other hand, the chapter shows the current status of the different electrolysis processes and the justification for the Wave Energy Converters (WECs) installation in a wind park for the offshore hydrogen production. Similar to the first part, the technical design selection of the WECs and the hydrogen production system and its auxiliaries is carried out. Based on the technical design, chapter four manifests the cost analysis approach and the prices for the selected models followed by the results of the carried out analysis. Finally, chapter five draws the conclusion while addressing the limitations of the study, ending up by suggesting directions for future research. The details of the carried out analyses are presented in five appendices.

2 METHODOLOGY

2.1 PROBLEM STATEMENT

The Netherlands is seeking a rapid energy transition in the upcoming years to fulfill its carbon-positive promises by 2050 (The Government of the Netherlands, 2020a). With the current technological development progress and with the existing barriers, the 2030 goals set by the Dutch government seem to be practically impossible unless radical solutions are implemented. The goal realization needs milestone achievements to alter the current progression trend. The barriers towards the energy transition using the hydrogen as an energy carrier can be summed up into five main categories; technological barriers, economic and market barriers, regulatory, policy and social barriers, and environmental barriers. This research primarily focused on the economic barriers as it can be understood from the presentation created by Wim van Hof, the Electricity Directorate at the Ministry of Economic Affairs and Climate Policy, that the main obstacle that hinders the Energy Transition is the economic barrier (Ministry of Economic Affairs and Climate Policy, 2018). Nevertheless, the economic barrier could hardly be assessed without taking the technical limitations into account. Therefore, the study focused on the technical limitations which impose financial barriers to find the most feasible green energy production approach.

2.2 RESEARCH QUESTION

The main Research Question:

To what extent can producing green hydrogen in the deep waters on the Dutch part of the Continental Shelf in 2030 be technically feasible and economically costs competitive to the costs of one MWh electricity generated by an offshore wind turbine park in deep water in 2030?

Sub-Research Questions:

1. What are the most up-to-date energy production systems that can be able to produce green energy in the Dutch Exclusive Economic Zone (EEZ)? and what are the best technologies in exporting energy back to the shore?

2. What are the associated costs of the selected designs for the energy production and transportation processes by 2020?

3. How could the technological advancements by 2030 for the selected energy systems affect the economic feasibility of the selected approaches?

2.3 TYPE OF COLLECTED DATA

In this research, cost analyses' results were a determinant factor for providing recommendations. Accordingly, quantitative analyses using a cost-benefit model were pivotal in the researching process. However, creating the financial model needed a technical design reference to address cost-specific data. In this manner, a combination of qualitative and quantitative data analysis methods was applied. This combination helped in delivering pragmatic understanding due to the complexity of the collected data.

2.4 DATA ANALYSIS

The analysis was done by relying mainly on intensive desk research. The analysis aimed to provide financial models to compare the conventional wind turbines farms approach that utilizes a grid connection for energy transporting in an electric form and the hydrogen production approach that converts the produced electricity into hydrogen before transporting it back to the shore.

The data analysis will be carried out in the following sequence and summed up in the research framework shown in Figure 2.1:

a) Before attempting to analyze the possible alternatives for a feasible offshore energy production, a refinement step was carried out. The objective of this step is to determine the most convenient location for the project. This step resulted in calculating important parameters needed for the cost analysis. These parameters are the average water depth, the distance to the shore, the distance to a planned-to-be-decommissioned platform.

b) The second step is carrying out an in-depth literature reviewing on the current offshore energy markets, including the state of the art of the available offshore energy systems with their associate investment costs, operation and maintenance costs, and the Levelized Cost of Energy (LCOE). This step's goal is to identify the gap between the capacity of the existing technologies and the ability to meet the energy positive goals. This step resulted in defining the main areas of studies and the literature gaps.

c) The third step comprised four main tasks; strongly interlinked with each other. The first task was designing the systems by selecting the most feasible technologies and study-proven to be able to produce hydrogen from offshore locations. These technologies also reviewed from a technological-advancement-potential perspective After selecting the models, the prices of each model were collected for the current year. The final task was to analyze the potential of these technologies to advance and how this technological advancement could affect the prices by 2030.

d) The fourth step was developing a trial simulation and four cost models. The trial simulation is used to determine the most profitable farm size for the hydrogen production approach. This simulation determined the number of the wind turbines and the WECs using the 2020 prices. For the cost models, the study assumed that this size is constant for all the models. Afterward, a cost model for the conventional approach and a cost model for the hydrogen production approaches with the current prices are developed. Another two cost models were developed by taking into account the expected cost reduction by 2030. This analysis compared the LCOE for the conventional and alternative energy production systems to understand which alternative is more cost-competitive, especially in the future. Besides, to understand which technologies are best suited for the locational requirements.

e) The final step is to conclude all the research analyses in formulating recommendations that could be applied to help in accelerating the energy transition and to guide future researches in this field.

2.5 DATA COLLECTION

The analysis started by attempting to design a system that can produce green hydrogen from the deep waters in the Dutch EEZ by 2030 and to compare this design costs with the most feasible conventional energy production approach that can be applied in the same location.

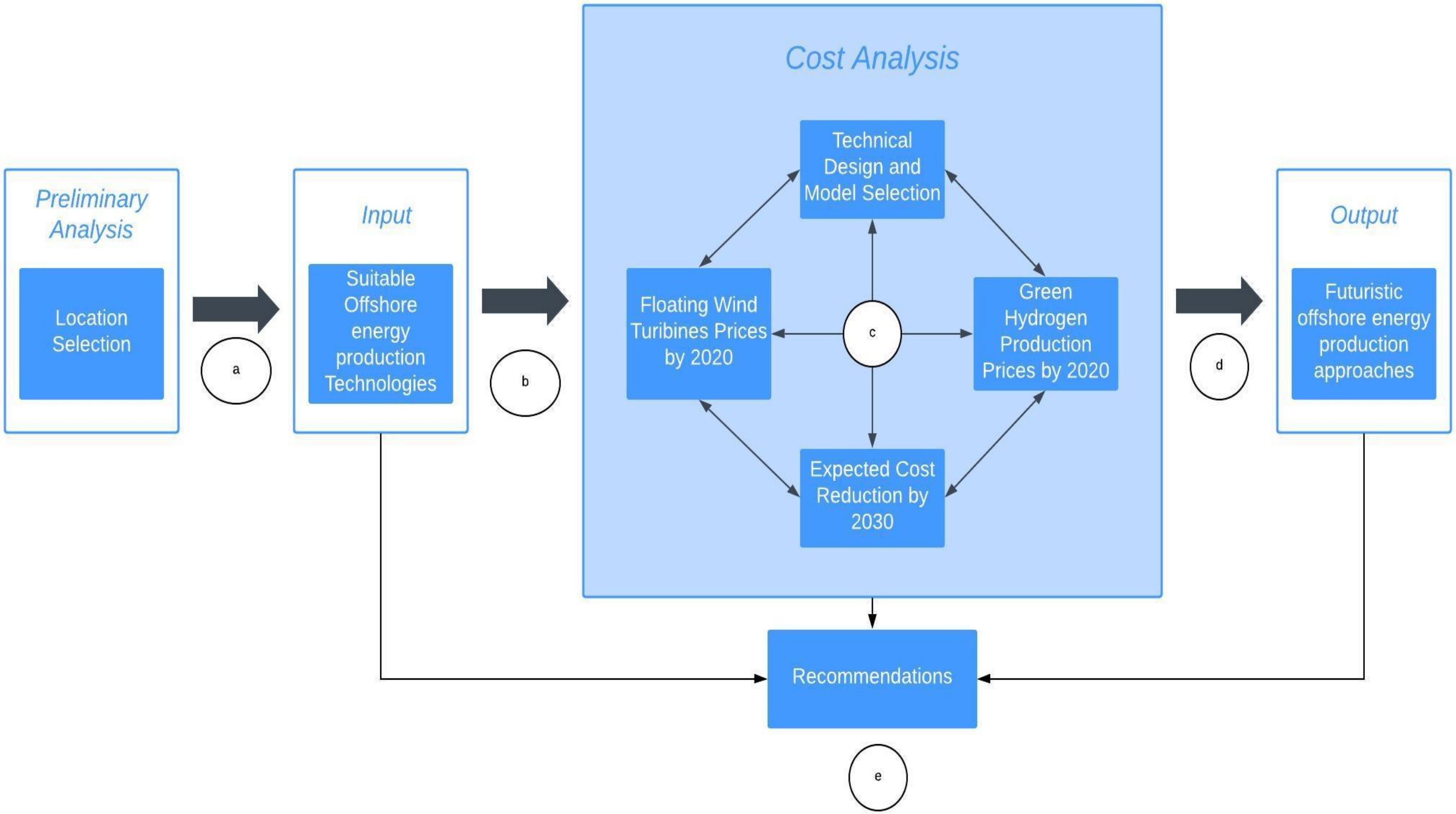

Figure 2.1 - Schematic presentation of the research framework

Before starting the analysis, the energy production capacity of the systems needed to be known to act as a reference point between the two approaches to compare the costs needed to produce the same amount of energy. Nonetheless, assuming this number at the start of the analysis without getting a better understanding of the technical design of the system and the energy production capabilities and efficiencies will ignore the fact that the economic feasibility of any energy production project is dependent on the total costs of the systems. In other words, this assumptions overlook that the energy production from an offshore farm could be costly in terms of total investments but profitable in terms of the LCOE and vice versa.

To overcome this limitation, the study assumed an initial value for the energy production based on the minimum expected energy yield from the project that can add significantly to the overall energy share in the Netherlands. However, this assumption is made only to help the researcher in collecting the costs of the available energy production systems in the market. For determining the feasibility, the most feasible energy yield from the systems is calculated using the study's cost model while ignoring the initial assumed value. In the research, the costs are gathered based on assuming initially a project capacity of 600 MW power production. This assumption was made based on an educated guess from the researcher returning to the fact that the total energy consumption in the Netherlands in 2019 is about 120 bn KWh (CBS, 2020) which is approximately 14000 MW. So a project share with around 24% of the total energy production will be considered in accelerating the energy transition.

Afterward, the study attempted to prove from analyzing the journal articles which systems are capable of producing renewable energy in deep waters with high energy density and competitive prices in 2020. The reason why 2020 is selected as the reference year for prices and not 2030 is the impossibility of finding exact technological state of the art with cost components in future terms. After collecting 2020 prices, the study collected data regarding the expected technological advancements in the selected energy components and the expected resulting cost reductions to calculate the prices in 2030.

To analyze the combination of data, the research utilized some techniques for producing meaning from the information such as making comparisons between the different models and constructing a coherent chain of evidence. The numbers then were presented in the quantitative analysis as they are typically associated with means of data collection as they are highly reliant on the qualitative technical analysis.

2.6 METHODS OF ANALYSIS

2.6.1 Energy Performance Assessment

Comparing the energy performances between diverse systems that depend on different engineering concepts is subjected to different criteria. The aim of the study was not to analyze the technical performance of the systems from an engineering perspective but to relate the energy performance of the selected systems to its contribution in resulting to a more feasible approach. Therefore, the criterion that was chosen in assessing the energy performances was the ratio between the input energy to the system and the output one. However, this criteria is not the only influencing factor because a system could have a low energy conversion efficiency but with a low cost that can compensate for this weakness. This criteria still can highlight areas for future improvements.

To commence the cost analysis, the study needed to verify the technical possibility of placing systems that can produce green energy from deep waters in the Dutch EEZ either using offshore wind turbines that can export electricity back to the shore or using a combination of offshore energy production systems that can export green hydrogen back to the shore. This verification process has done by setting several criteria while filtering the collected literature. The selected models had to be equipped with the most up-to-date technologies, commercially available and their technical specifications are compatible with the selected location for the project (See Site Selection Assumptions subheading).

2.6.2 Cost Assessment

While thinking about the expense of energy projects, there are a few viewpoints and ways to deal with it. Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) are the fundamental characteristics that need to be assessed to determine the economic potential. These components are frequently used for auditing of large investment ventures, yet are not appropriate for distinguishing between concepts with significant differences in their design (Ågotnes, 2013). This is particularly obvious when assessing capital-intensive projects that will amass the payments over a more drawn out period as the offshore industry projects. While considering a wide time length, measurement of the costs in various phases gets significant because of capital expenses, and risk identification. This is frequently analyzed in Life Cycle Cost Analysis (LCCA) or Cradle to Grave (CG) and this method is a helpful way and generally utilized to assess the potential profitability (Chozas, et al., 2012). In this study, LCCA is carried out on each system because of its ability in presenting the findings per phase, and this can help the in understanding the different phases the energy projects go through.

To build the centrality of the LCCA concerning the design examination, it is prudent to use a levelised cost to characterize a comparative reference for estimation of cash at various phases of the project (Ågotnes, 2013). It is advantageous to level the LCCA results by the anticipated energy production. This takes into account a better analysis and risk assessment of all the expenses during the lifetime and is regularly referred to as a LCOE Analysis. The comparative reference estimation of cash is acquired by limiting the expenses to a given date by the annuity strategy; which means to calculate based on the present values. Once acquired, the LCOE might be estimated as the base unit cost of energy and is a reasonable variable to assess the presence of various ideas.

The life cycle is divided into main four phases, which are;

- Pre-installation phase
- Implementation phase
- Operation phase
- Decommissioning

The procedure proposed depends on the life cycle cost approach and covers the full systems life cycle expenses of the farms. The study uses the LCOE in this study as it is a common measure by which numerous renewable energy production innovations are compared. Hence, LCOE is estimated in Euro/MWh in genuine terms, and is illustrative of the break-even cost of energy. In spite of the fact that the introduced cost technique can be applied to any area, the LCOE measure is context-specific, as reflected in the situation study appeared in this study.

For the future cost models, many studies have been reviewed to decide the best cost reduction predictions by 2030. Most of the studies lacked certainty and provided a large spectrum of speculations. The study followed two main logical assumptions used by some studies. The first assumption assumed that technological advancements will result in cost reduction in the current wind turbines models as in IRENA’s Future of Wind report (IRENA , 2019a). The second one assumed that technological advancement will accelerate the power generation capacity by producing new models with a slight increase in the current prices as in Peterson & Miller, 2016.

The study followed the latter assumption path as the study was looking for maximizing the energy production potential from the selected location regardless of the total investment costs.

The calculations are carried out using the Mathcad ® software by developing two models, one for the conventional wind turbines approach and the other for the green hydrogen production one in 2020. After selecting the cost reduction criteria for the energy systems, similar two cost models were developed to represent the expected costs with respect to the energy production by 2030. The operation and maintenance costs are estimated based on Myhr, et al. (2014) study results that used the Operation and Maintenace Cost Estimator (OMCE-Calculator) tool developed by the Energy Research Center of the Netherlands (ECN).

2.7 MODELING ASSUMPTIONS

All the analyses are based on a set of global assumptions that comprises a set of time-related assumptions and a set of project characteristics.

2.7.1 Global Assumptions

- Real (end-2019) prices.
- Fixed exchange rates at the average for 2020 (EUR 1 is equivalent to USD 1.18) (XE Currency Converter, 2020).
- For the Net Present Value (NPV) calculation, the inflation rate is assumed to be constant through the projects' life with 2020's value which is 1.4% (Trading Economics, 2020).
- All the assumed values in this model are based on the best available technologies and the most ideal operational conditions. All the equations are used with SI units.

2.7.2 Site Selection Assumptions

To select a realistic location for the proposed hydrogen production approach, the SeaSketch© platform is used to represent the main hotspots in the Dutch EEZ. Figure 2.2 is developed using the platform to show the key features that can impose conflicts with other authorities or stakeholders. The main areas presented in the figure below are the Natura 2000 areas, the other nature conservation areas, military zones, oil and gas platforms, subsea pipelines, and shipping lanes. This challenge is addressed as it hinders any renewable energy production projects nd makes the alternatives for selecting a site very limited (Ministry of Infrastructure and the Environment, 2011).

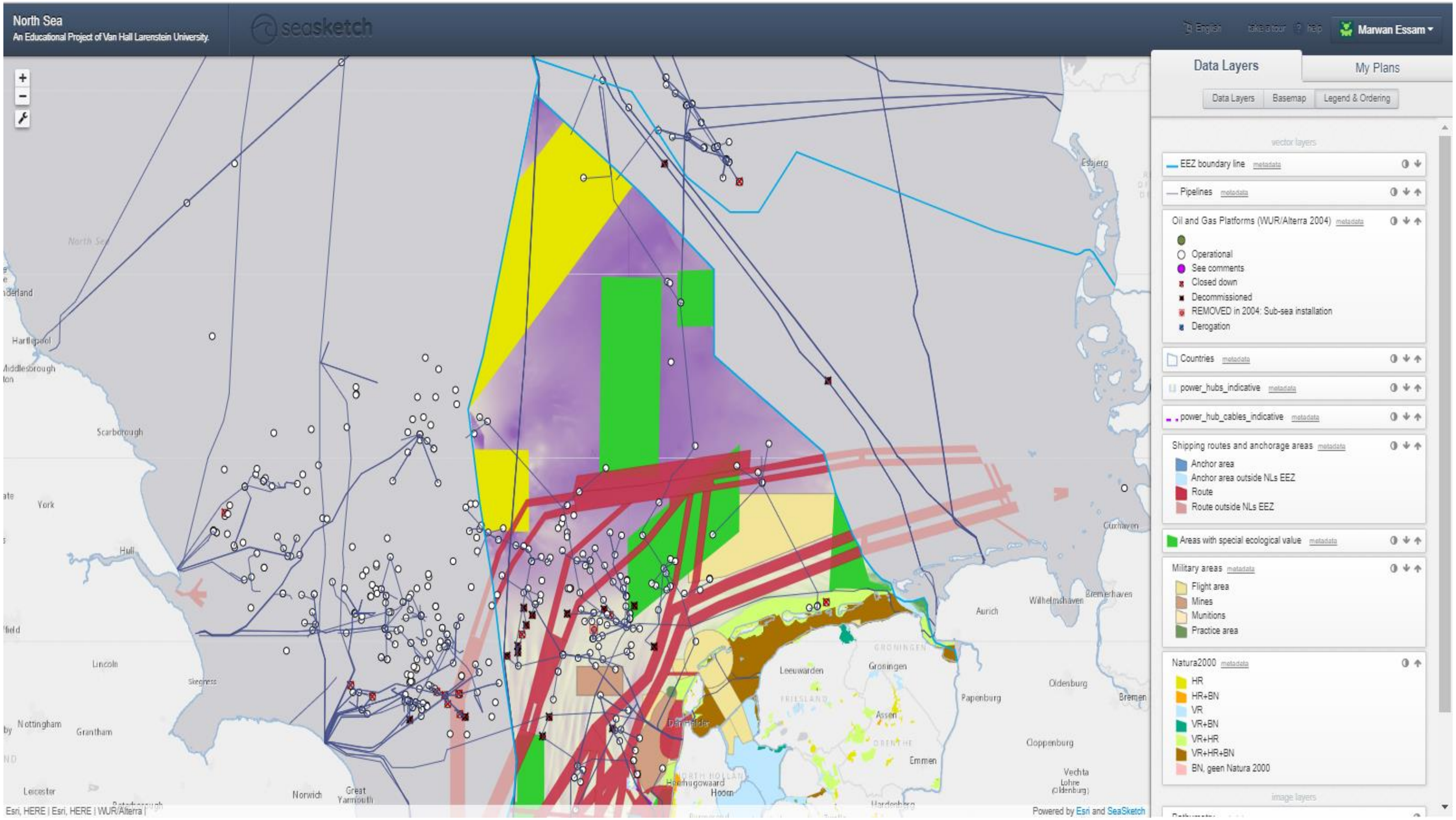

Figure 2.2 - The Dutch EEZ map with the important features using SeaSketch© platform

To solve this problem, the study decided to locate the project in the deepwater where little to no interest conflicts can arise. Figure 2.3 shows the proposed location for the study in the purple color. The selected area is free from any potential interest conflicts.

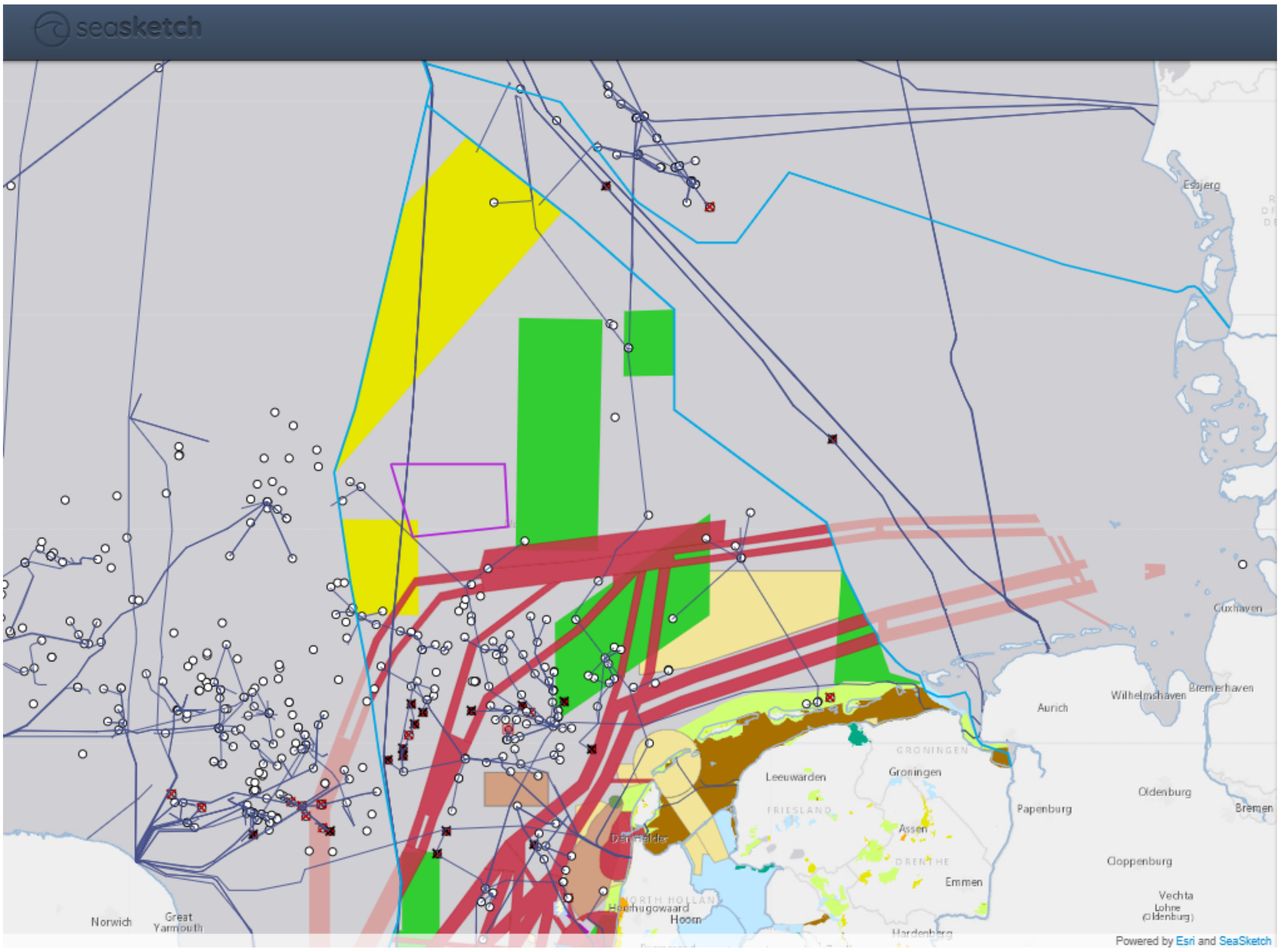

Figure 2.3 - The selected location for the study (the purple box)

The selected area for the project was not only chosen for its strategic location that can minimize any conflicts with any other Dutch party but also due to its proximity to the K5-D gas platform (see Figure 2.4). This platform has been commissioned in 1994 for a lifetime of 25 years. Currently, this platform is on the decommissioning plan. What makes this feature unique in this platform is the possibility of reusing it for the hydrogen production setup with no additional platform or pipeline costs.

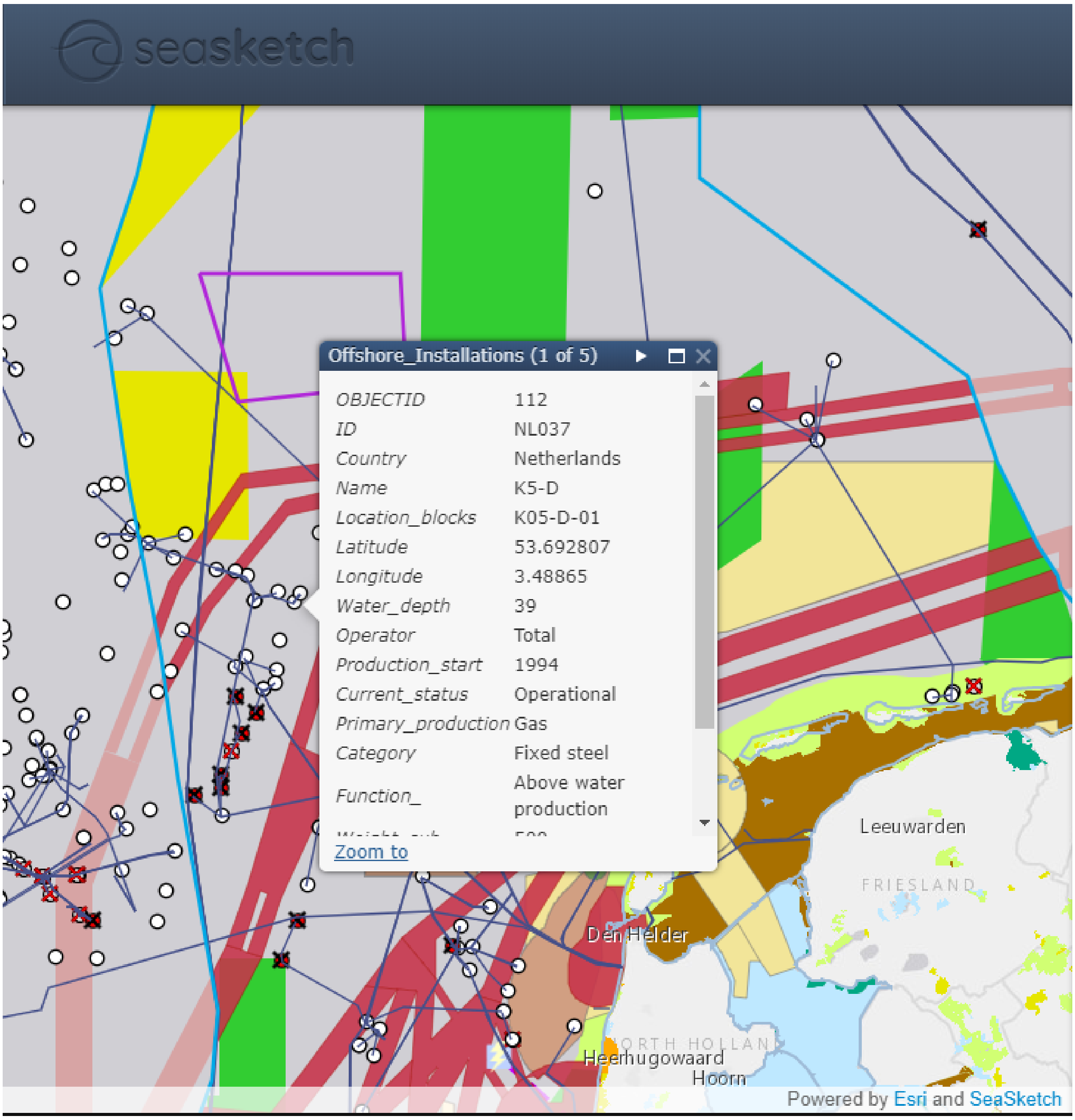

Figure 2.4 - K5-D platform location and characteristics

2.7.3 Distances Assumptions

For conducting a location-specific analysis, environmental data had to be collected. The study's scope and the time limitations constrained collecting up-to-date environmental data for the selected location; however, data from several studies are collected to be used for the analysis. Summary of the collected environmental data is shown in Table 2.1.

More importantly, distances calculations are carried out before starting the analysis. These distances included average distance from the site's location to the nearest shipyard and the average distance to the hydrogen production platform. These calculations are needed to calculate the grid connection costs to the shore and the hydrogen production platform. The location of the nearest shipyard is located using Google maps. The main shipyards are shown in Figure 2.5 while the distance calculations are presented in Figure 2.6 and Figure 2.7.

Figure 2.5 - Shipyards locations in the Netherlands using Google Maps

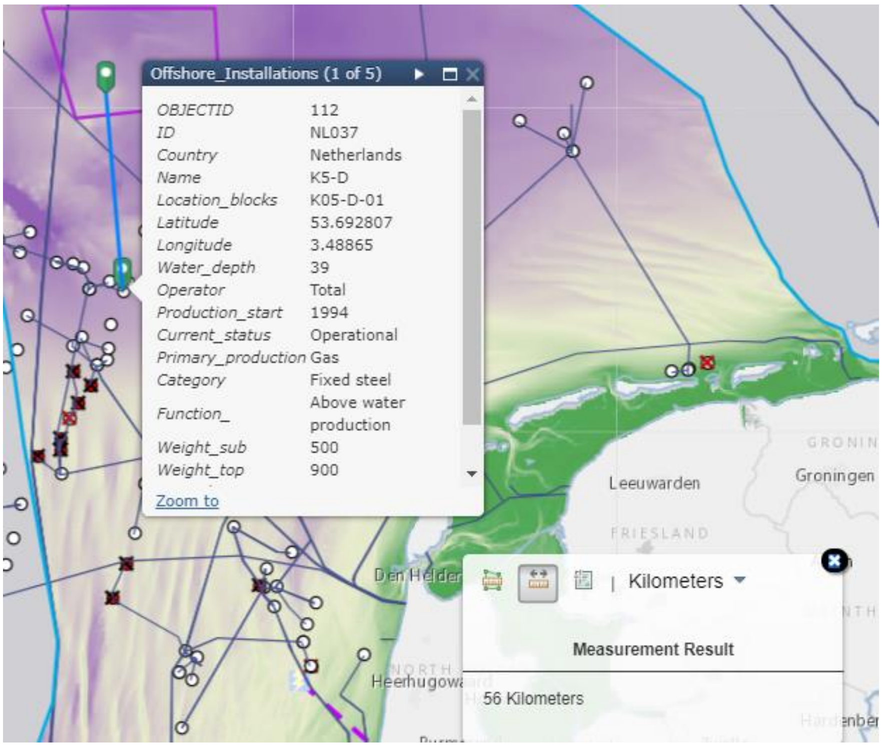

Figure 2.6 - Average distance from the site's location to the hydrogen production platform

Figure 2.7 - Average distance from the site's location to the nearest shipyard

Table 2.1 - Site's Characteristics

Parameter	Value	References
Average water depth (m)	42	(Ministry of Infrastructure and the Environment, 2011)
Mean wave height (m)	2.5	(George & Henk, 2019)
Mean wave period (sec)	5.5	(George & Henk, 2019)
Distance to the nearest shipyard (km)	165	Calculated using Seasketch
Distance to the hydrogen production platform (km)	56	Calculated using Seasketch

3 TECHNICAL DESIGN OF THE SYSTEMS

This chapter attempted to design the most technically feasible wind turbines park in 2020 by selecting the most efficient wind turbine foundation and model according to the selected location characteristics with respect to the associated costs of these systems calculated in other studies. Afterward, the design of the grid connection based on the best available technology is selected to export the energy back to the shore. Since the study is more concerned with the green hydrogen production as an energy carrier instead of exporting back the electricity through grid connection, so a clear state of the art description about this technology is reviewed to analyze the potential of the technology. While reviewing the state of the art, the researcher found some problems in utilizing the electricity produced from the wind turbines, so a solution of an energy combination is proposed by adding WECs to the wind turbines park approach before selecting the design for the green hydrogen production systems. Similar to designing the grid connection, the electrolyzer model and its auxiliaries are selected. Subsequently, selecting the most technically feasible design that can be implemented in the deep waters of the Dutch EEZ. For all the selected models, the engineering equations that calculate the energy production are presented.

3.1 BACKGROUND

Offshore wind innovations permit countries to harness the higher, and in some cases, smoother wind resources, while accomplishing gigawatt-scale projects near to the highly populated coastal zones pervasive in numerous countries in the world (DNV GL, 2018). These innovations make offshore wind a significant addition to the portfolio of low carbon advances accessible to decarbonize the energy segment of numerous countries. Offshore wind energy is one of the rising renewables technologies that has grown up in the last few years. This growth is reasoned to the quick innovation enhancements, and production network efficiencies in firmly connected markets in Europe have seen rapid cost reductions and the beginnings of significant take-up in new markets (IRENA, 2019a). Prodded by policy support and fiscal-related motivating factors, offshore wind is picking up energy as it gives a correlative alternative to some of the challenges faced by onshore wind. Principally, concerning transmission congestion and land constraints, that makes it all the more challenging to convey onshore wind in certain areas (IRENA, 2019b).

3.2 WIND FARM DESIGN

Offshore wind farm characteristics vary from the onshore ones as they need an extra step in designing by selecting the most appropriate foundation that suits the environmental characteristics. This section is attempting to select the best available foundation design and the most technological model with their associated grid connection design.

3.2.1 Foundation Selection

The majority of the offshore wind parks are built with fixed-foundation wind turbines (GlobalData, 2019). Contingent upon water depth and soil conditions, different models are used; however, the most basic is the monopile. Nonetheless, at deeper waters, regularly around 30 m, the monopile configuration arrives at designing limits as for pliable diameters and wall thicknesses (Myhr, et al., 2014). For deeper waters, the more costly jacket establishment is a substantial alternative. It is constrained to a depth of under 50 m, not because of design limitation, yet financial reasonability (GE Renewable Energy, 2018).

One may contend that the depth restrictions for fixed turbines narrow down the likelihood to use the immense amounts of offshore wind assets. For deeper waters, investors should approach diverse ideas, for example, the floating platforms. New ideas implemented in new areas may include expanded costs but floating foundations may simultaneously offer valuable perspectives as for improved wind conditions, diminished wave loading, decreased, and less visual impact (Fazeres-Ferradosa, et al., 2019).

A study conducted by Myhr, et al. in 2014 analyzed nine different wind turbines concepts that are reviewed to decide on the most feasible concept that can be implemented in a location that shares many similar characteristics as the selected one for this research. This study investigated life cycle cost assessments for many floating concepts under variant conditions, some of them are similar project’s conditions to the studied one in this thesis.

The floating design concepts comprise of four spar ideas, a semisubmersible and, a tri-floater. Stabilizer, displacement, mooring lines, or on the other hand a combination of these may balance out a floating system. Floating frameworks become accessible in waters from 30 m and more. The base fixed foundation ideas consist of a jacketed structure, used at average depths (30 to 50 m), while a monopile reasonable for shallower water. The entirety of the foundations is visually explained in Figure 3.1.

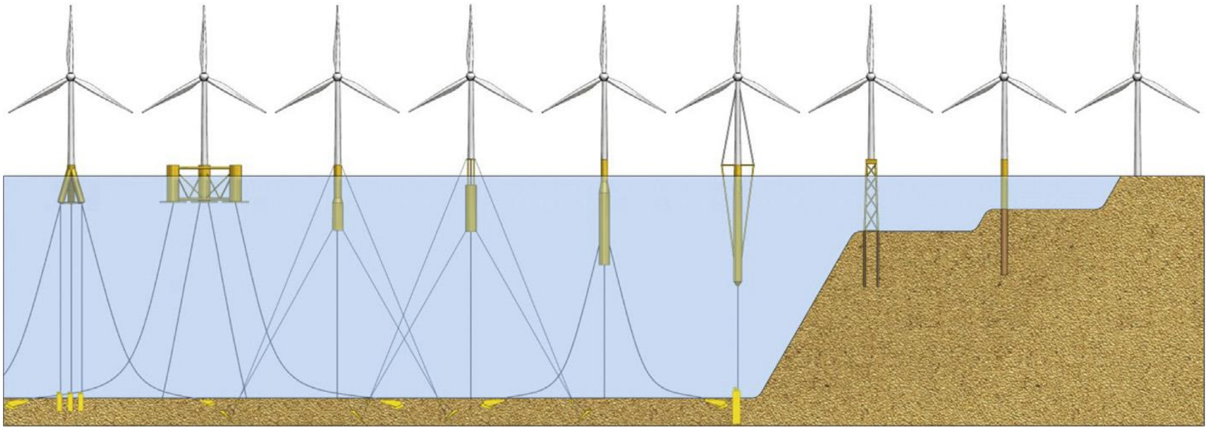

Figure 3.1 - Illustration of the different concepts, from left to right; TLWT, WindFloat, TLB B, TLB X3, Hywind II, SWAY, Jacket, Monopile and the onshore reference (Myhr, et al., 2014)

The Tension-Leg-Wind-Turbine (TLWT) used in this study accomplishes strength through dislodging and securing lines. It is created by the International Design, Engineering, and Examination Service (I.D.E.A.S) and independent on the Tension Leg Platform (TLP) framework; a supported solution in the offshore oil and gas sector. The TLP idea is notable for its performance using vertical ligaments to diminish the movements along the vertical pivot. Be that as it may, the TLWT highlights an investigated and advanced structure and separated tri-floater sub-structure. The TLWT may use a lot of three slanted tendons under explicit conditions; however, the arrangement utilized in this work highlights three vertical tendons held by suction anchors.

More importantly, the study showed that TLWT foundations are with one of the least accumulative LCOE compared to the other foundations as shown in Figure 3.2. The figure shows a diverse range of LCOE because of the different analyzed scenarios like different water depths, different distance to shore, etc. After looking into the water depth and the distance to the shore factors, a decision is made to select the TLWT wind turbine foundation model in the cost analysis as the TLWT is found to be cheaper for depths range from 30 to 100 m.

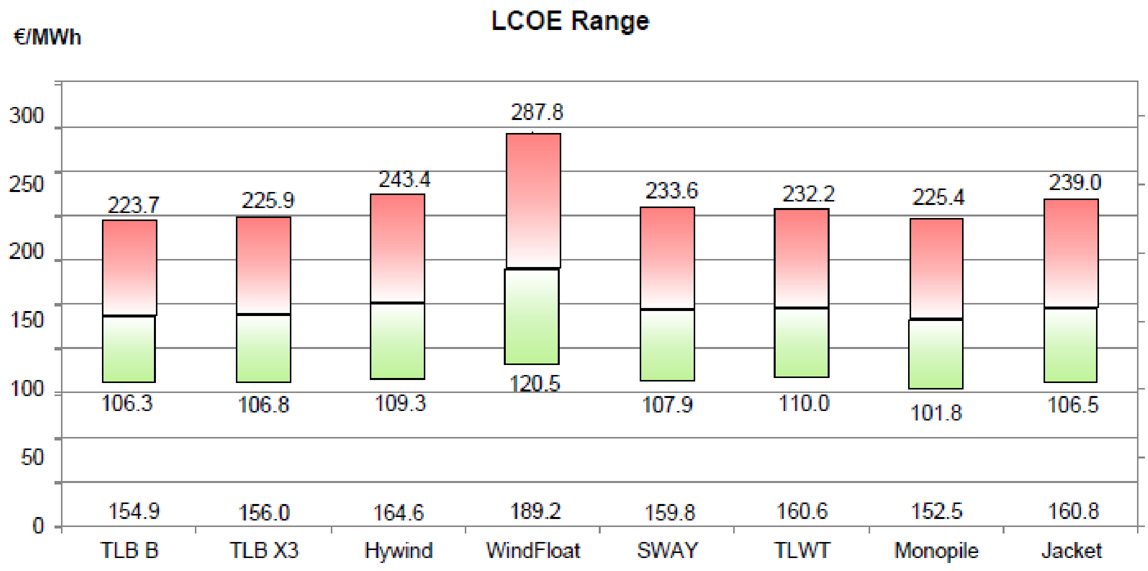

Figure 3.2 - LCOE for the reference wind farm for each of the concepts with indications on both best- and worst-case scenarios (Myhr, et al., 2014).

3.2.2 Turbine Model Selection

Walney Extension project in the Irish sea is considered as the world's largest operational wind farm (Fazeres-Ferradosa, et al., 2019). Moreover, the project has utilized the world's best available wind turbine models as they can deliver 659 MW of electricity using 87 turbines. The turbines models used are 47 x Siemens Gamesa 7 MW and 40 x MHI Vestas V164 8.25 MW (Digital Journal, 2018). Accordingly, for the 2020 analysis, the study has selected the MHI Vestas V164 wind turbine model as the turbine unit used in the energy production.

3.2.3 Wind Energy Production

Each turbine has a rated, cut-in and cut-out wind speeds. When the when speed is lower than or above the cut-out wind speeds, the turbine cannot produce electricity (Jensen, 1983). The rated wind speed of any turbine model can be calculated using Equation 3.1. These speeds average for most of the models should be between 4 and 15 m/s (Jensen, 1983).

$$P_{wind} = 0.5\, \rho_{air} A_s U^3 c_p \tag{3.1}$$

Where ρ_{air} is the air density at the turbine's hub, A_s is the swept area by the turbine's blade, U is the wind speed at the turbine's hub and c_p is the power coefficient. In this study, the power coefficient is assumed to be 45%.

3.2.4 Grid Connections Design

Firstly, it is obvious to differentiate between the inter-array cables and the export cables. The inter-array framework is partitioned into strands, each is able to support five turbines with a 33 kV 400 mm^2 of copper cable (ofgem, 2020). The separation in the reference grid is 1 km for each turbine (Nambiar, et al., 2016). Interfacing between inter-array cables is assumed to be 1.4 km long (Fragoso Rodrigues, 2016). To adjust the length of the cables to the water depth, the depth is added to the length. The inter-array cables will result in an energy loss of 0.68% (Ågotnes, 2013). Alternatively, the export cables are considerably bigger and more costly than the between inter-array ones. In terms of energy losses, the power loss due to the export cables is approximately 5.8% (Fragoso Rodrigues, 2016). This study center around distant offshore wind parks, therefore, Direct Current (DC) is the better alternative (Ågotnes, 2013). There is also a need for stepping up the current to a suitable voltage in order to minimize the losses, in this case, an onshore substation needs to be installed (Ågotnes, 2013). A schematic layout of the wind farm layout is shown in Figure 3.3.

Figure 3.3 - The wind farm schematic layout

3.3 GREEN HYDROGEN PRODUCTION DESIGN

This section analyzes the level of maturity of the technology and the existing hindrance along with discussing the available solutions to overcome them. The section highlights the synergies that could be resulted from using different systems in producing energy while attempting to design the most-effective and least-costly models available in the international market.

3.3.1 State of the Art

Hydrogen Production Status

Hydrogen is a perfect energy carrier that can play a significant role in the global energy transition. Green hydrogen from renewable energy resources is a close to zero-carbon creation course (Hydrogen Council, 2020). Significant cooperative synergies could exist between quickened deployment of sustainable energy resources, and hydrogen creation and use.

Energy conversion to hydrogen could become an approach to transport sustainable energy over long distances, particularly in those situations where the electricity grid has deficient capacity or when it is illogical or costly to construct. This may be the situation with offshore wind, where hydrogen could be created offshore, and it can be transported to the shore through subsea pipelines, where the expenses are lower than those for laying subsea cables (IRENA, 2018b).

Today, around 120 million tons of hydrogen are created every year, of which 66% is unadulterated hydrogen, and 33% is in blend with different gases. This equivalents 14.4 exajoules (EJ), about 4% of final worldwide energy and feedstock use, as per International Energy Agency measurements (IEA, 2019). Around 95% of the hydrogen is created from coal and natural gas, while the rest is created as a by-product of chlorine production through electrolysis. As of now, there is no substantial hydrogen creation from sustainable sources (IRENA, IEA and REN21, 2018).

Most by far of hydrogen today is produced and utilized on-site in industry. The creation of ammonia and oil refining are the main purposes, representing 66% of hydrogen use (Hydrogen Council, 2020). Ammonia is utilized as nitrogen compost and for the creation of different synthetic compounds. At oil processing plants, hydrogen is added to heavier oil for transport fuel creation.

While the present hydrogen use has secondary importance for the energy transition, it has brought an abundant experience in hydrogen handling. Hydrogen pipeline crossing many kilometers are in place in different nations and districts and have worked without incidents for a considerable length of time. Additionally, there is a wide reputation for shipping hydrogen in well-designed trucks. Large scope investment of hydrogen (or hydrogen-inferred energizes and items) can result in an increment in the demand for renewable energy production. Altogether, it can be predicted that there will be a worldwide economic potential for 19 EJ of hydrogen from renewable energy in the energy consumption by 2050 (IRENA, 2019a).

However, direct electrification through heat pumps is having a higher actual energy or an end-use efficiency than the hydrogen alternatives. For example, heat pumps can provide up to 270% more energy services when compared to hydrogen boilers. Thus, hydrogen production inefficiency has mainly resulted from the significant losses in the logistics chain as in the liquification or the electrolysis phases, as the losses can reach up to 45%. This challenge imposes a great challenge for this sector as it needs only to be utilized in a big scale where the monetary value of the losses is less than the infrastructure needed for electricity connections (Hydrogen Council, 2020).

Hydrogen Electrolysis

One of the most basic concepts in hydrogen production is water electrolysis. Water molecules can be split into hydrogen and oxygen using an electrolyzer. The electrolysis can play an important role in the green hydrogen deployment. Electrolyser can be concluded in three main technologies, namely; Alkaline (ALK) electrolyzers, Proton Exchange Membrane (PEM) electrolyzers, and Solid Oxide Electrolyser Cell (SOEC) (Hydrogen Council, 2020).

Alkaline electrolyzers work simply by immersing two electrodes in a liquid electrolyte when a voltage is applied, and the hydrogen gas is released. This electrolyzer poses some problems as it is unable to make efficient use of intermittent power supplies which means that it is incompatible with renewable energy resources, i.e, not functional with the fluctuation in the electricity production from wind turbines because of the unsteadiness in the wind supply. It also compromises efficiency during storage as the produced hydrogen needs a huge tank or an additional compressor (IEA, 2019). PEM electrolyzers works by using a solid polymer electrolyte instead, which is the membrane responsible for protons production that separates the hydrogen from oxygen and provides electric insulation from the electrodes. This electrolyzer can make use of the fluctuating nature of the renewables power supply; however, it has a prohibitively high cost because it uses gold, iridium, and platinum (IRENA, 2019c).

The ALK was not initially intended to be adaptable and has been operated at a steady load to serve industrial demands. However, Ongoing advancement ought to be noted, making ALK innovation perfect with the infrastructure of grid services on a short timescale. At present, ALK innovation stays less adaptable than PEM technology, which at last confines the measure of additional income that the operator might collect from adaptability.

SOEC innovation holds the guarantee of more prominent efficiencies contrasted with ALK and PEM. Nevertheless, SOEC is an immature technology, just showed at the lab-scale (IEA, 2019). Notwithstanding, the SOEC system requires ceramic and not many uncommon materials for their stimulus layers, while PEM electrolyzers need huge amounts of platinum for their layers (Meier, 2014).

With a counter-intuitive result, electrolyzers can operate with a higher efficiency at lower loads compared to their maximum capacity, in contrast with most of the current energy systems. In other words, lower load factors can result in a high Levelized Cost of Hydrogen (LCOH). In comparison, at higher load factors, any reduction in the CAPEX will have a minimal impact on LCOH values, assuming the current high electricity prices. For instance, the load factors generally exceed 50% with the current investment level; however, the optimal hydrogen cost is achieved at around 35% (IRENA, 2019c).

When directly associated with an off-grid Variable Renewable Energy (VRE) plant, the electrolyzer should follow the VRE production fluctuations, which requires the adaptability of a PEM electrolyzer. Consequently, the CAPEX part of the LCOH will be dictated by the load factor of the VRE plant. Moreover, there is no increase in LCOH with increased consumption for the off-grid systems. One of the most radical solutions for increasing the load factor of electrolyzers in off-grid systems is a combination of different energy resources. This can regulate the fluctuating nature of the energy production of an individual renewable energy system (IRENA, 2018b).

Energy Technologies Combination

While examining the performance of the electrolyzer, the offshore wind park characteristics must be thought of. offshore wind power is exceptionally variable. In any case, as indicated by the European Wind Energy Association (EWEA), it is not discontinuous, which means that significance sporadic and capricious changes or start/stop intervals in power yield on a minute or even second basis do not happen. Momentary inconstancy (within the minute) is not an issue, while varieties inside the hour are critical (Konrad, 2014). The variability is one of the most significant factors for the designing of a hydrogen production plant, as it requires electrolyzers and systems to have the option to deal with this variety and force converters to convey the correct voltage at various limits with the same effectiveness.

Wave energy presents many possibilities for the future, thanks to its enormous potential for electricity production (Astariz et al., 2015). The wave energy potential globally has been estimated at 10 TW, and by taking into account the exploitation ability, this can meet from 15% to 66% of the total world energy consumption (Zheng et al., 2020). Must be remembered is the technology's immaturity level, regardless of the late research attempts on WECs (Astariz et al., 2015). Additionally, it presents higher LCOE compared to a non-sustainable power source and more than many renewables (Pérez et al., 2012). Along these lines, in due time, wave energy is not economically feasible and might only be under subsidy schemes (DNV GL, 2018).

In principle, wave energy converters catch the energy contained in sea waves and use it to create power. There are three principal classes, which are oscillating water columns, oscillating body converters, and overtopping converters. The oscillating water column utilizes trapped air pockets in a water column to drive a turbine. In contrast, oscillating body converters use the wave movement (up/down, advances/ in reverse, side to side) to generate electricity. Overtopping converters utilize reservoirs to make a pressure head so they can drive turbines (Zheng et al., 2020).

Wave and Wind Combination

The integration of wave and wind energy systems comprises of different layouts, shown in Figure 3.4. A point often overlooked that these systems do not offer the same foundation system for the wind turbines and the WECs but only sharing the same marine space, connections to the grid, and O&M equipment (Soares, 2016).

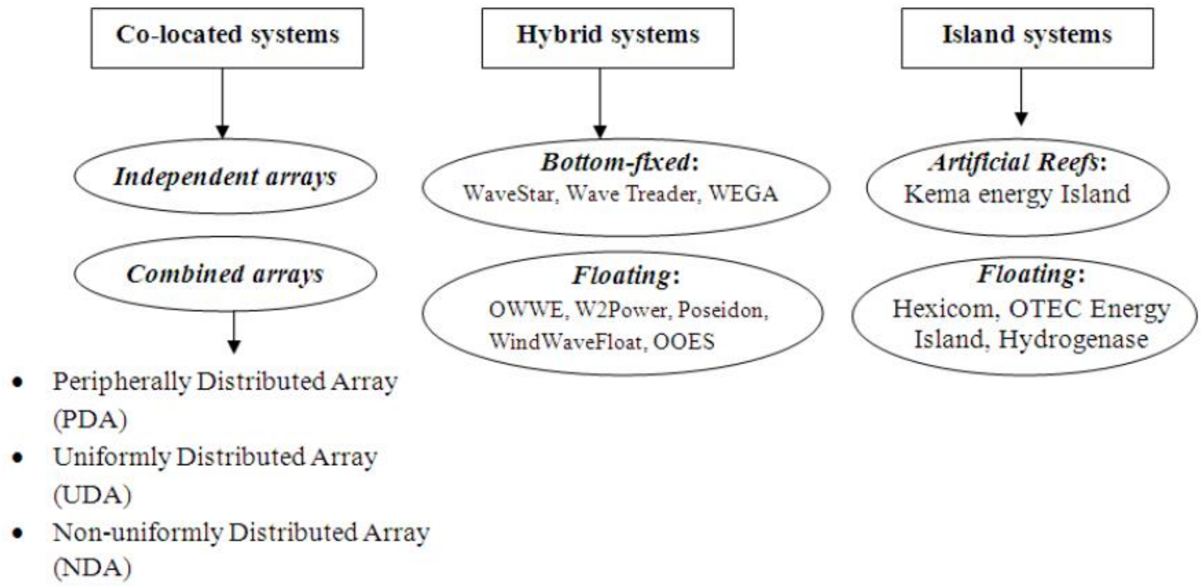

Figure 3.4 - Classification of combined wave-wind technologies (Soares, 2016)

Numerous synergies could be exploitable to beat the hindrances that marine energies could face to achieve competitiveness. Above all else, significant cost alleviations could be accomplished during the arrangement of the energy farms provided that coordinated strategies took place (Buchner, et al., 2010). A significant cost savings would be accomplished in the grid connections, since the export cables can be unified. At the point when hybrid innovation was created, significant cost reductions in the substructure foundation would be accomplished as wave converter could share the same foundation with the offshore wind turbine (Smith et al., 2012). Besides, the expense of O&M activities can be decreased in these farms since the planned maintenance of wind and wave can be done simultaneously or in a ceaseless period (Falcão, et al., 2016). An ongoing study (Astariz, et al., 2015) reported cost savings around 25% in the capital expenses and up to 14% in the operational expenses of integrated wave and wind parks. Also, offshore energy companies pay for leases as per occupied areas, so covering the same place with two systems decreases these expenses.

Equally important, the mix of two distinct innovations exploiting various energy resources at a single site will expand the energy yield per unit and, in this way, add to a more practical utilization of the renewable assets (Pérez-Collazo, et al., 2013). Besides, integrated systems would decrease the economic expenses of remediating the environmental impacts of these marine systems since the influenced area will be smaller compared with separate wind and wave farms. Moreover, studies have presumed that presenting WECs in offshore wind farms offset the power generation's inconstancy and, forthwith, smooths the force yield (Stoutenburg et al. 2010). Based on these factors, adjusting costs could be diminished by up to 35% (Chozas, et al. 2012). Besides, another study conducted by Chozas, et al. 2013, found that the power yield of WECs is 35% more predictable than wind turbine power yield. Given these points, engineers can take the monetary risks in their designs by synchronizing with wind projects.

Together with the mentioned synergies, other technological synergies could be achieved through this integration, notably, the shadow effect. The operational limitations of offshore vessels for O&M assignments are at a significant wave height of 1.5 meters (Bierbooms, et al., 2002). At the point when this limit is exceeded, delays in maintenance activities follow, and the downtime resulted from the delay adds more to the OPEX. On the other hand, WECs launched at the wind park periphery could create a protecting effect over the area that broadens the weather windows for O&M. Subsequently, this expansion in the accessibility to the turbines gets significant cost savings around 25% of the O&M costs that would prompt a reduction in overall project's expenses equivalent to 2.3% (Scottish Enterprise, 2012)

3.3.2 WEC Model Selection

From the many wave energy devices, the Pelamis WEC is one of the first converters that has arrived at a commercial scale (Dalton, et al., 2010). The reached milestone and the analysis behind the Pelamis converter are uncommon and unparalleled by some other devices. The device's physical qualities and cost assessment can be utilized because of the huge literature on the Pelamis to test the monetary feasibility of wave energy. It utilizes the movement of the waves to produce power in an offshore location, working in water depth more than 50 m and introduced somewhere in the range of two and ten kilometers from the shoreline (Kempener & Neumann, 2014). Appraised at 750 kW, one machine ought to be equipped for giving adequate capacity to meet the yearly power request of around 500 homes (Pelamis, 2014). Pelamis is comprised of four cylinders connected by joints that permit two-dimensional flexing. It is semi lowered and faces into the waves (Previsic, 2004). As waves go down the length of the machine, the areas twist in the water and the development is changed over into electrical energy by means of water-powered force take-off frameworks housed inside each joint of the gadget (Pelamis, 2014). The gadget should be sufficiently secured to withstand the states of an offshore environment. The securing comprises of a three-point mooring arrangement. It permits the device to transform into the wave bearing inside its securing limitations (Previsic, 2004) Table 3.1 records the specifications of the Pelamis gadget.

Table 3.1 - Pelamis WEC model specifications

Feature	Specification
Overall Length	150 m
Diameter	4.6 m
Displacement	700 Ton
Weight	380 Ton
Average Power	750 KW
Total Anchor Weight	14.5 Ton
Total Mooring Chain Weight	100 Ton
Mooring Type	Compliant slack moored (site-specific requirements). Combination of steel wire, chain, dead weights, and embedment anchors.

Interestingly, the Pelamis can join a structure with a fast interface/disengage framework, which facilitates a quick deployment and maintenance with relatively small vessels. The subsystems and segments are structured so they can be lifted without the utilization of cranes and replaced with advanced subsystems. The Pelamis device has remote checking abilities to identify any faults and determine the specific reason. Sometimes, the deficiency might be redressed without physical interference as the administrator checking the system can recognize the reason. In increasingly complex conditions, major issues would require the Pelamis to be towed to a protected site for maintenance (Pelamis, 2014). Therefore, the Pelamis WEC is considered as the best option to be installed with the TLWT wind turbines. Though the Pelamis is the most mature wave energy converting technology and the cheapest commercially available device, the Pelamis models are now unlikely to be selected for energy projects because of the economic barriers behind the devices. Nevertheless, the Pelamis acts as a benchmark for other WECs in the development process. Since the Pelamis is the best alternative to overcome the power intermittence problem resulting from the energy fluctuation from the wind turbines, the study tried to implement the solution on a limited scale with the least possible number of gadgets.

3.3.3 Wave Energy Production

The energy delivered by the farm is produced from the selected system models for the site, their design (which decides their intuitive impacts on power production), and site-specific energy availability. The energy production of the park (in MWh/year) is the entirety of the wave energy delivered by the WECs and the wind energy delivered by the wind turbines), and is efficiency on the productivity of transmission equipment.

The wave energy delivered by a WEC device can be determined either by utilization of the WECs experimentally calculated energy matrix and the local environmental data matrix or by the calculation of the accessible wave energy dependent on wave period and significant wave height (Beels, et al., 2007). In this analysis, the latter technique is utilized using Equation (4.1) due to the complexity of the first approach.

$$P_{wave} = \frac{\rho_{water}\ x\ g^2\ x\ T_e\ x\ {H_{mo}}^2}{64\pi} \tag{4.1}$$

Where ρ_{water} is the seawater density, g is the gravitational acceleration, T_e is the significant wave period, and H_{mo} is the significant wave height. Afterward, the available wave energy available in the location is multiplied by the Pelamis model energy conversion factor.

3.3.4 Electrolyzer Model Selection

Brine solution electrolysis would be the most logical system as it utilizes a sodium chloride (NaCl) water solution which is fundamentally a type of concentrated ocean water. Be that as it may, there was near no information found on seawater electrolysis. This returns to the fact of the impurities influence and the low concentration of NaCl (Buck, 2012). Therefore, this system will not be examined in this study. Nevertheless, it is a normalized industry procedure to deliver caustic soda with hydrogen as a byproduct. The most widely recognized electrolysis process is Alkaline electrolysis that utilizes potassium hydroxide (KOH) - water solution, which would require storage and transport of KOH and is subsequently not considered as practical either (Williams, et al., 2009). The proton exchange membrane (PEM) electrolysis cell and the SOEC are electrolysis systems which require just water as feed in.

Similar to the selection methodology applied to the wind turbine foundation, the decision between selecting PEM and SOEC will be made. Both picked electrolyzers use water as a feed-in stream, however, there are differences in procedure and configurations. The SOEC requires a steam generator and a high performing compressor as the resulting hydrogen is produced at the atmospheric pressure (Konrad, 2014). The PEM operates at pressurized conditions so the compressor requires less force and the input stream of the PEM electrolyzer is freshwater. The SOEC ceramic material requires no noble and uncommon metals as the PEM, which makes it conceivably less expensive (Konrad, 2014).

The examined study in this section is conducted by Konrad (2014), which examines the total costs of hydrogen production from a Norwegian offshore wind park with a production of only 100 MW of electricity and not close to 600 MW as explained in chapter two. This is justified by the author as wind parks are typically evolved with time, it is practicable to utilize a basic number as a base case. Mathur et al. have demonstrated that the limit of 100 MW speaks to the base limit with regards to monetarily plausible hydrogen creation utilizing offshore wind (Marthur, et al., 2008). The study is selected due to the numerous similarities between the reviewed base case and this study's location characteristics as the shore distance, the water depth, and both are located in the North Sea.

The study shows that the SOEC electrolyzer is relatively cheaper than the PEM in the base case analyzed in this paper. The main factor contributed to this result is the price of the electrolyzer itself while the other factors are almost with the same prices or negligible influence on the total costs (see Figure 3.5).

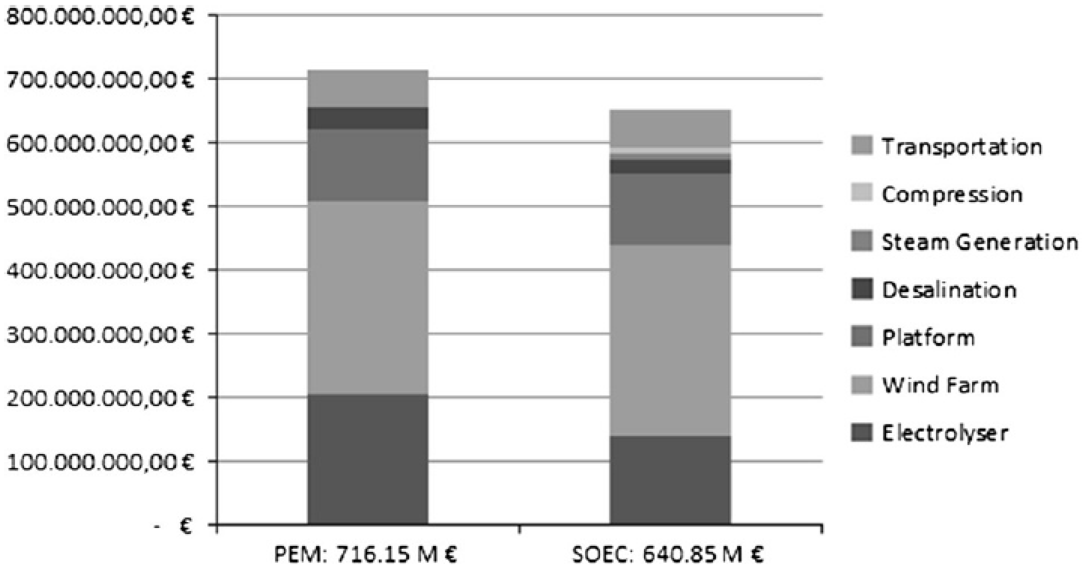

Figure 3.5 - Cost components influence on the total investment of PEM and SOEC electrolyzers (Konrad, 2014)

3.3.5 Array Layout

Following the same assumed layout in Clark et al. (2019) study, the wind turbines are laid out in a sloping rectangle at an average depth of 42 m. The turbines were placed 560 m distant from each other while the WECs were kept at a distance of 280 m from the wind turbines, and 198 m from each other. The study used the TLWT type platform as a foundation, and the MHI Vestas V164 turbine model as in the conventional wind turbine approach discussed earlier in the turbine model selection section.

3.3.6 Hydrogen Production Platform Design

The platform where all needed systems and machinery for hydrogen creation are based is the primary vulnerability in monetary terms. Nevertheless, offshore platforms designing and construction industries became very mature in the recent decades. The offshore oil and gas industry construct platforms where modern systems, for example, chemical handling, treatment processes, and living quarters, are set on the platform (Statoil, 2007).

Taking advantage of the numerous oil and gas platform placed in the North Sea, the study selected a platform on the Dutch government decommissioning plan to install the needed systems and auxiliaries for the hydrogen production process as described in Chapter 2.

The hydrogen production process will start from consuming the electricity produced from wind and wave integrated farm to supply mainly the SOEC stacks. Nevertheless, some auxiliary systems are required for the hydrogen production process which operates with the electrical supply. Since the SOEC stacks cannot process the seawater due to the high concentration levels of salts and minerals, a desalination plant is required to provide a boiler-feed water quality for the process (Ghaffour, et al., 2012). The desalination process can be done using reverse osmosis or thermal treatment (Tewari, et al., 1990). The selected process here is the multi-stage flash distillation as it produces better-quality water which requires much less post-treatment processes. The problem with the post-treatment processes that they require chemical treatment to react with the remaining dissolved ions and salts (Ghaffour, et al., 2012). Using chemicals is challenging on a remotely-located offshore platform and adding significant extra costs in delivering the needed chemicals regularly. On the other hand, The flash distillation requires a nearby boiler to deliver the required heat for the process (Ophir & Gendel, 1994). Therefore, the boiler is needed for heating the treated water influent into a steam for the SOEC's electrolyzing process beside the electricity supply (Ghaffour, et al., 2012). After the electrolysis, the hydrogen is separated from steam to pass through the compressor as the produced hydrogen's pressure is atmospheric. The compressed hydrogen is transported back to the shore then via the existing platform's pipeline. A schematic of the process is shown in Figure 3.6.

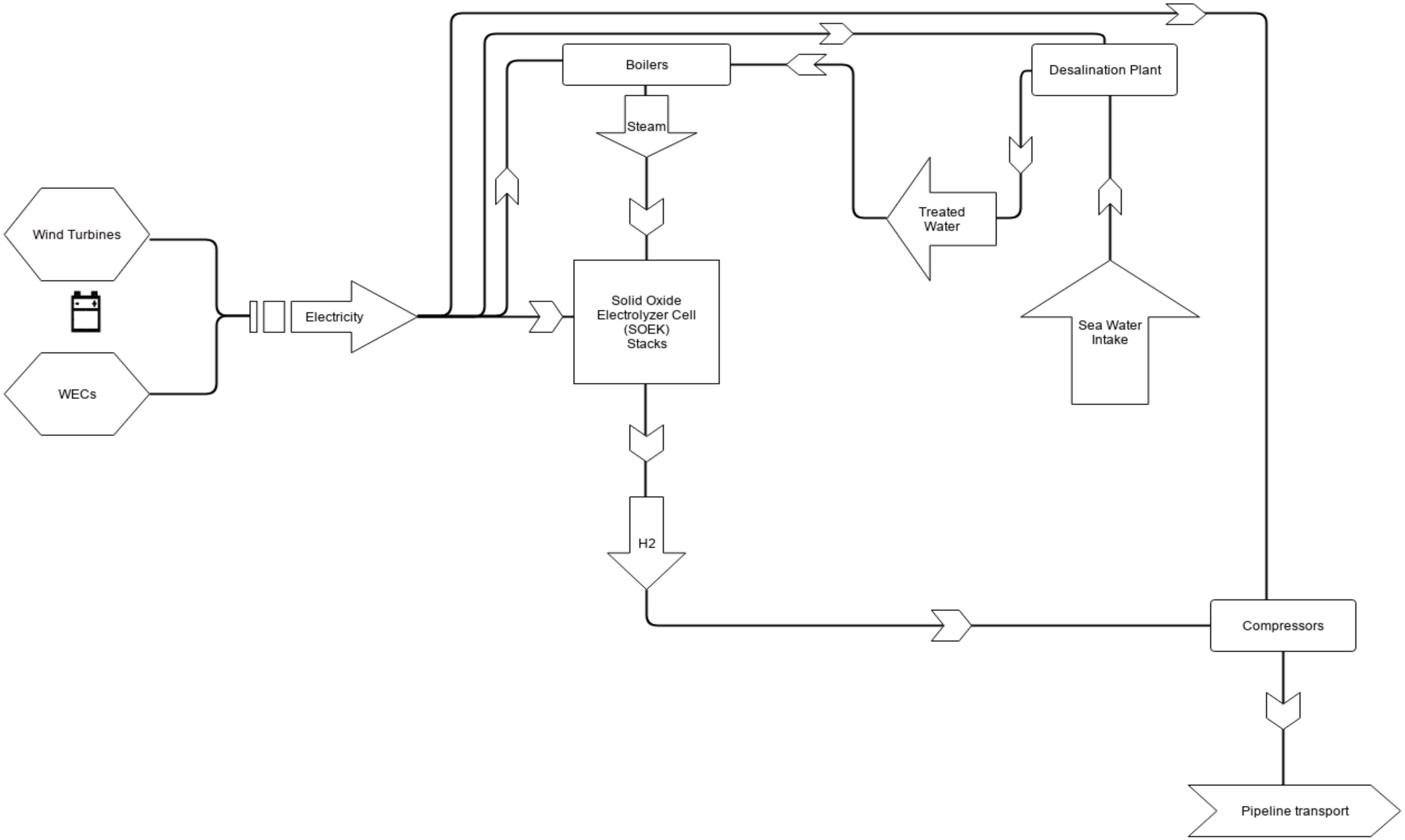

Figure 3.6 - A schematic layout of the hydrogen production

3.3.7 Hydrogen Production

The basic reaction for electrolysis is in Equation 4.2 (Tewari, et al., 1990).

$$H_2O + Electricity \rightarrow H_2 + 0.5O_2 \tag{4.2}$$

This reaction is considered as an endothermic one; which means that it requires an external source of energy. The required energy is presented in Equation 4.3.

$$\Delta H = T\Delta S + \Delta G \tag{4.3}$$

Where ΔH is the enthalpy change which is equal to the multiplication of the process temperature (T) and the entropy change (ΔS) which represents the minimum required thermal energy and ΔG which is Gibbs free energy which represents the minimum required electrical energy (Ferrero, et al., 2013).

Based on the enthalpy change, the voltage for a SOEC electrolyzer cell to start operating can be determined with Equation 4.4,

$$V_C = \frac{\Delta H}{2F} \tag{4.4}$$

where F is Faraday's constant and 2 is the number of the electrons. The required enthalpy change for a SOEC electrolyzer is equal to 119.93 kJ for each gram of hydrogen multiplied by a hydrogen atom's molar mass (Ferrero, et al., 2013).

Consequently, the amount of hydrogen (m_{h2}) that can be produced is determined by Equation 4.5,

$$m_{h2} = \frac{P_{total}\ x\ M\ x\ \eta}{V_C\ x\ 2F} \tag{4.5}$$

where P_{total} is the total power input, M is the molar mass of the hydrogen, η is the electrolyzer efficiency (El-Bassuoni, et al., 1982) which is 67% for the SOEC based on the current best technology (IEA, 2019).

Sine the SOEC electrolyzer can not operate directly with the seawater, the water intake needs to be treated. This water treatment comprises of purification and desalination. Based on the reviewed literature, there was not any reliable data on how to calculate the required chemicals for the treatment and filling frequency. The researcher returned this to the fact that this approach has not been used in hydrogen production for energy purposes. Therefore, the thermal desalination option is selected for the analysis, thought the reverse osmosis can be considered as a more efficient, it delivers a low-quality hydrogen that needs complicated post-treatment.

The energy needed for the heating process ($E_{heating}$) is calculated using Equation 4.6,

$$E_{heating} = \frac{m_{h20}\ x\ C_s\ x\ (T_{final} - T_{intake})}{\eta_{boiler}} \tag{4.6}$$

where m_{h20} is the amount of water needed for heating, C_s is the specific heat of water, T_{final} is the desired temperature from the heating process; which is assumed to be 110℃, $T_{intake}$is the seawater's temperature and $\eta_{boiler}$is the boiler's efficiency (Ferrero, et al., 2013); which is assumed to be 99% (Konrad, 2014). The amount of water needed for the desalination m_{h20} is calculated with Equation 4.7,

$$m_{h20} = \frac{m_{h2}}{M} M_{h2o} \tag{4.7}$$

where $M_{h2o}$is the molar mass of water.

For the desalination, the energy required for the process is 12 kWh for each cubic meter of water (Konrad, 2014).

Since the SOEC operates at the atmospheric temperature, the produced hydrogen needs to be compressed for transportation. The energy required for the compression (E_{comp}) is calculated by Equation 4.8,

$$E_{comp} = \frac{\frac{m_{h2}}{M}\ x\ R\ x\ T_{ambient}\ x\ \ln\left(\frac{P_{final}}{P_{intake}}\right)}{\eta_{comp}} \tag{4.8}$$

where R is the universal gas constant, $T_{ambient}$ is the ambient atmospheric gas temperature, $\ln\left(\frac{P_{final}}{P_{intake}}\right)$ is a logarithm of the ratio between desired pressure from the compression process; which is assumed to be 100 bars, and the atmospheric pressure, and η_{comp} is the compressor's efficiency; which is assumed to be 70% (Konrad, 2014).

3.4 DISCUSSION

The chapter analyzed the available technologies with respect to their costs to design two approaches for producing energy from the deep waters and exporting it back to the shore. The two approaches were approved to be feasible by the reviewed studies in this chapter. Though the chapter described the energy performance for the selected models, it did not compare the final energy that could be exported back to the shore from both approaches. The reason behind that is the inability to determine the size of the farm at this stage as the most optimal farm size is determined later in the study based on the collected costs.

4 COST ANALYSIS

After selecting the models which will be used in both approaches, this chapter presents the cost components for the selected models by 2020 prices based on the LCCA which was described earlier in the methodology chapter. These costs are calculated to compare the total investment costs of each approach based on the present values with the final energy transported back from the shore, in this way, the LCOE could be calculated for each approach. Afterward, the expected technological advancement and cost reduction by 2030 is discussed to help in calculating the future LCOE. Finally, the results of the carried out analyses in the five appendices are presented starting from a trial analysis from the green hydrogen production approach to calculate the farm size with the least LCOE value based on 2020 prices followed by the results of the 2020 approaches then the 2030 ones. The farm size resulted from this trial is assumed to be constant for the remaining cost models while ignoring the differences coming from the reductions in the 2030 costs.

4.1 COST ANALYSIS BASED ON 2020 PRICES

4.1.1 Energy Production Costs

The energy delivered by the farm is produced from the selected system models for the site, their design (which decides their intuitive impacts on power production), and site-specific energy availability. The energy production of the park (in MWh/year) is the summation of the wave energy delivered by the WECs and the wind energy delivered by the wind turbines.

The described cost model in this section is applicable for both the wind-wave collocated farm or the conventional wind farm. The extra costs of the WECs are included as well as the influence of the WECs on other cost items.

The LCOE is equivalent to the costs (C_t) through the lifetime (t) of the project, divided by the energy delivered in that time span as shown in Equation 5.1 (Gielen, 2012).

$$LCOE = \frac{PV\ (costs)}{PV\ (output)} \tag{5.1}$$

The costs included over the project's life cycle include the cost of pre-installation ($C_{pre\text{-}installation}$), implementation ($C_{implementation}$), OPEX ($C_{Operation}$), and decommissioning ($C_{decomissioning}$) phases described in Equation 5.2.

$$C_t = C_{pre-installation} + C_{installation} + C_{operation} + C_{decommissioning} \tag{5.2}$$

Pre-installation costs

Pre-installations costs comprise mainly the costs related to the feasibility study, site selection, permits, viewshed, legislative factors, engineering analysis, and GHG investigations described in Equation 5.3 (Dalton, et al., 2010).

$$C_{pre-installation} = C_{feas} + C_{eng} + C_{leg} + C_{design} + C_{viewshed} + C_{permit} + C_{GHG} \tag{5.3}$$

The collected pre-installation costs are summarized in Table 4.1.

Table 4.1 - Pre-installation phase costs

Description	Costs (euros)	Reference
Engineering analysis	570000	(Astariz & Iglesias, 2015)
Feasibility study	100000	(Castro-Santos, et al., 2016)
Legislative factors	475000	(Castro-Santos, et al., 2016)
Layout Design	5141382	(Myhr, et al., 2014)
Initial costs	Summation of the previous costs	-

Viewshed	3% of initial costs	(Chiang, et al., 2016)
Permits	2% of initial costs	(Bedard, et al., 2004)
GHG Investigations	0.5% of initial costs	(Chiang, et al., 2016)

Implementation Costs

The costs of implementation include the costs of transportation, designing of the wind turbine model, designing of the WEC model, construction of the wind turbines, construction of the WEC devices, mooring costs, inter-array cables, export cable to the hydrogen production platform or to the shore, installation of the wind turbines and the WEC device and the onshore substation. Summary of cost terms presented in Equation 5.4

$$C_{implementation} = C_{design} + C_{build} + C_{transportation} + C_{installation} + C_{cable} + C_{substation} \quad (5.4)$$

Designing, construction, and transportation costs are considered here to be separate for WECs and turbines, albeit there could be some components that share expenses (MacGillivray, et al., 2014). Therefore, the costs of the co-located systems are the summation of these expenses for WECs and turbines as shown in Equation 5.5 and Equation 5.6.

$$C_{build} = C_{buildturb} + C_{buildwec} \quad (5.5)$$

$$C_{design} = C_{designturb} + C_{designwec} \quad (5.6)$$

The costs of the cable connection is the sum between the inter-array cables and the export ones.

$$C_{cable} = C_{cableinter} + C_{cableexport} \quad (5.7)$$

Summary of the implementation costs are shown in Table 4.2.

Table 4.2 - Implementation phase costs

Description	Costs (euro)	Reference
Transportation	220000 per km	(Myhr, et al, 2014)
WEC design	245371	(Bosserelle, et al., 2015)

TWLT Foundation design	240000	(Myhr, et al, 2014)
WEC Construction	5500000 per device	(Bosserelle, et al., 2015)
Wind turbine Construction	1480000 per MW of electricity production	(Ørsted, 2018)
Mooring	560592 + (1096 per meter of water depth)	(Clark, et al., 2019)
Inter-array cables	307 per meter distance	(ofgem, 2020)
Export cables*	500000000 per each 50 kilometer	(Hans, 2019)

**The distance used in the calculations is the distance to the shore in case of the conventional wind turbine farm or to the hydrogen production platform used in the calculations in case of the hydrogen production cluster.*

Operation Costs

Operational costs are mainly the O&M costs during the lifetime of the project. Insurance and administration costs are also included in this phase as in Equation 5.8.

$$C_{operation} = C_{O\&M} + C_{insurance} + C_{adminstration} \tag{5.8}$$

Insurance and administration costs are calculated by multiplying the annual costs by the project's lifetime. O&M costs are also calculated by multiplying the annual maintenance activities costs for each system by the project's lifetime. Since the presence of the WECs will create a shadow effect that will increase the maintenance vessels' operational window, the O&M costs will be reduced as discussed in Chapter 4. This cost reduction is accounted for 18% of the total O&M costs (Astariz & Iglesias, 2015). Table 5 summarizes the operational costs.

Table 4.3 - Operational phase costs

Description	Costs (euros)	References
O&M for the turbines	13300 for each MW production per year	(van de Pieterman & Asgarpour, 2014)
O&M costs for the WECs	228564 for each MW production per year	(Bosserelle, et al., 2015)
WECs insurance	4020843 per year	(Castro-Santos, et al., 2016)
Wind turbines insurance	17500 for each MW production per year	(Astariz & Iglesias, 2015)
Administration	3000000 per year	(Castro-Santos, et al., 2016)

Decommissioning Costs

The decommissioning costs include the costs of the dismantling, transportation, and processing between the site's location and the nearest port. These costs can be calculated as a percentage of the total project's cost as shown in Equation 5.9 (Clark, et al., 2019).

$$C_{decommissioning} = 0.03C_t \qquad (5.9)$$

4.1.2 Hydrogen Production Costs

The objective of this cost assessment is to determine the price of the kilogram of hydrogen for the proposed system. Based on the collected data for all each as a function of the needed energy for operating, the total investment costs through the project's lifetime can be calculated. Table 4.4 sums the used prices in the analysis. The electrolyzers price is based on the best available technology price while the auxiliaries and the maintenance costs are collected based on a case study with similar features to the study's one.

Table 4.4 - Hydrogen production costs

Description	Costs (euros)	Reference
SOEC Electrolyzers	2810 per kW	(Schmidt, et al., 2017)

Compressors	950 per kW	(Konrad, 2014)
Desalination units	1450 per kW	(Konrad, 2014)
Boilers	1215 per kW	(Konrad, 2014)

The operation and maintenance costs for the systems is for these systems are 2% of the total project's CAPEX per year according to Konrad's study in 2014.

4.2 2030 COST REDUCTION

4.2.1 Wind Turbines

Based on IRENA predictions, the wind turbines radii will jump from 164 m in 2020 to 230 m by 2030 (IRENA, 2019a). The study assumed that the costs of the two models will be the same, and the only variable parameter is the influence of the inflation rate. This assumption is applied only to the CAPEX. For the operation and maintenance, as technological advancements are expected to reduce O&M costs. A study conducted by van de Pieterman and Asgarpour in 2014 is reviewed that predicted a cost reduction on the total operational phase of 10.58% by 2030.

4.2.2 Electrolyzers

Many experts believe that the SOEC electrolyzer will become a dominant technology by 2030 instead of the Alkaline electrolyzers (Bazzanella & Ausfelder, 2017). A study conducted by Schmidt et al. (2017) calculated the expected cost reductions in the upcoming years based on the experts' judgments and the anticipated R&D fundings in the SOEC electrolyzers development. The study matched the beforementioned predictions of the high-cost potential of the SOEC electrolyzer by 2020 and reasoned it due to the insufficient funding in developing the SOEC.

The study categorized the experts' estimates who were interviewed as a function of the R&D funding. The categorization comprised of three multiplier; 1x, 2x and 10x. Each multiplier represents the multiplication factor of the funding. Furthermore, for each multiplier, costs based on percentiles are calculated. 50^{th} percentiles are the data points while 10^{th} and 90^{th} percentiles represented the uncertainties. Based on the authors' arguments on the most reliable cost estimates, the 2x multiplier case with the 50^{th} percentile is selected to carry out the project's cost prediction. Therefore, the capital cost in the study after selected these two criteria is € 1450 per kW. The cost is based on the monetary value of the Euro in 2016, so the inflation rate is considered.

The expected technological advancements will not only affect the total investment costs, but also the electrolyzer power consumption efficiency. A study conducted by Peterson and Miller (2016) showed an improvement potential in the SOEC efficiency to reach around 77% by 2030.

4.3 RESULTS

4.3.1 Determining the Optimal Farm Size

Determining the most profitable wind turbines number on the farm is an iterative process. Therefore, an array of wind turbines number is assumed starting from 5 turbines up to 100. Afterward, a complete cost analysis is carried out to determine the number that produces the most hydrogen with the cheapest price of hydrogen. The analysis showed that the more wind turbines, the cheaper the final price of hydrogen. Accordingly, this thesis attempted to determine the number of turbines where the slope of the price decrease is steady enough so that no more significance on the final price but mainly adds to the total costs. The number of the attached WECs is a function of the number of wind turbines. The analysis is carried out on the 2020 hydrogen production scenario and the results of this simulation are assumed for the other scenarios. As shown below, Figure 4.1 presents the price of one kilogram of hydrogen in euros for each wind turbines number and Figure 4.2 shows the equivalent LCOE. The analysis of this simulation is attached in Appendix I.

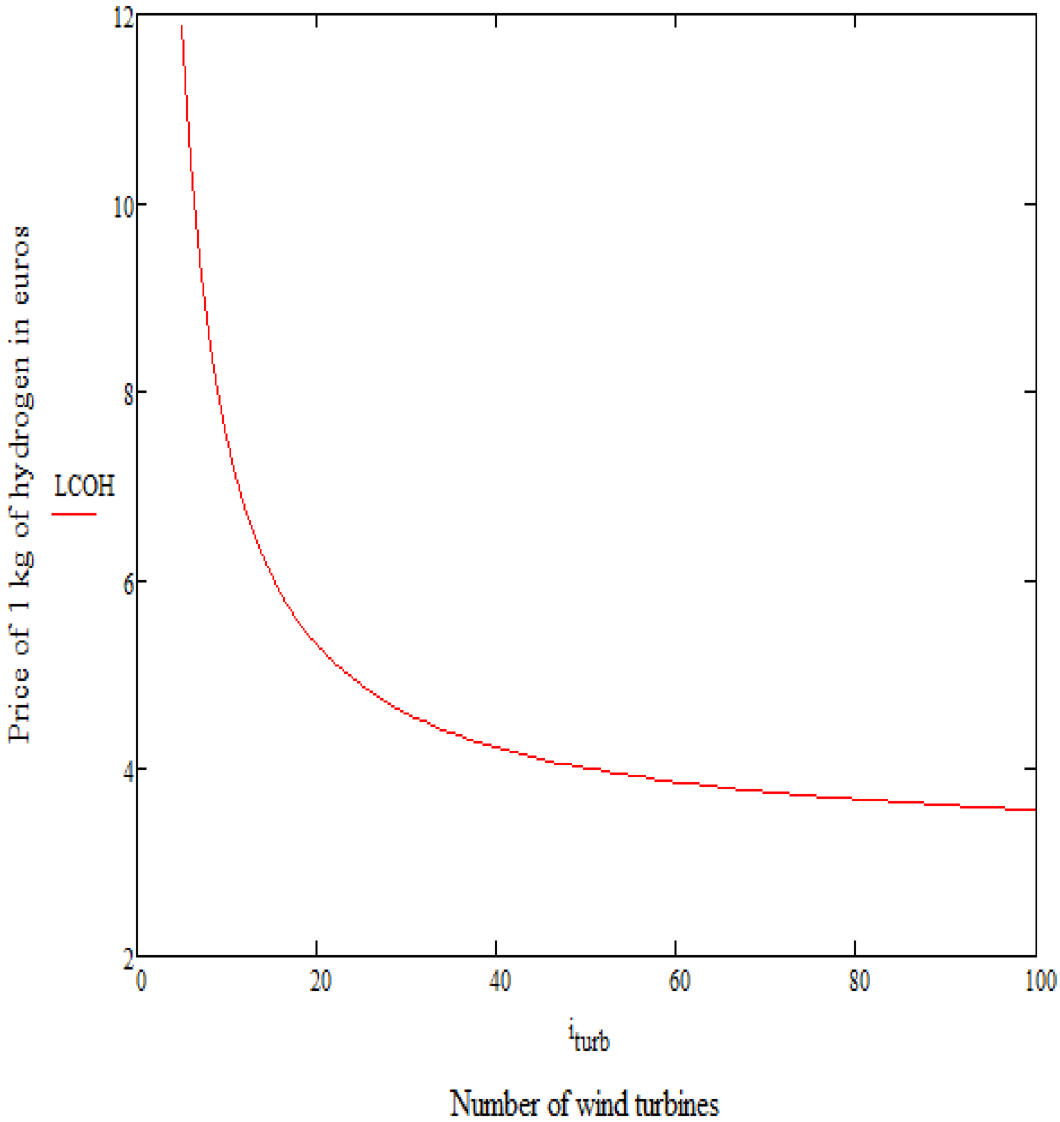

Figure 4.1 - LCOH against the number of wind turbines

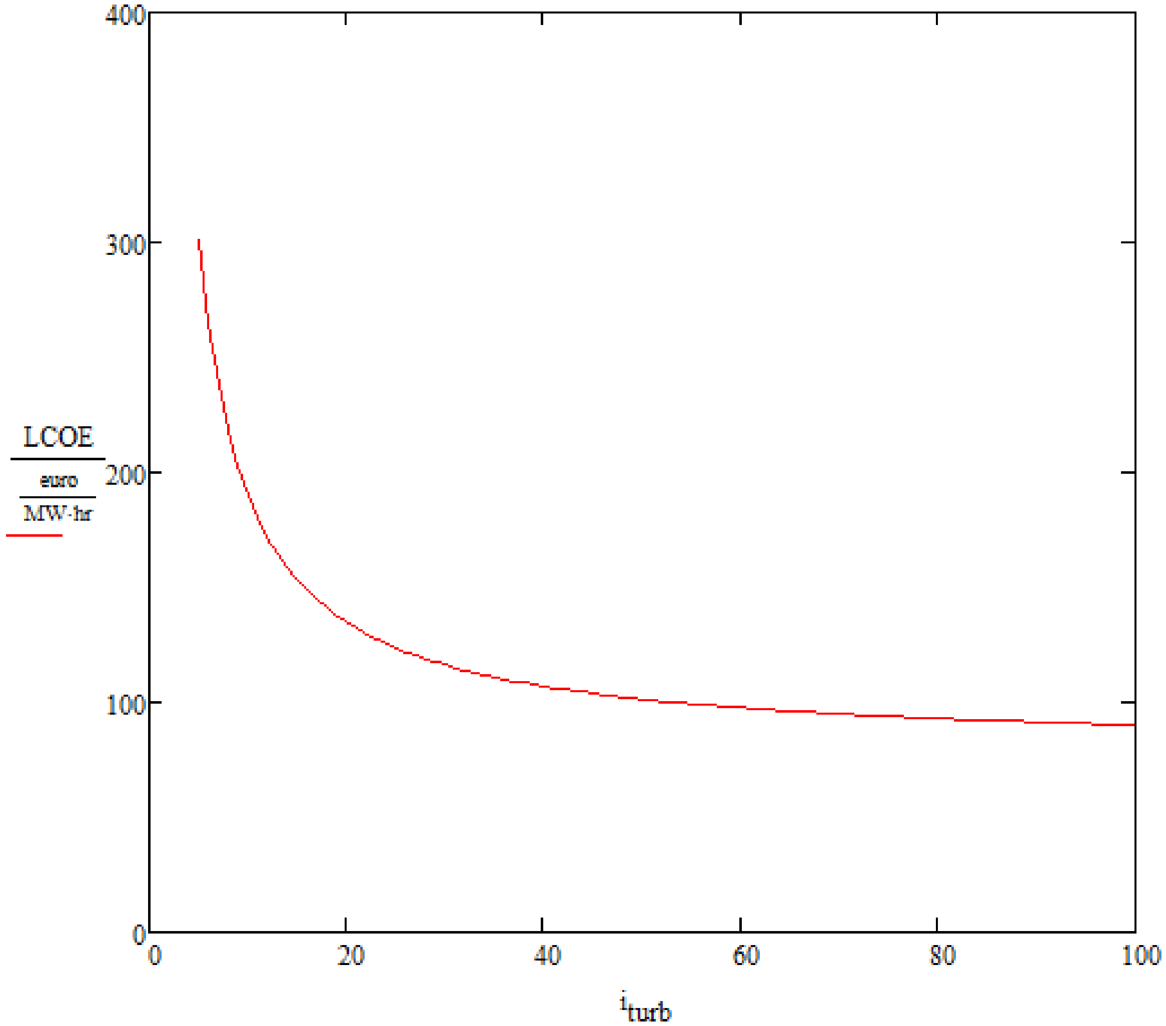

Figure 4.2 - LCOE against the number of wind turbines

To find the most optimal farm size, approximate equations were created to describe the trend of the LCOE and the LCOH against the number of the wind turbines. Then the first derivate was taken for these equations with respect to the number of wind turbines variable to determine the slope of each point followed by comparing each point's slope to its previous and next one to locate the point with the least relative drop rate compared to the previous point. It is found that the optimal farm size is 38 turbines. Increasing the turbines number after this point will not affect the LCOH or the equivalent LCOE significantly but will increase the project's hydrogen production capacity.

4.3.2 2020 Cost Analysis

The suggested cluster for hydrogen production total costs with its present value is € 2.755 Billion. The costs for the electricity generation from the wind and wave collocated farm are €

1.564 Billion while € 1.191 Billion are for the hydrogen production investment. A summary of all the cost components is presented in Figure 4.3.

This project will be able to produce 279 MW from the wind turbines and 12 MW from the WECs. The produced electricity will be able to produce 825000 tonnes of hydrogen through the project's lifetime with an LCOH of € 4.814 per kg. The equivalent LCOE is € 122.13 per MWh. The system's main energy flow components are shown in Figure 4.4. The analysis of this scenario is described in Appendix II.

On the other hand, the conventional wind turbines farm total costs are 2.472 Billion. This farm will be able to produce 293 MW of electricity. Two Extra turbines were added on the wind farm on the hydrogen production scenario to approximately equalize the electricity production from both scenarios. Taking into account the electrical losses in the transmission cables, only 275 MW of electricity will be delivered. The LCOE of the conventional approach is € 4.463 per MWh. Figure 4.5 shows a summary of the total investment costs needed for the project and the energy flow is described in Figure 4.6. The analysis of this scenario is explained in Appendix III.

4.3.3 2030 Cost Analysis

The hydrogen production platform investment costs are € 0.89 Billion while the wind and wave collocated farm investment costs are € 2.06 Billion. These two cost components adding up a total investment of € 2.87 Billion. The cluster will be able to produce 1679502 tonnes of hydrogen from a total electric energy input of 560 MW from the farm. The LCOH is 2.52 per each kg. The equivalent LCOE is 64 per MWh. Summaries of the main cost components and the energy components are shown in Figure 4.7 and Figure 4.8 respectively. The analysis of this scenario is described in Appendix IV.

The conventional wind approach costs € 3.06 Billion with a final energy delivery of 528 MW. The LCOE of the system is 40 per MWh. The main cost components are summarized in Figure 4.9 and the energy flow is illustrated in Figure 4.10. The analysis of this scenario is explained in Appendix V.

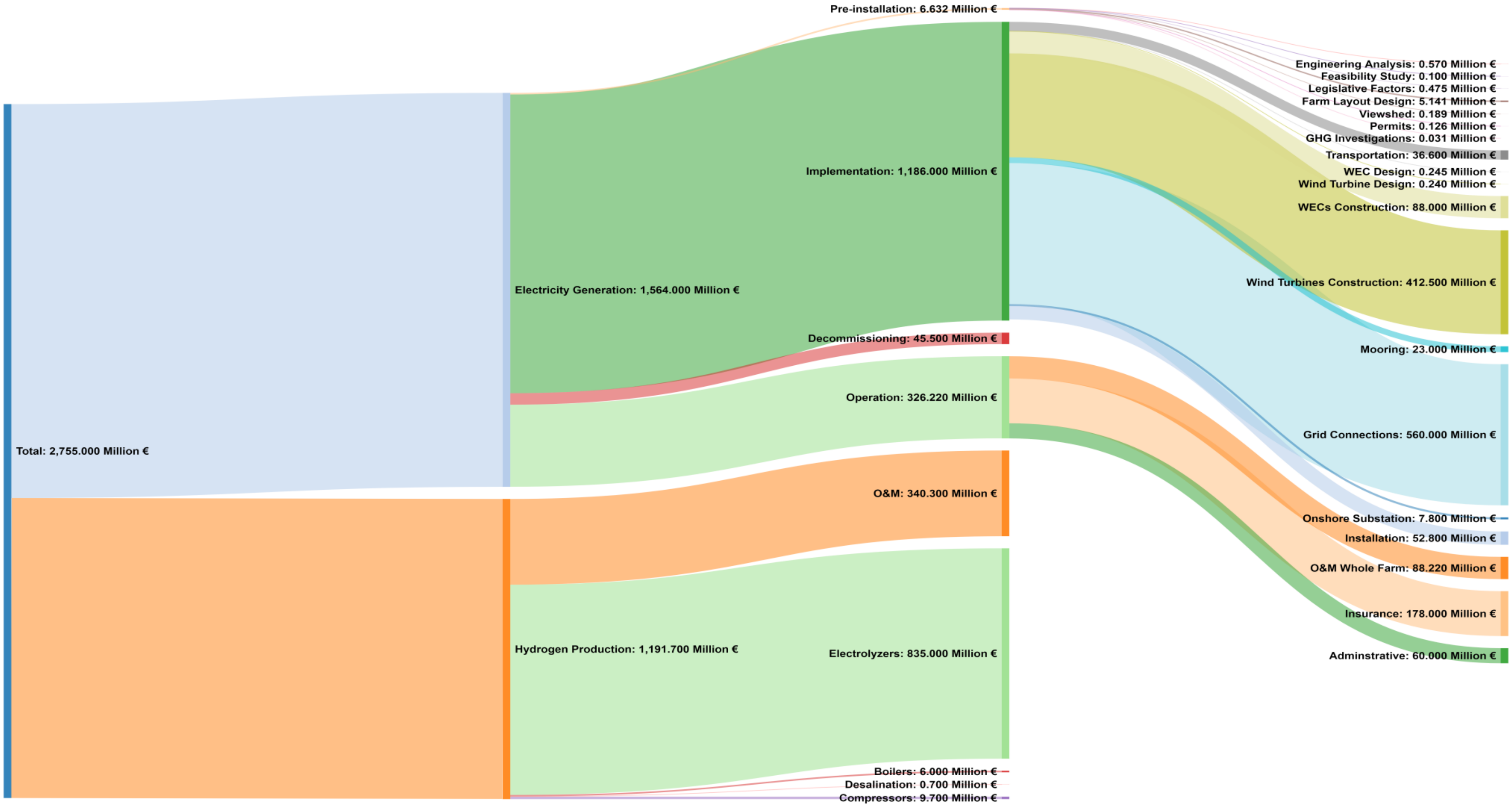

Figure 4.3 - Cost flow of the 2020 hydrogen production scenario

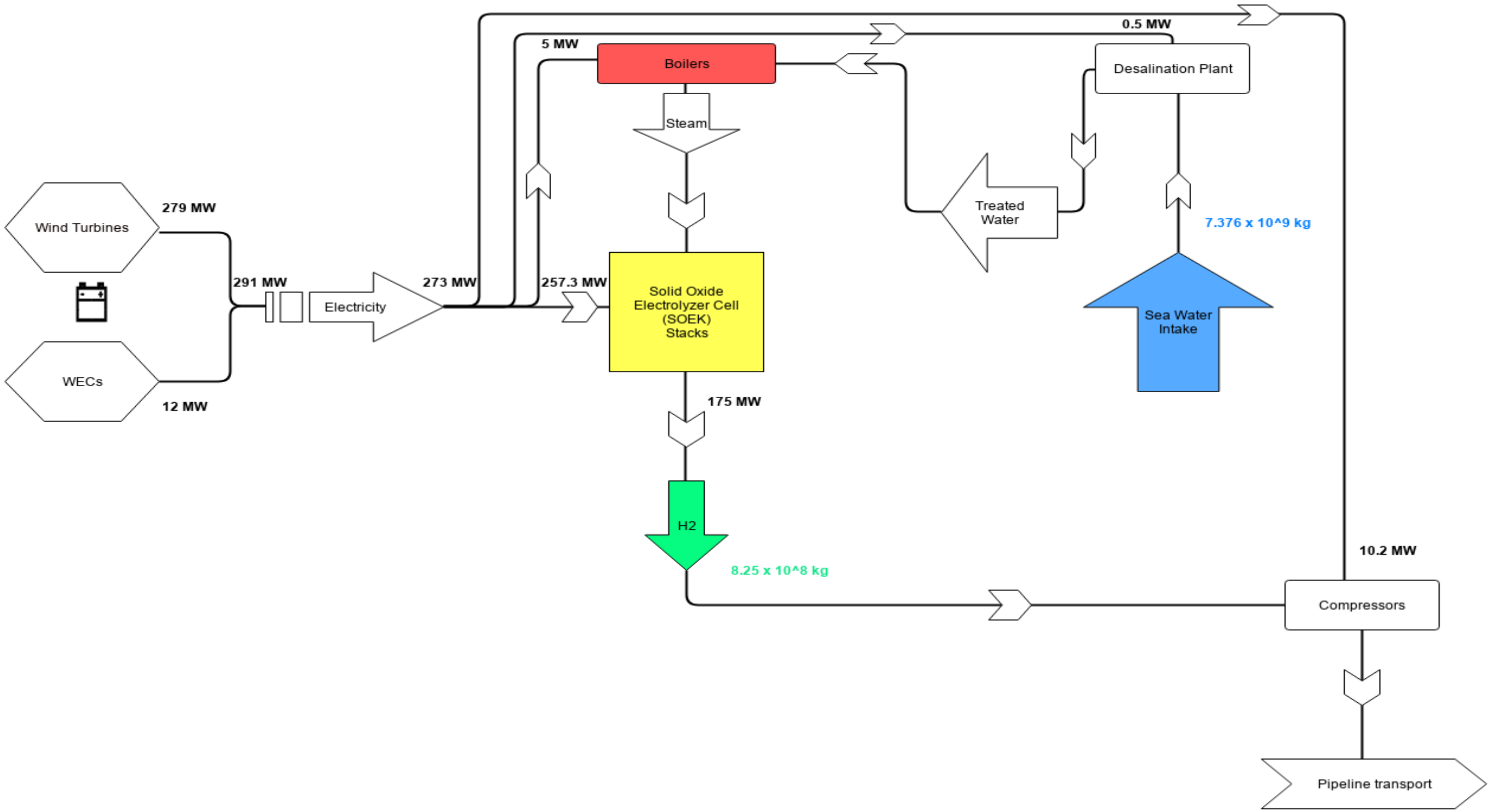

Figure 4.4 - Energy flow of the hydrogen production process in the 2020 scenario

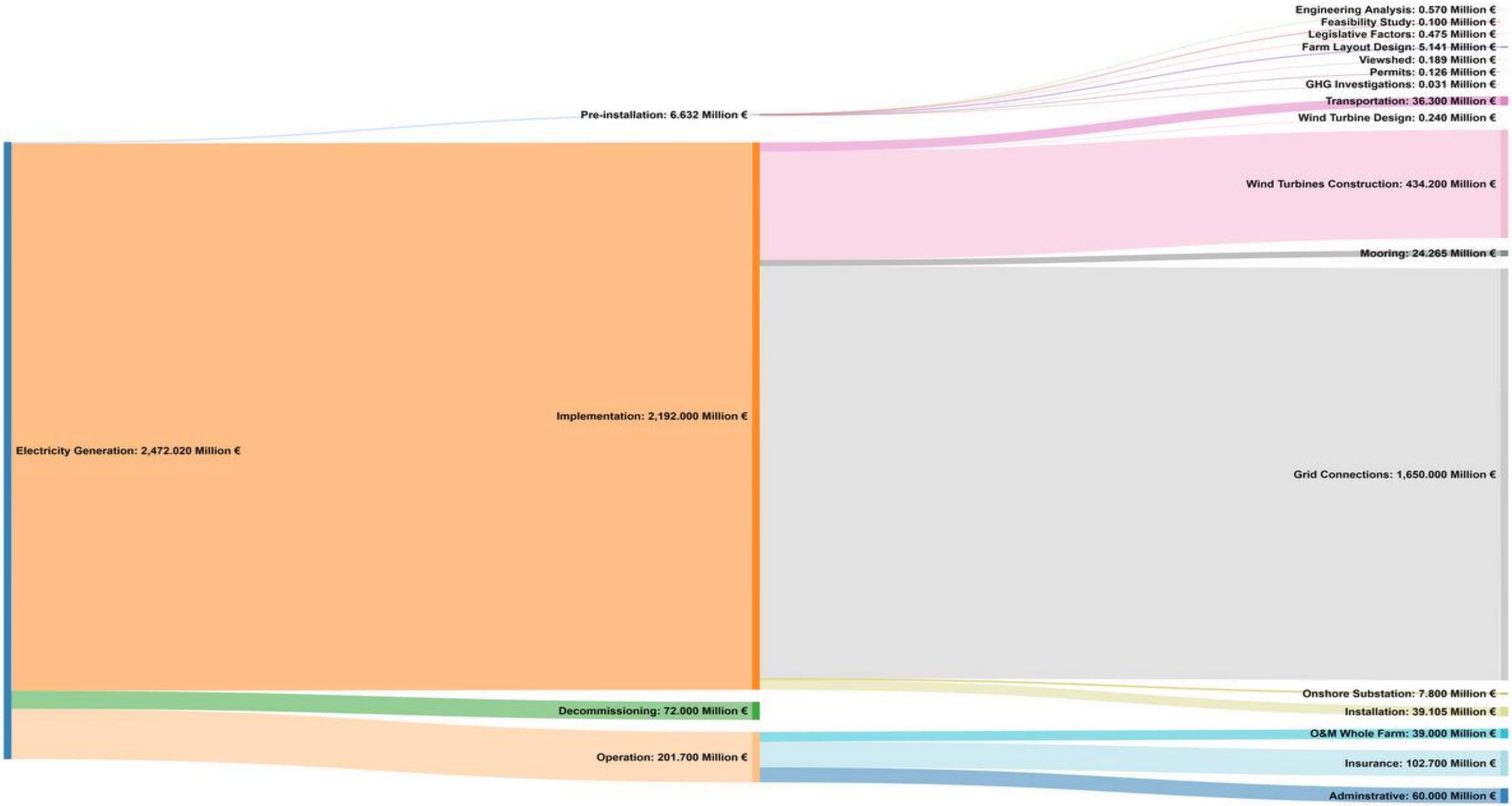

Figure 4.5 - Cost flow of the 2020 conventional approach scenario

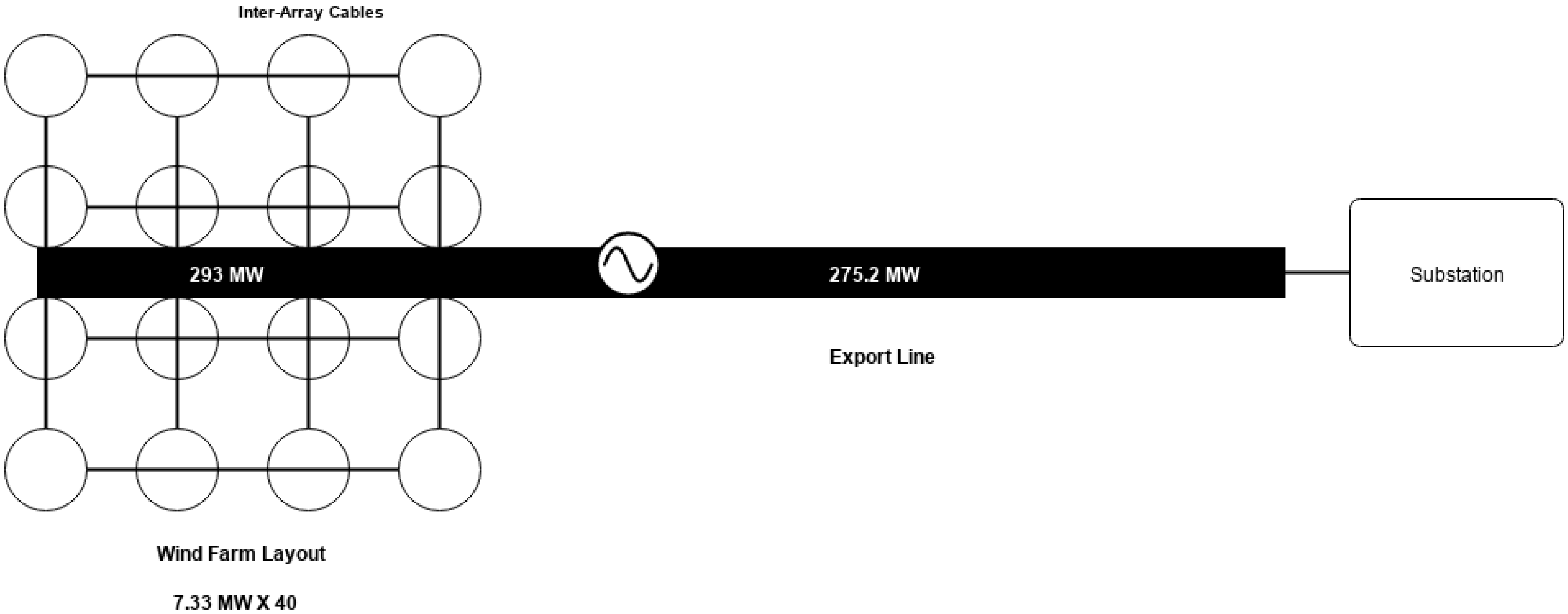

Figure 4.6 - Energy flow of the conventional approach in the 2020 scenario

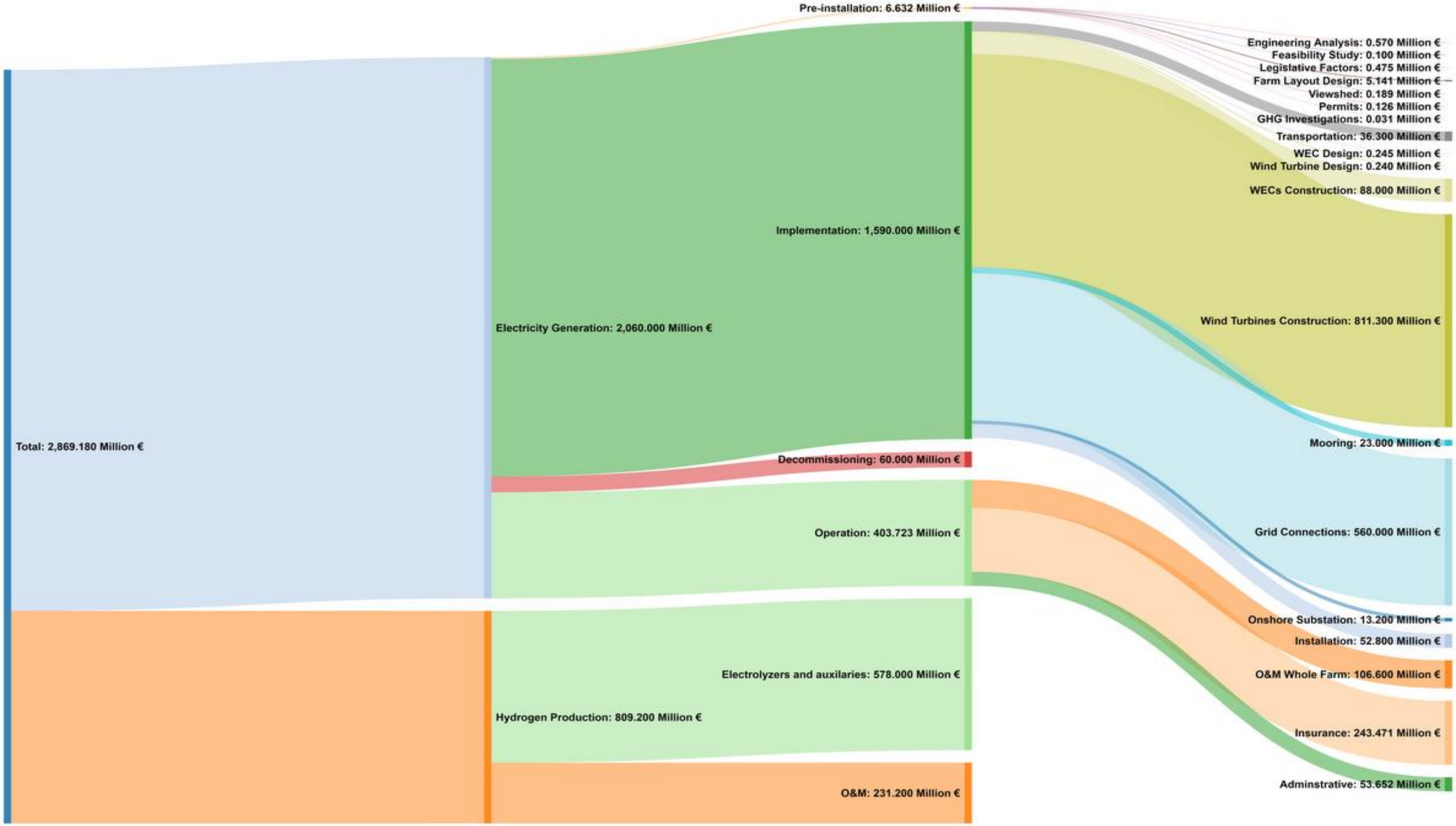

Figure 4.7 - Cost flow of the 2030 hydrogen production scenario

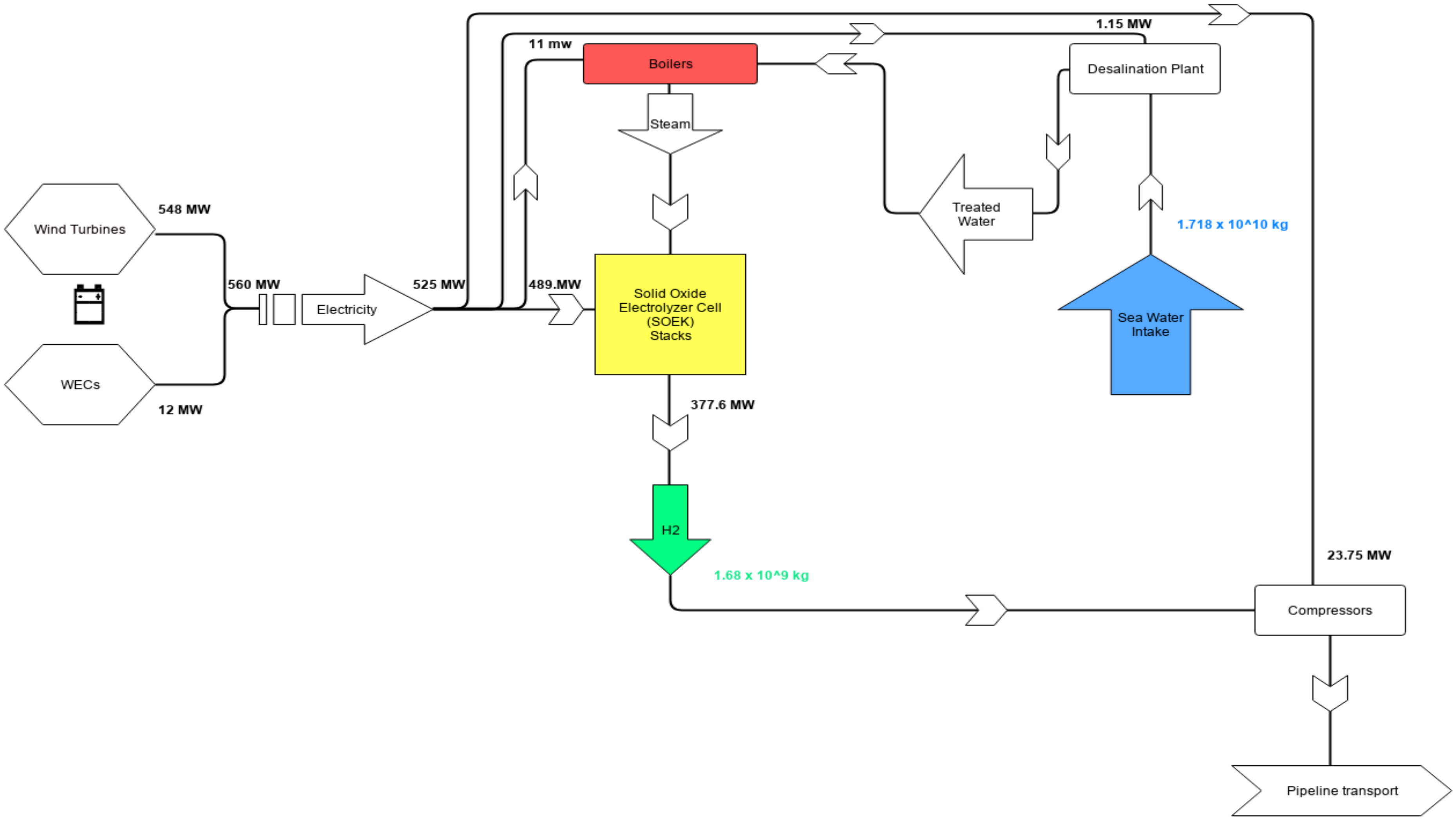

Figure 4.8 - Energy flow of the hydrogen production process in the 2030 scenario

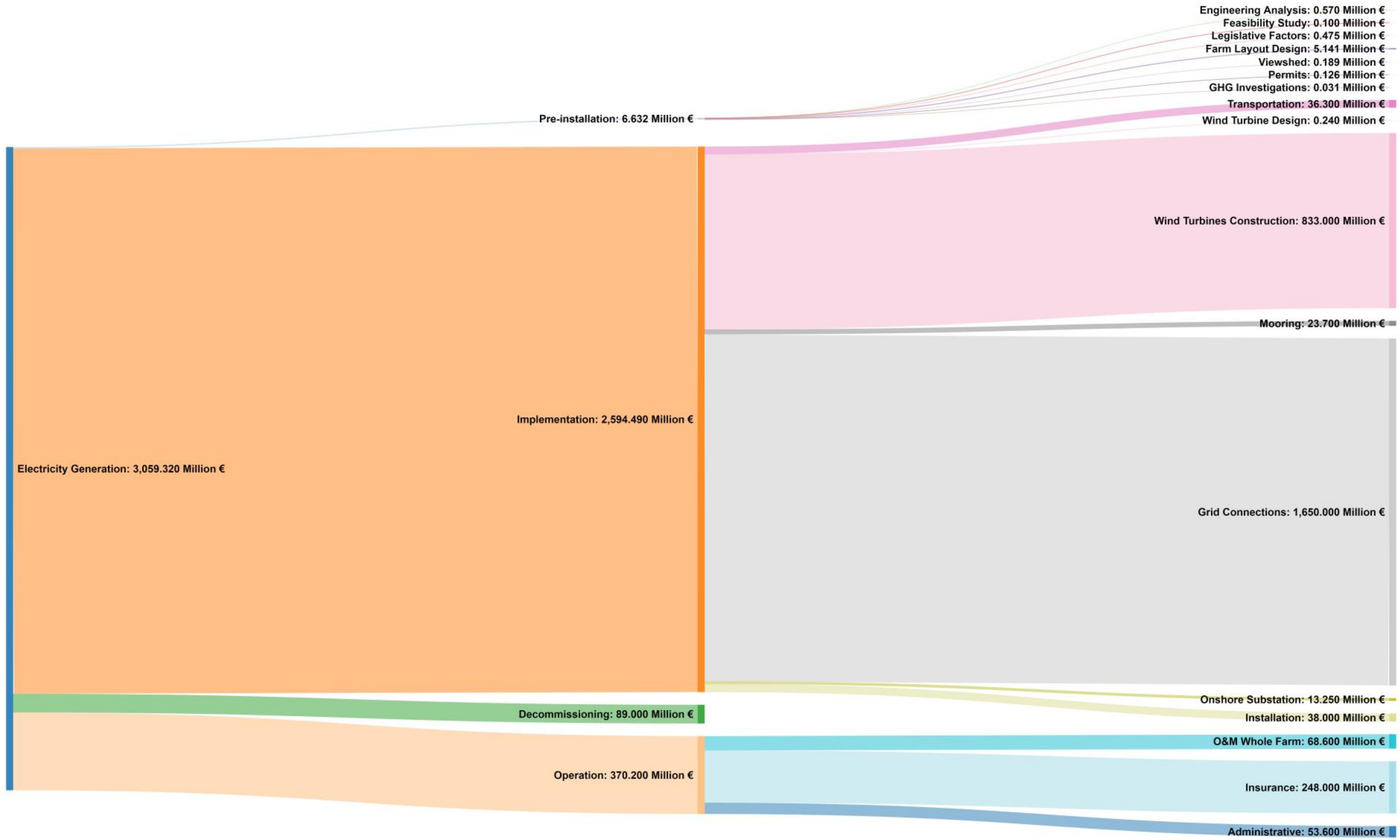

Figure 4.9 - Cost flow of the 2030 conventional approach scenario

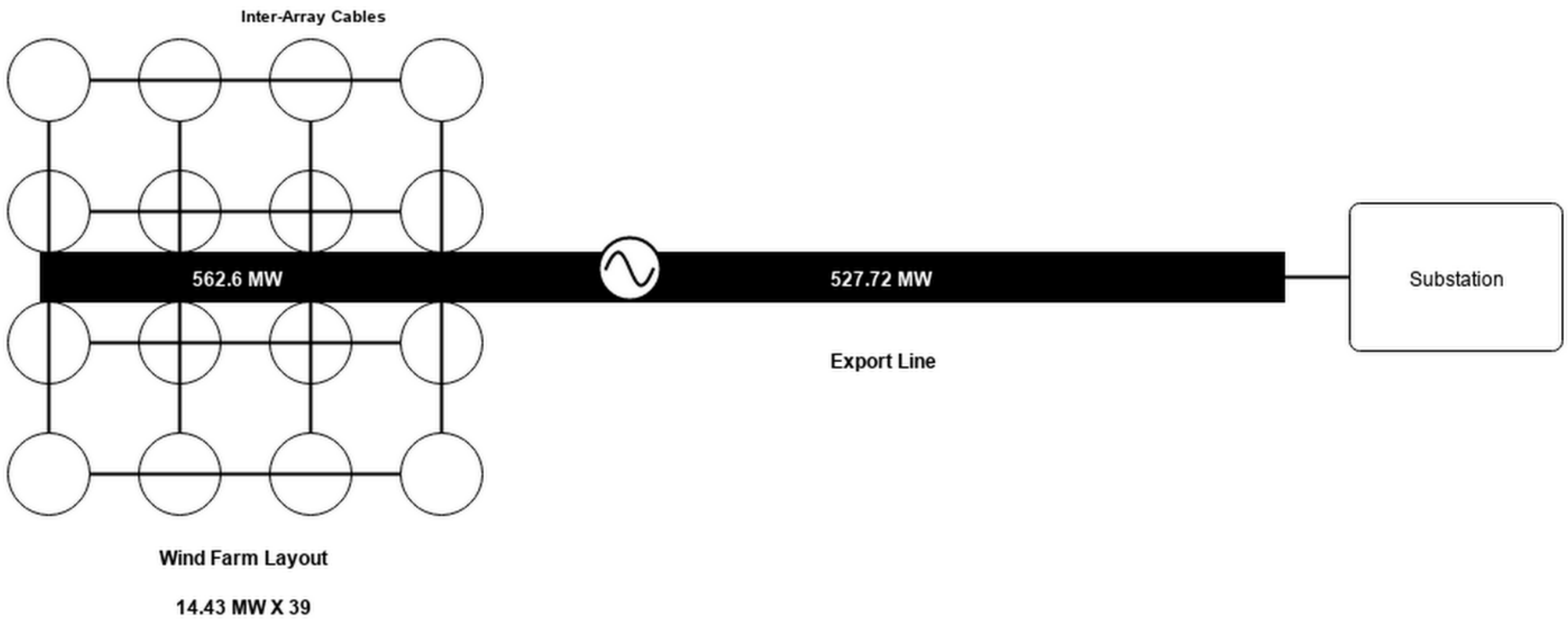

Figure 4.10 - Energy flow of the conventional approach in the 2030 scenario

4.4 DISCUSSION

The results of the cost analysis in 2020 shows a noticeable difference between the LCOE values of the hydrogen production and the conventional wind farm approaches. Despite the fact that the offshore platform and the pipeline costs were eliminated in an attempt to make the LCOE value of the hydrogen approach competitive, and with including all the best available technology efficiencies, its value did not even come close to be competitive with the wind farm approach. However, the LCOE and the LCOH values of the hydrogen production approach could be considered relatively cheaper with respect to the values reviewed in the literature from studies based on previous years' prices.

By taking a closer look at the grid connection costs at the conventional approach and total hydrogen production investment, it is found that the grid connection investments are more expensive than the total hydrogen production. This comparison for the first while can give the impression that the hydrogen production solution is more feasible than installing grid connections to transport the energy back to the shore. In fact, this comparison does not take the energy losses in the hydrogen production process into account. The energy losses from the transporting the energy in electrical form is about 6.2% of the total energy while in the hydrogen production reaches up to 39.8%.

Considering an increase in the SOEC electrolyzer efficiency and the expected significant capital cost reduction by 2030, the LCOE value of the hydrogen production approach got much closer to the LCOE value of the conventional wind farm approach than in the 2020 scenario. Nevertheless, the conventional approach is still cheaper in terms of LCOE than the hydrogen production one.

Interestingly, the LCOE value reduction percentage of the hydrogen production approach from 2020 to 2030 is 47.6% while the cost reduction in the conventional one is 38%. Moreover, the total hydrogen production investment costs are less than the grid connection costs in the conventional approach by 51% while in the 2020 prices by only 28%. Thought the energy efficiency differences are still a significant factor, the reduction in transportation costs using hydrogen production instead of grid connections could be an important factor in selecting this approach. The energy efficiencies included in this study are limited to the upstream scope. The utilization of the delivered energy in further processes in not analyzed. For a thorough feasibility evaluation, the form of the delivered energy should be considered.

The WECs are added to the hydrogen production system to compensate for the discontinuous energy supply problem from the wind turbines. Adding WECs to the system increases significantly the total costs with a slight contribution to the energy output. From a mere monetary perspective, the presence of the WECs is not profitable. However, the study did not technically investigate the impacts of the discontinuity problem on the hydrogen production process and hence on the total investments.

5 CONCLUSION

5.1 CONCLUSION

The study demonstrated that green hydrogen production could be feasible against its counterpart approach of exporting the energy through the grid connections by 2030 but too far from that with the current prices. Nevertheless, the 2020 cost model for green hydrogen production is already cost-competitive compared to the current offshore wind parks in the Netherlands which were installed to accelerate the energy transition. For instance, the LCOE range between € 170 per MWh for Hollandse Kust (Zuid) sites III and IV, and € 280 per MWh for IJmuiden Ver (PBL Netherlands Environmental Assessment Agency, 2019), while the LCOE for the green hydrogen approach in the 2020 model is € 122.13 per MWh. The reason behind this competitiveness is the Walney Extension project prices. This project has been proven to be successfully decreasing the LCOE of the offshore farms projects. As shown in the study's analysis, the 2020 conventional approach LCOE using 38 turbines is considered as very competitive with respect to the current electricity prices; however, the total investments could be considered relatively high.

The study proved that producing green hydrogen from deep waters in the Dutch EEZ is technically feasible with the current level of technology maturity. The Dutch government acknowledged that already as it is trying to measure the potential of this technology but in shallower waters as the Dutch continental shelf is the first place on the planet where a pilot-level project to construct an offshore hydrogen plant is arranged. Around ten kilometers off the shoreline of The Hague, an oil and gas platform will house a plant that will deliver green hydrogen from the energy that is produced by wind and sun (TNO, 2020b). This project can help the Netherlands significantly in its energy transition goals. However, the only limitation addressed by the government of the Netherlands and discussed in chapter four is the cost limitation.

In conclusion, regarding the hydrogen production approach in 2030, even if lower electricity prices are available, the main challenge is to increase the efficiency of the electrolyzer with high load factors (Roussanaly, et al., 2019). Technical considerations were not a limitation in designing the process, but the associated costs impose challenges for investors. Nevertheless, with the expected abatement of both electrolyzer costs and sustainable power costs in the long-term, the electrolyzer load factor will be less significant, and hydrogen from renewables will be or less expensive than all types of hydrogen production from petroleum products. Additionally, higher capacity factors at wind parks that could result from innovation upgrades are a significant factor in diminishing total expenses. Accordingly, the question here is how early competitiveness is to be accomplished given the anticipated improvements in the various parameters, and to what degree corresponding innovations can or will support this development.

5.2 RECOMMENDATIONS AND STUDY LIMITATIONS

To bridge the gap between the 2030 targets and the current situation, the Dutch government can build on the success of the Walney Extension project. However, the study did not develop a complete capital costs analysis for the selected technologies, as the study's primary goal was not analyzing the financial engineering benefits but to compare the current state of various offshore energy technologies. This returns to the fact that the financial engineering models will require complete technical engineering models, while the study aims to provide estimated costs for the already-designed systems. In other words, this study is providing an overview of the potential of investing in the green hydrogen production technology but without specific technical analysis for these systems in the Dutch deep waters.

The environmental data, the yield and wake effects, and cost functions are either neglected or collected based on simplified approaches. In reality, these data should be further explored, and detailed site investigations should be performed. Moreover, given the uncertainties instigated by the study's simplifications, the researcher considers small differences to be insignificant; however, the subtle differences between the current LCOEs and the calculated ones in the study approve the overall ‘gut-feeling’ about the effects of the limitations and the assumptions and therefore contribute to the overall reliability of the taken approach.

The study is created on comparing the LCOE for the given alternatives. The main reason why the study selected this parameter is that it allows for a reasonable comparison between the different alternatives. It includes the NPV of all costs that an investor could consider to construct and operate a wind park divided by the predicted yield. The assumption is that each MWh produced has a comparable value. This is a reliable assumption if a subsidy policy is applied to ensure a minimum price for the energy or electricity. Practically, the business feasibility studies of an offshore wind farm is mainly determined by the internal rate of return (IRR), which decides the feasibility of an investment. The IRR depends on the expected income from the energy sales and subsidy if available subtracted from all costs to construct and operate the park but this price varies with time contingent upon the market’s demand and supply. In the study, the income aspect in the energy sales is neglected. Possible fluctuations in the market value of a unit of energy yield are not taken into account.

Additionally, the results contained in this study can be changed by different assumptions regarding capital costs, like the willingness of the Dutch government to accept lower returns in order to increase its green hydrogen share rather than producing electricity. In this case, the total investment costs will not be the only variable to be evaluated. Some key factors are examined like the inflation rate while other factors will not be explored which could also have a significant effect on the results but have not been examined in the scope of this current analysis. These factors are including import tariffs, generation distribution related to stranded costs, future network upgrades, or other development costs; and complying costs with the Dutch environmental regulations. Moreover, this research did not address the associated ecological and social boundaries.

Therefore, the study recommends to research further on the influence of a variable energy price on the income differences between variants for an unsubsidized wind park and also the effect of different environmental conditions on the energy production. For instance, a lower energy yield under high wind speeds conditions could intensify the differences in total costs between the different alternatives and hence, affect the decision-making process. Furthermore, location-specific technical analysis on the selected energy components is highly recommended to highlight the technical barriers concerning the Dutch capabilities as most of the reviewed studies were not conducted for the Netherlands but with very similar characteristics to the chosen location.

6 REFERENCES

Aakko-Saksa, P., Cook, C., Kiviaho, J., & Repo, T. (2018). Liquid organic hydrogen carriers for transportation and storing of renewable energy – Review and discussion. *J. Power Sources*, 803–823.

Acheson, J. M., & Acheson, A. W. (2016). Offshore wind power development in Maine: A rational choice perspective. *Economic Anthropology*, 161–173.

Ågotnes, B. C. (2013). Levelised cost of energy for offshore floating wind turbine concepts. *Department of Mathematical Sciences and Technology, University of Life Sciences*, 206.

Astariz, S., & Iglesias, G. (2015). Co-located wave-wind farms: Economic assessment as a function of layout. *Renew. Energy*, 83, 837–849.

Astariz, S., & Iglesias, G. (2015). Enhancing Wave Energy Competitiveness through Co-Located Wind and Wave Energy Farms. A Review on the Shadow Effect. *Energies*, 7344-7366.

Bartels, J. R., Pate, M. B., & Olson, N. K. (2010). An economic survey of hydrogen production from conventional and alternative energy sources. *International Journal of Hydrogen Energy*, 8371-8384.

Bazzanella, A., & Ausfelder, F. (2017). *Low carbon energy and feedstock for the European chemical industry.* Frankfurt: DECHEMA.

Bedard, R., Hagerman, G., & Siddiqui, O. (2004). System Level Design , Performance and Costs Oregon State Offshore Wave Power Plant. 1-63.

Beels, C., Henriques, J., De Rouck, J., Pontes, M., De Backer, G., & Verhaeghe, H. (2007). Wave energy resource in the North Sea.

Bierbooms, W., & Bussel, G. (2002). *The Impact of Different Means of Transport on the Operation and Maintenance Strategy for Offshore Wind Farms.* Delft, The Netherlands: Delft University of Technology.

Bosserelle, C., Reddy, S., & Krüger, J. (2015). *Cost analysis of wave energy in the Pacific.* Fiji Islands: Pacific Community.

Buchner, B., & Hoefakker, K. (2010). SIMULATIONS AND MODEL TESTS ON A WAVE ENERGY CONVERTER BASED ON INVERSE OFFSHORE ENGINEERING. *The 16th Offshore Symposium.* Texas: The Society of Naval Architects and Marine Engineers.

Buck, C. (2012, April 13). Retrieved from Siemens: http://www.siemens.com/innovation/apps/pof_microsite/_pof-spring-2012/_html_en/electrolysis.html

Castro-Santos, L., Martins, E., & Guedes Soares, C. (2016). Cost assessment methodology for combined wind and wave floating offshore renewable energy systems. *Renewable Energy 97*, 866-880.

CBS. (2020, March 17). *Electricity production at record high*. Retrieved from CBS: https://www.cbs.nl/en-gb/news/2020/12/electricity-production-at-record-high

CCC. (2018). *Hydrogen in a low-carbon economy.* London: Committee on Climate Change.

Chiang, A., Keoleian, G., Moore, M., & Kelly, J. (2016). Investment cost and view damage cost of siting an offshore wind farm: a spatial analysis of Lake Michigan. *Renewable Energy 96* , 966-976.

Chozas, J., Jensen, N., & Sørensen, H. (2012). Economic Benefit of Combining Wave and Wind Power Productions in Day-Ahead Electricity Markets. *the 4th International Conference on Ocean Energy (ICOE)* . Dublin, Ireland.

Chozas, J., Kofoed, J., & Sørensen, H. (2013). *Predictability and Variability of Wave and Wind and Wind Forecasting and Diversified Energy Systems in the Danish North Sea.* Aalborg: Department of Civil Engineering, Aalborg University.

Clark, C. E., Miller, A., & DuPont, B. (2019). An analytical cost model for co-located floating wind-wave energy arrays. *Renewable Energy 132* , 885-897.
Dalton, G., Alcorn, R., & Lewis, T. (2010). Case study feasibility analysis of the Pelamis wave energy convertor in Ireland, Portugal and North America. *Renewable Energy*, 443–455.
Digital Journal. (2018, September 6). *World's largest offshore wind farm opens off northwest England*. Retrieved from Digital Journal: http://www.digitaljournal.com/tech-and-science/technology/world-s-largest-offshore-wind-farm-opens-off-northwest-england/article/531308
DNV GL. (2018). *Energy transition outlook 2018: A global and regional forecast of the energy transition to 2050.* Oslo: DNV GL.
El-Bassuoni, A., Sheffield, S., & Veziroglu, T. (1982). Hydrogen and fresh water production from sea water. *Int. J. Hydrogen Energy 7*, 919–923.
Energieakkord. (2020). *Het energieakkoord*. Retrieved from energieopwek: https://energieopwek.nl/
Equinor. (2017). *World's first floating wind farm has started production*. Retrieved 3 5, 2020, from Equinor: https://www.equinor.com/en/news/worlds-first-floating-wind-farm-started-production.html
European Comission. (2019). *The European Green Deal: COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS.* Brussels.
European MSP Platform. (2015). *Integrated Management Plan for the North Sea 2015 (NL).* Rijswijk: Rijkswaterstaat Noordzee.
F.O.Falcão, A., & C.C.Henriques, J. (2016). Oscillating-water-column wave energy converters and air turbines: A review. *Renwable Energy*, 1391-1424.
Fazeres-Ferradosa, T., Rosa-Santos, P., Taveira-Pinto, F., Vanem, E., Carvalho, H., & Correia, J. (2019). Editorial: Advanced research on offshore structures and foundation design: part 1. *Institution of Civil Engineers - Maritime Engineering* (pp. 118–123). ICE publishing.
Ferrero, D., Lanzini, A., Santarelli, M., & Leone, P. (2013). A comparative assessment on hydrogen production from low- and high-temperature electrolysis. *Int. J. Hydrogen Energy 38*, 3523–3536.
Fragoso Rodrigues, S. (2016). *A Multi-Objective Optimization Framework for the Design of Offshore Wind Farms.* Retrieved from https://doi.org/10.4233/uuid:0dafc70a-594d-4882-8785-a7a3e1c58ba8
GE Renewable Energy. (2018). *Haliade-X Offshore Wind Turbine Platform*. Retrieved 3 2020, 10, from GE: www.ge.com/renewableenergy/
George, L., & Henk, P. (2019). North Sea Wave Database (NSWD) and the Need for Reliable Resource Data: A 38 Year Database for Metocean and Wave Energy Assessments. *Atmoshpere*.
Ghaffour, N., Missimer, T., & Amy, G. (2012). Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability. *Desalination 309*, 197-207.
Gielen, D. (2012). *Renewable energy technologies: cost analysis series - wind power.* IRENA.
GlobalData. (2019). *Floating foundations: The future of deeper offshore wind.* Retrieved from GlobalData: https://store.globaldata.com/report/gdae02208ei--floating-foundations-the-future-of-deeper-offshore-wind/
Gnana, K. (2015). Lazard's Levelized Cost of Energy Analysis ("LCOE") ver 8. *10.13140/RG.2.1.4823.6969.* .
Goswami, A., Sadhu, P., Goswami, U., & Sadhu, P. K. (2019). Floating solar power plant for sustainable development: A techno-economic analysis. *Sustainable Energy*.
Hans, C. (2019, June 27). *Cost of offshore transmission.* Retrieved from Tennet: https://www.tennet.eu/fileadmin/user_upload/Company/News/Dutch/2019/20190624_DNV_GL_Comparison_Offshore_Transmission_update_French_projects.pdf
Hydrogen Council. (2020). *Path to hydrogen competitiveness: A cost perspective.* Hydrogen Council.
I.Marvik, J., V.Øyslebø, E., & Korpås, M. (2013). Electrification of offshore petroleum installations with offshore wind integration. *Renewable Energy*, 558-564.

IEA. (2019). *The Future of Hydrogen* . Paris: International Energy Agency.
Institute for Sustainable Process Technology. (2019, March 19). *KICK-OFF FOR DESIGNING A GIGAWATT ELECTROLYSIS PLANT*. Retrieved from Institute for Sustainable Process Technology: https://ispt.eu/news/kick-off-for-designing-a-gigawatt-electrolysis-plant/
IPCC. (2018). *Global warming of 1.5 °C: An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways.* Geneva: Intergovernmental Panel on Climate Change.
IRENA . (2019a). *Future of Wind: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation paper).* Abu Dhabi.: International Renewable Energy Agency.
IRENA. (2014). *Wave Energy: Technology Brief.* Abu Dhabi.
IRENA. (2018a). *Offshore innovation widens renewable energy options: Opportunities, challenges and the vital role of international co-operation to spur the global energy transformation (Brief to G7 policy makers).* Abu Dhabi: International Renewable Energy Agency.
IRENA. (2018b). *Hydrogen from renewable power: Technology outlook for the energy transition.* Abu Dhabi: IRENA.
IRENA. (2019b). *Renewable power generation costs in 2018.* Abu Dhabi: International Renewable Energy Agency.
IRENA. (2019c). *Hydrogen: A renewable energy perspective, International Renewable Energy Agency.* Abu Dhabi: IRENA.
IRENA. (2019d). *Renewable Energy Statistics 2019.* Abu Dhabi: IRENA.
IRENA, IEA and REN21. (2018). *Renewable energy policies in a time of transition.* Abu Dhabi.: International Renewable Energy Agency, International Energy Agency and Renewable Energy Policy Network for the 21st Century.
Jensen, N. (1983). A Note on Wind Generator Interaction. Roskilde, Denmark: Riso National Laboratory.
Kawulich, B. (2015). Qualitative Data Analysis Techniques. Carrollton: State University of West Georgia.
Kemp, R. (2010). The Dutch energy transition approach. *International Economics and Economic Policy*, 291–316.
Kempener, R., & Neumann, F. (2014). *Wave energy technology brief.* IRENA.
Konrad, M. (2014). Hydrogen production with sea water electrolysis using Norwegian offshore wind energy potentials. *International Journal of Energy and Environmental Engineering*.
MacGillivray, A., Jeffrey, H., Winskel, M., & Bryden, I. (2014). Innovation and cost reduction or marine renewable energy: a learning investment sensitivity analysis . *Technol. Forecast. Soc. Change 87*, 108-124.
Marthur, J., Agarwal, N., Swaroop, R., & Shah, N. (2008). Economics of producing hydrogen as transportation fuel using offshore wind energy systems. *Energy Policy 36*, 1212-1222.
Meier, K. (2014). Hydrogen production with sea water electrolysis using Norwegian offshore wind energy potentials: Techno-economic assessment for an offshore-based hydrogen production approach with state-of-the-art technology. *International Journal of Energy and Environmental Engineering*.
Ministry of Economic Affairs and Climate Policy. (2018, October 16). *Energy transition in the Netherlands – phasing out of gas.* Retrieved from European Commission: https://ec.europa.eu/energy/sites/ener/files/documents/01.b.02_mf31_presentation_nl-fuel_switch-vanthof.pdf
Ministry of Infrastructure and the Environment. (2011). *Summary National Policy Strategy for Infrastructure and Spatial Planning.* The Hague: Ministry of Infrastructure and the Environment.
Myhr, A., Bjerkseter, C., Ågotnes, A., & Nygaard, T. A. (2014). Levelised cost of energy for offshore floating wind turbines in a life cycle perspective. *Renewable Energy*, 714-728.
Nambiar, A. J., Collin, A. J., Karatzounis, S., Rea, J., Whitby, B., Jeffrey, H., & E., K. A. (2016). Optimising power transmission options for marine energy converter farms. *International Journal of Marine Energy*, 127–139.
Nextstep. (2018). *Re-use & decommissioning report.*

Nouryon. (2019, May 27). *Nouryon and Gasunie study scale-up of green hydrogen project to meet aviation fuels demand*. Retrieved from Nouryon: https://www.nouryon.com/news-and-events/news-overview/2019/nouryon-and-gasunie-study-scale-up-of-green-hydrogen-project-to-meet-aviation-fuels-demand/

Oceans of Energy. (2020a, Februaru). *Offshore floating solar farm installed and operational at the Dutch North Sea*. Retrieved from Oceans of Energy: https://oceansofenergy.blue/north-sea-1-offshore-solar-project/

Oceans of Energy. (2020b, January). *Oceans of Energy verdubbelt aantal zonnepanelen van drijvend zonnepark op Noordzee*. Retrieved from Oceans of Energy: https://oceansofenergy.blue/2020/01/29/oceans-of-energy-verdubbelt-aantal-zonnepanelen-van-drijvend-zonnepark-op-noordzee-29-01-2020/

ofgem. (2020). *Offshore Transmission: Draft Cost Assessment for the Walney* . London: ofgem.

Ophir, A., & Gendel, A. (1994). Adaptation of the multi-effect distillation (MED) process to yield high purity distillate for utilities, refineries and chemical industry. *Desalination 98*, 383–390.

Ørsted. (2018). *Annual report.* Denmark.

PBL Netherlands Environmental Assessment Agency. (2019, Decemeber 02). *Costs of offshore wind energy 2018.* The Hague: The Government of the Netherlands. Retrieved from PBL Netherlands Environmental Assessment Agency: https://www.pbl.nl/en/publications/costs-of-offshore-wind-energy-2018

Pelamis. (2014). *Pelamis technology.* Retrieved from http://www.pelamiswave.com/pelamistechnology

Pérez, C., & Iglesias, G. (2012). Integration of Wave Energy Converters and Offshore Windmills. *4th International Conference on Ocean Energy.* Dublin.

Pérez-Collazo, C., Jakobsen, M., Buckland, H., & Fernández-Chozas, J. (2013). Synergies for a Wave-Wind Energy Concept. *EWEA Offshore 2013.* Messe Frankfurt: The European Wind Energy Association.

Peterson, D., & Miller, E. (2016). *Hydrogen Production Cost from Solid Oxide Electrolysis.* DOE Hydrogen and Fuel Cells Program Record.

Previsic, M. (2004). Offshore wave energy conversion devices. *E.I. Institute*.

Roussanaly, S., Aasen, A., Anantharaman, R., Danielsen, B., Jakobsena, J., Heme-De-Lacotte, L., . . . Dreux, R. (2019). Offshore power generation with carbon capture and storage to decarbonise mainland electricity and offshore oil and gas installations: A technoeconomic analysis. *Applied Energy*, 233-234.

Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J., & Few, S. (2017). Future cost and performance of water electrolysis An expert elicitation study. *International Journal of Hydrogen Energy 42*, 30470-30492.

Scottish Enterprise. (2012). *Innovation in Offshore Wind. Installation, Operation & Maintenance.* Retrieved from Opportunities in energy: http://www.scottish-enterprise.com/~/media/SE/Resources/Documents/MNO/OW%20Innovation%20-%20IOM%20v1.0.pdf

Smith, H., Pearce, C., & Millar, D. (2012). Further analysis of change in nearshore wave climate due to an offshore wave farm: An enhanced case study for the Wave Hub site. *Renew. Energy*, 51–64.

Soares, C. G. (2016). *Progress in Renewable Energies Offshore.* Lisbon: CRC Press.

Statoil. (2007). Retrieved from Statoil: http://www.statoil.com. http://www.statoil.com/en/OurOperations/ExplorationProd/ncs/Njord/Pages/default.aspx

Stoutenburg, E., Jenkins, N., & Jacobson, M. (2010). Power output variations of co-located offshore wind turbines and wave energy converters in California. *Renew. Energy*, 2781–2791.

Tewari, P., Prabhakar, S., & Ramani, M. (1990). Evaluation of thermal desalination and reverse osmosis for the production of boiler feed water from sea water for coastal thermal power stations in India. *Desalination 79*, 85–93.

The Government of the Netherlands. (2019). *Climate Agreement.* The Hague.

The Government of the Netherlands. (2020a). *Dutch goals within the EU*. Retrieved from Government of the Netherlands: https://www.government.nl/topics/climate-change/eu-policy

The Government of the Netherlands. (2020b, January 1). *National long-term strategies.* Retrieved from European Comission: https://ec.europa.eu/info/energy-climate-change-environment/overall-targets/long-term-strategies_en

TNO. (2020a). *FROM GREY AND BLUE TO GREEN HYDROGEN*. Retrieved from TNO: https://www.tno.nl/hydrogen

TNO. (2020b). *WORLD FIRST: AN OFFSHORE PILOT PLANT FOR GREEN HYDROGEN*. Retrieved from TNO: https://www.tno.nl/en/focus-areas/energy-transition/roadmaps/towards-co2-neutral-fuels-and-feedstock/hydrogen-for-a-sustainable-energy-supply/world-first-an-offshore-pilot-plant-for-green-hydrogen/

Trading Economics. (2020). *Netherlands Inflation Rate1971-2020 Data*. Retrieved from Trading Economics: https://tradingeconomics.com/netherlands/inflation-cpi

University of Twente. (2019, OCTOBER 07). Research Ethics Policy. Enschede, the Netherlands.

van de Pieterman, R., & Asgarpour, M. (2014). *O&M Cost Reduction of Offshore Wind Farms - A Novel Case Study.* ECN.

Verschuren, P., Doorewaard, H., & In Mellion, M. J. (2010). *Designing a research project.* eleven international publishing.

Vrees, L. d. (2019). Adaptive marine spatial planning in the Netherlands sector of the North Sea. *Marine Policy*.

Wijayanta, A., Oda, T., C.W., P., Kashiwagi, T., & Aziz, M. (2019). Liquid hydrogen, methylcyclohexane, and ammonia as potential hydrogen storage: Comparison review. *Int. J. Hydrog. Energy*, 15026–15044.

Williams, M., Narayanan, S., Trulove, P., & Weidner, J. (2009). *Hydrogen, Production, Transport, and Storage 3.* New Jersey: The Electromechanical Society.

WindEurope. (2019). *Wind energy in Europe in 2018 – Trends and statistics.* Brussels: WindEurope.

XE Currency Converter. (2020). *XE Currency Converter: 1 EUR to USD*. Retrieved from XE Currency Converter: https://www.xe.com/currencyconverter/convert/?Amount=1&From=EUR&To=USD

Zheng, S., Zhu, G., Simmonds, D., Greaves, D., & Iglesias, G. (2020). Wave power extraction from a tubular structure integrated oscillating water column. *Renewable Energy*, 342-355.

APPENDIX I. FARM SIZE ANALYSIS

Wind Turbine and WEC Analysis [trial]

Site and location characteristics

$dis_{shore} := 165km$ .. distance from the offshore site to the nearest shipyard

$t := 20yr$ .. project's lifetime

$d := 42m$ .. water depth

$\rho_{air} := 1.225 \frac{kg}{m^3}$ .. air density

$\rho_{water} := 1025 \frac{kg}{m^3}$ .. sea water density

$T_e := 5.5s$ .. significant wave period at the site

$H_{mo} := 2.5m$ .. significant wave height at the site

$l_{interarray} := 80km$ .. total inter array cables distances

$l_{export} := 56km$ .. distance to the nearest platform in the decomssioning plan

Wind turbine charactersitcs

wind turbine type: tlb b

$r := \frac{164}{2} m$ .. Rotor radius

$A_{swept} := \pi \cdot r^2 = 2 \times 10^4 \, m^2$ .. swept area by a turbine's blade

$U := 10.8 \frac{m}{s}$ .. wind velocity at a turbine's

$c_p := 0.592$ .. power coefficient (max)

$P_{turbine} := 0.5 \rho_{air} \cdot A_{swept} \cdot U^3 \cdot c_p = 9.649 \cdot MW$ .. generated power by a single turbine

$i_{turb} := 5 .. 100 =$

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WEC characteristics

WEC type:

$P_{wave} := \frac{\rho_{water} \cdot g^2}{64\pi} \cdot T_e \cdot H_{mo}^2$ .. wave energy in the location per wave crest

$C_{pelamis} := 44.5m$ .. WEC conversion factor

$P_{wec} := P_{wave} \cdot C_{pelamis}$ .. generated power by a single wec device

$i_{wec} := round\left(\frac{i_{turb}}{3}\right)$ .. number of wec devices

$P_{total} := P_{turbine} \cdot i_{turb} + P_{wec} \cdot i_{wec}$ .. total power generation of the farm

Cost Analysis

Pre-installation costs

$c_{eng} := 570000euro$ .. engineering analyses cost

$c_{feas} := 100000euro$ .. feasibility study costs

$c_{leg} := 475000euro$ .. legislative factors cost

$c_{design} := 5141382euro$ .. farm layout cost

$IC := c_{design} + c_{leg} + c_{feas} + c_{eng} = 6.286 \cdot Meuro$ .. Initial costs

$c_{viewshed} := 3\% \cdot IC = 0.189 \cdot Meuro$ .. viewshed cost

$c_{permit} := 2\% \cdot IC = 0.126 \cdot Meuro$ .. siting and permits cost

$c_{GHG} := 0.5\% \cdot IC = 0.031 \cdot Meur$ .. GHG investigation cost

$c_{pre} := IC + c_{viewshed} + c_{permit} + c_{GHG} = 6.632 \cdot Meur$ .. pre-installation costs

Implementation costs

$c_{transportation} := 220000 \frac{euro}{km} \cdot dis_{shore} = 36.3 \cdot Meuro$ .. installations' transportation cost

$c_{designwec} := 245371euro$ .. design of pelamis wec cost

$c_{designwind} := 0.24 \cdot 10^{6} euro$ .. design of tlb b turbine cost

$c_{buildwec} := 5500000euro \cdot i_{wec}$ .. construction costs of the wec devices

$c_{buildturb} := \frac{P_{turbine}}{MW} \cdot 1480000.euro \cdot i_{turb}$ .. construction costs of the turbines

$c_{build} := c_{buildturb} + c_{buildwec}$ .. total construction costs

$c_{mooringturb} := \left(39772euro + 520820euro + \frac{1096 \cdot d}{m} euro\right) \cdot i_{turb}$ .. mooring costs for the tlb

$c_{installation} := 977620euro \cdot (i_{turb} + i_{wec})$ .. installation costs

$c_{cableinter} := \frac{307euro}{m} \cdot l_{interarray} = 24.56 \, Meuro$ .. interarray costs

$c_{cableexport} := \frac{500Meuro}{50km} \cdot l_{export} = 560 \cdot Meuro$ .. export cables costs

$c_{cable} := c_{cableinter} + c_{cableexport}$

$c_{implementation} := c_{design} + c_{build} + c_{transportation} + c_{installation} + c_{cable}$ .. implementation phase costs

Operation costs

$c_{omturb} := \frac{P_{turbine}}{MW} \cdot 13300 \frac{euro}{yr} \cdot \frac{t}{yr}$ .. annual operation and maintenace costs for the turbines

$c_{omwec} := \frac{P_{wec}}{MW} \cdot 228564 \frac{euro}{yr} \cdot \frac{t}{yr}$ .. annual operation and maintenace costs for the WEC devices

$c_{om} := c_{omturb} + c_{omwec}$ .. total annual operation and maintenace costs

$c_{insurance} := 4020843 \frac{euro}{yr} + \frac{17500euro}{MW \cdot yr} \cdot P_{turbine} \cdot i_{turb}$ .. total insurance costs (wec+ tubines)

$c_{adminstarion} := \frac{3Meuro}{yr}$ .. adminstative costs

$c_{operation} := 0.82t \cdot c_{om} + t \cdot c_{insurance} + c_{adminstarion} \cdot t$ .. total operation costs

$c_t := c_{pre} + c_{implementation} + c_{operation}$ .. total costs exduding decomisioning

$c_{decomissioning} := 0.03c_t$ .. decomissiong costs

$P := P_{total} \cdot t \cdot 93.8\%$ .. total electricity generated (with taking into account the energy losses in the cables)

Hydrogen production Analysis [trial]

$C_s := 4.184 \frac{J}{gm \cdot \Delta °C}$ .. specific heat of water

$T_{ambient} := 15°C$ .. ambient temperature

$T_{final} := 110°C$ .. final heating temperature

$\rho_{h2} := 0.0649 \frac{kg}{m^3}$ .. density of hydrogen

$R := 8.314 \frac{J}{mole \cdot K}$ .. universal gas constant

$P_{ambient} := 1 \cdot atm$ .. ambient pressure

$P_{final} := 100bar$ .. final compression pressure

$M := 2.015 \frac{gm}{mol}$ .. molar mass of hydrogen

$F := 96485.3329 \frac{C}{mole}$ .. faraday's constant

$V_c := \frac{141860J \cdot M}{2F \cdot gm} = 1.481 \cdot V$ .. SOEC's cell voltage

$\eta := 68\%$ .. electrolyzer efficiency

$m_{h2} := \frac{93.8\% P_{total}}{V_c \cdot 2 \cdot F} \cdot M \cdot \eta$ .. amount of hydrogen produced

$M_{h2o} := 18.015 \frac{gm}{mole}$ .. molar mass of water

$$\eta_{boiler} := 99\%$$

$$m_{h2o} := \frac{m_{h2}}{M} \cdot M_{h2o}$$ .. amount of water needed for desalination

$$E_{desalination} := 12\,kW \cdot \frac{hr}{m^3} \cdot \frac{m_{h2o}}{\rho_{water}}$$. energy required for desalination

$$E_{heating} := \frac{m_{h2o} \cdot C_s \cdot \left(T_{final} - T_{ambient}\right)}{\eta_{boiler}}$$ .. energy required for heating

$$\eta_{comp} := 70\%$$

$$E_{comp} := \frac{\frac{m_{h2}}{M} \cdot R \cdot T_{ambient} \cdot \ln\left(\frac{P_{final}}{P_{ambient}}\right)}{\eta_{comp}}$$ .. energy required for compression

$$m_{h2} := \frac{93.8\% \cdot P_{total} - \left(E_{desalination} + E_{heating} + E_{comp}\right)}{V_c \cdot 2 \cdot F} \cdot M \cdot \eta$$

$$E_{h2} := 33889 \frac{kcal}{kg} \cdot m_{h2}$$

$$c_{desalination} := 1450 \frac{euro}{kW}$$

$$c_{electrolysis} := 4500 \cdot (100\% + 1.4\% \cdot 4) \frac{euro}{kW}$$ .. cost of SOEC electrolyzer per input energy

$$c_{steam} := 1215 \frac{euro}{kW}$$ .. cost of heating and desalination auxilaries per needed energy

$$C_{electrolyzers} := c_{electrolysis} \cdot \left(E_{h2}\right)$$ .. SOEC electroyzer costs

$$C_{steam} := c_{steam} \cdot (93.8\%) \cdot E_{heating}$$ .. heating and desalination costs

$$C_{desalination} := c_{desalination} \cdot E_{desalination}$$

$$c_{compression} := 950 \frac{euro}{kW}$$

$$C_{compression} := c_{compression} \cdot E_{comp}$$

$$c_{omsoec} := \frac{2\% \cdot \left(C_{electrolyzers} + C_{steam} + C_{desalination} + C_{compression}\right)}{yr} \cdot t$$ .. operation and maintenace costs

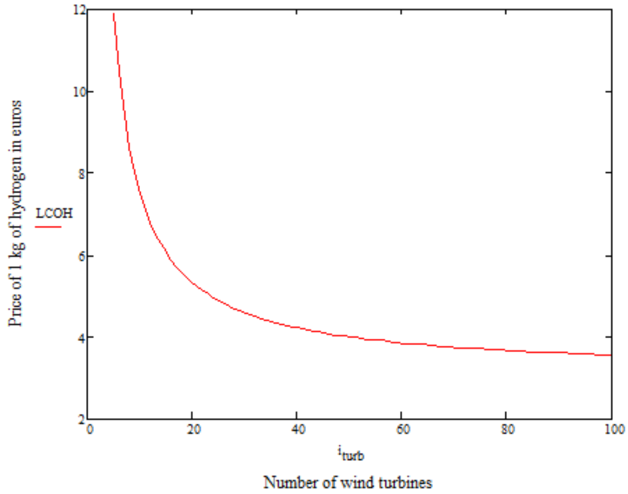
$$C_{total} := C_{electrolyzers} + C_{steam} + C_{desalination} + C_{compression} + c_{omsoec}$$ .. total hydrogen production costs

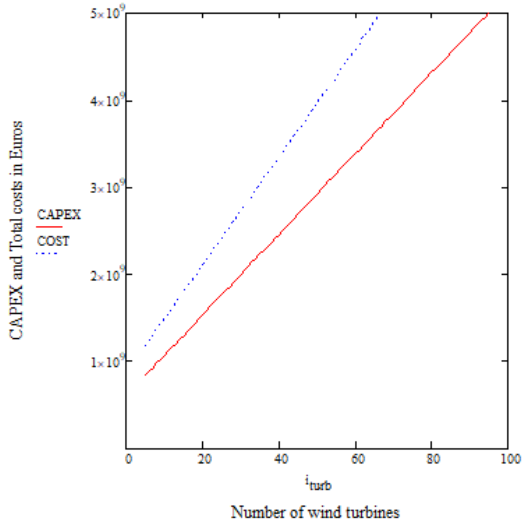
$$COST := C_{total} + c_{decomissioning} + c_t$$

$$OPEX := c_{operation} + c_{decomissioning} + c_{omsoec}$$

$$CAPEX := c_{pre} + c_{implementation} + \left(C_{total} - c_{omsoec}\right)$$

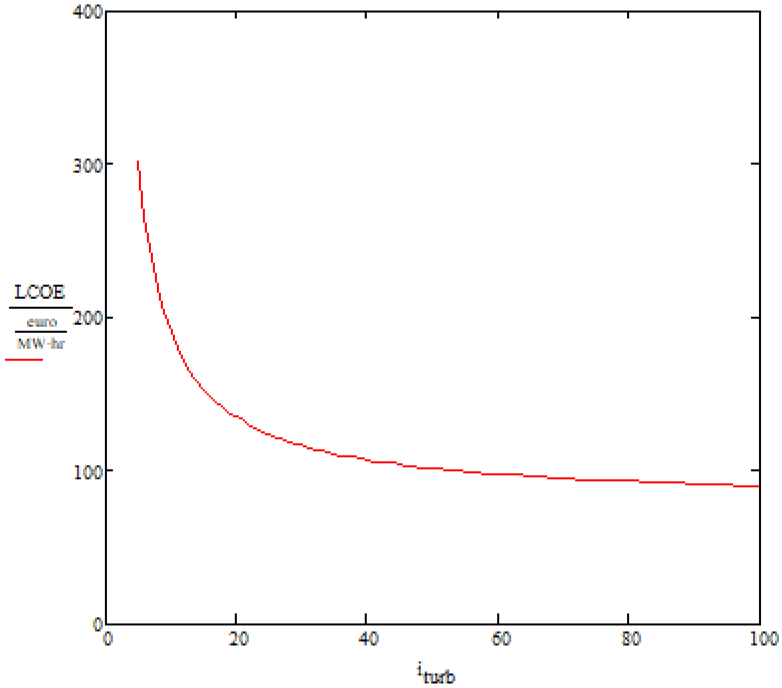
$$\frac{(CAPEX + OPEX) \cdot \left[100\% + \frac{1.4\%}{yr} \cdot (4yr + t)\right]}{m_{h2} \cdot t}$$ .. final price of kilogram of hydrogen





$E_{h2} := 33889 \frac{kcal}{kg} \cdot m_{h2}$ .. equivalent energy from hydrogen

$$LCOE := \frac{COST \cdot \left[100\% + \frac{1.4\%}{yr} \cdot (4yr + t)\right]}{E_{h2} \cdot t}$$



APPENDIX II. 2020 HYDROGEN PRODUCTION APPROACHANALYSIS

Wind Turbine and WEC Analysis

Site and location characteristics

$dis_{shore} := 165km$ .. distance from the offshore site to the nearest shipyard

$t := 20yr$ .. project's lifetime

$d := 42m$ .. water depth

$\rho_{air} := 1.225 \frac{kg}{m^3}$ .. air density

$\rho_{water} := 1025 \frac{kg}{m^3}$ .. sea water density

$T_e := 5.5s$ .. significant wave period at the site

$H_{mo} := 2.5m$ .. significant wave height at the site

$l_{interarray} := 80km$ .. total inter array cables distances

$l_{export} := 56km$ .. distance to the nearest platform in the decomssioning plan

Wind turbine charactersitcs

wind turbine type: tlb b

$r := \frac{164}{2} m$ .. Rotor radius

$A_{swept} := \pi \cdot r^2 = 2 \times 10^4 m^2$ .. swept area by a turbine's blade

$U := 10.8 \frac{m}{s}$ .. wind velocity at a turbine's hub

$c_p := 0.45$ .. power coefficient (max)

$P_{turbine} := 0.5\rho_{air} \cdot A_{swept} \cdot U^3 \cdot c_p = 7.334 \cdot MW$ .. generated power by a single turbine

$i_{turb} := 38$ .. number of wind turbines

$P_{turbine} \cdot i_{turb} = 278.709 \cdot MW$ .. total wind energy production

WEC characteristics

WEC type:

$P_{wave} := \frac{\rho_{water} \cdot g^2}{64\pi} \cdot T_e \cdot H_{mo}^2 = 16.853 \frac{1}{m} \cdot kW$ .. wave energy in the location per wave crest

$C_{pelamis} := 44.5m$ .. WEC conversion factor

$P_{wec} := P_{wave} \cdot C_{pelamis} = 749.96 \cdot kW$ .. generated power by a single wec device

$i_{wec} := ceil\left(\frac{48}{3}\right) = 16$ .. number of wecdevices

$P_{wec} \cdot i_{wec} = 11.999 \cdot MW$ .. total wecenergy production

Cost Analysis

$P_{total} := P_{turbine} \cdot i_{turb} + P_{wec} \cdot i_{wec} = 291 \cdot MW$ .. total power generation of the farm

Pre-installation costs

$c_{eng} := 570000euro = 0.57 \cdot Meuro$ .. engineering analyses cost

$c_{feas} := 100000euro = 0.1 \cdot Meuro$ .. feasibility study costs

$c_{leg} := 475000euro = 0.475 \cdot Meuro$ .. legislative factors cost

$c_{design} := 5141382euro = 5.141 \cdot Meuro$ .. farm layout cost

$IC := c_{design} + c_{leg} + c_{feas} + c_{eng} = 6.286 \cdot Meuro$ .. Initial costs

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$c_{viewshed} := 3\% \cdot IC = 0.189 \cdot Meuro$ .. viewshed cost

$c_{permit} := 2\% \cdot IC = 0.126 \cdot Meuro$ .. siting and permits cost

$c_{GHG} := 0.5\% \cdot IC = 0.031 \cdot Meuro$ .. GHG investigation cost

$c_{pre} := IC + c_{viewshed} + c_{permit} + c_{GHG} = 6.632 \cdot Meuro$ .. pre-installation costs

Implementation costs

$c_{transportation} := 220000 \frac{euro}{km} \cdot dis_{shore} = 36.3 \cdot Meuro$ .. installations' transportation cost

$c_{designwec} := 245371euro = 0.245 \cdot Meuro$ .. design of pelamis wec cost

$c_{designwind} := 0.24 \cdot 10^{6} euro = 0.24 \cdot Meuro$ .. design of tlb b turbine cost

$c_{buildwec} := 5500000 euro \cdot i_{wec} = 88 \cdot Meuro$ .. construction costs of the wec devices

$c_{buildturb} := \frac{P_{turbine}}{MW} \cdot 1480000.euro \cdot i_{turb} = 412.489 \cdot Meuro$ .. construction costs of the turbines

$c_{build} := c_{buildturb} + c_{buildwec}$ .. total construction costs

$c_{mooringturb} := \left(39772euro + 520820euro + \frac{1096 \cdot d}{m} euro\right) \cdot i_{turb} = 23.052 \cdot Meuro$ .. mooring costs for the tlb

$c_{installation} := 977620euro \cdot (i_{turb} + i_{wec}) = 52.791 \cdot Meuro$ .. installation costs

$c_{cableinter} := \frac{307euro}{m} \cdot l_{interarray} = 24.56 \cdot Meuro$ .. interarray costs

$c_{cableexport} := \frac{500Meuro}{50km} \cdot l_{export} = 560 \cdot Meuro$ .. export cables costs

$c_{cable} := c_{cableinter} + c_{cableexport}$

$c_{substation} := 20000euro \cdot \frac{P_{total}}{MW} + 2000000euro = 7.814 \cdot Meuro$

$c_{implementation} := c_{design} + c_{build} + c_{transportation} + c_{installation} + c_{cable} + c_{mooringturb} + c_{substation} = 1186 \cdot Meuro$

Operation costs

$c_{omturb} := \frac{P_{turbine}}{MW} \cdot 13300 \frac{euro}{yr} \cdot \frac{t}{yr} = 1.951 \cdot \frac{Meuro}{yr}$ .. annual operation and maintenace costs for the turbines

$c_{omwec} := \frac{P_{wec}}{MW} \cdot 228564 \frac{euro}{yr} \cdot \frac{t}{yr} = 3.428 \cdot \frac{Meuro}{yr}$ .. annual operation and maintenace costs for the WEC devices

$c_{om} := c_{omturb} + c_{omwec} = 5.379 \cdot \frac{Meuro}{yr}$ .. total annual operation and maintenace costs

$c_{insurance} := 4020843 \frac{euro}{yr} + \frac{17500euro}{MW \cdot yr} \cdot P_{turbine} \cdot i_{turb} = 8.898 \cdot \frac{Meuro}{yr}$ .. total insurance costs (wec+ tubines)

$c_{adminstarion} := \frac{3Meuro}{yr}$ .. adminstative costs

$c_{operation} := 0.82t \cdot c_{om} + t \cdot c_{insurance} + c_{adminstarion} \cdot t = 326.185 \cdot Meuro$ .. total operation costs

$c_t := c_{pre} + c_{implementation} + c_{operation} = 1518 \cdot Meuro$ .. total costs exduding decomisioning

$c_{decomissioning} := 0.03c_t = 45.552 \cdot Meuro$ .. decomisiong costs

$P := P_{total} \cdot t \cdot 93.8\% = 4.781 \times 10^7 \cdot MW \cdot$ .. total electricity generated (with taking into account the energy losses in the cables)

Hydrogen production Analysis

$C_s := 4.184 \frac{J}{gm \cdot \Delta°C}$ .. water specific heat

$T_{ambient} := 15°C$ .. water ambient temp

$T_{final} := 110°C$ .. desired temp in heating

$\rho_{h2} := 0.0649 \frac{kg}{m^3}$ .. hydrogen density at the desired condition

$R := 8.314 \frac{J}{mole \cdot K}$ .. universal molar constat

$P_{ambient} := 1 atm$ .. atmospheric pressure

$P_{final} := 100bar$ .. desired pressure

$M := 2.015 \frac{gm}{mol}$ .. molar mass of hydrogen

$F := 96485.3329 \frac{C}{mole}$ .. faraday's constant

$V_c := \frac{141860J \cdot M}{2F \cdot gm} = 1.481 \cdot$ .. SOEC's cell voltage

$\eta := 68\%$ .. electrolyzer efficiency

$m_{h2} := \frac{93.8\% P_{total}}{V_c \cdot 2 \cdot F} \cdot M \cdot \eta = 1 \frac{kg}{s}$ .. amount of hydrogen produced

$M_{h2o} := 18.015 \frac{gm}{mole}$ .. molar mass of water

$\eta_{boiler} := 99\%$

$m_{h2o} := \frac{m_{h2}}{M} \cdot M_{h2o} = 11.686 \frac{kg}{s}$ .. amount of water needed for desalination

$$E_{desalination} := 12\,kW\cdot\frac{hr}{m^3}\cdot\frac{m_{h2o}}{\rho_{water}} = 0.493\cdot MW$$. energy required for desalination

$$E_{heating} := \frac{m_{h2o}\cdot C_s\cdot(T_{final} - T_{ambient})}{\eta_{boiler}} = 5\cdot MW$$ .. energy required for heating

$$\eta_{comp} := 70\%$$

$$E_{comp} := \frac{\frac{m_{h2}}{M}\cdot R\cdot T_{ambient}\cdot\ln\left(\frac{P_{final}}{P_{ambient}}\right)}{\eta_{comp}} = 10.195\cdot M$$ .. energy required for compression

$$m_{h2} := \frac{93.8\%\cdot P_{total} - (E_{desalination} + E_{heating} + E_{comp})}{V_c\cdot 2\cdot F}\cdot M\cdot\eta = 1\,\frac{kg}{s}$$

$$E_{h2} := 33889\,\frac{kcal}{kg}\cdot m_{h2} = 175\cdot MW$$ .. Equivalent electric energy from the produced hydrogen

$$c_{compression} := 950\,\frac{euro}{kW}$$ .. cost of compressors per input energy

$$c_{desalination} := 1450\,\frac{euro}{kW}$$ .. cost of desalination per input energy

$$c_{electrolysis} := 4500\cdot(100\% + r_{inflation}\cdot 4)\,\frac{euro}{kW}$$ .. cost of SOEC electrolyzer per input energy

$$c_{steam} := 1215\,\frac{euro}{kW}$$ .. cost of boilers per needed energy

$$C_{electrolyzers} := c_{electrolysis}\cdot(E_{h2}) = 834.75186\cdot Meuro$$

$$C_{steam} := c_{steam}\cdot E_{heating} = 6\cdot Meuro$$ .. boilers costs

$$C_{desalination} := c_{desalination}\cdot E_{desalination} = 0.714\cdot Meuro$$ .. desalination costs

$$C_{compression} := c_{compression}\cdot E_{comp} = 9.685\cdot Meuro$$ .. compressors costs

$$c_{omsoec} := \frac{2\%\cdot(C_{electrolyzers} + C_{steam} + C_{desalination} + C_{compression})}{yr}\cdot t = 340.341\cdot Meuro$$ .. operation and maintenace costs

$$C_{total} := C_{electrolyzers} + C_{steam} + C_{desalination} + C_{compression} + c_{omsoec} = 1191.1921\cdot Meuro$$ .. total hydrogen prodution costs

$$COST := C_{total} + c_{decomissioning} + c_t = 2755\cdot Meuro$$ .. total project's costs

$$CAPEX := c_{pre} + c_{implementation} + (C_{total} - c_{omsoec}) = 2043.07174\cdot Meuro$$ capital expenditure

$$OPEX := c_{operation} + c_{decomissioning} + c_{omsoec} = 712.077\cdot Meuro$$ operational expenditure

$$LCOH := \frac{(CAPEX + OPEX)\cdot\left[100\% + \frac{r_{inflation}}{yr}\cdot(4yr + t)\right]}{m_{h2}\cdot t} = 4.814\,\frac{€}{kg}$$ .. final price of kilogram of hydrogen

$$4500\,\frac{euro}{kW}\cdot P_{total} = 1308\cdot Meuro$$ .. nominal cost of offshore wind farms per unit energy (reference for comparison)

$$LCOE := \frac{COST\cdot\left[100\% + \frac{r_{inflation}}{yr}\cdot(4yr + t)\right]}{E_{h2}\cdot t} = 122.13\cdot\frac{euro}{MW\cdot hr}$$

APPENDIX III. 2020 CONVENTIONAL APPROACH ANALYSIS

Wind Turbine and WEC Analysis

Site and location characteristics

$dis_{shore} := 165km$ .. distance from the offshore site to the nearest shipyard

$t := 20yr$ .. project's lifetime

$d := 42m$ .. water depth

$\rho_{air} := 1.225 \frac{kg}{m^3}$ .. air density

$\rho_{water} := 1025 \frac{kg}{m^3}$ .. sea water density

$T_e := 5.5s$ .. significant wave period at the site

$H_{mo} := 2.5m$ .. significant wave height at the site

$I_{interarray} := 80km$ .. total inter array cables distances

$I_{export} := 56km$ .. distance to the nearest platform in the decomssioning plan

Wind turbine charactersitcs

wind turbine type:
tlb b

$r := \frac{164}{2} m$ .. Rotor radius

$A_{swept} := \pi \cdot r^2 = 2 \times 10^4 m^2$ .. swept area by a turbine's blade

$U := 10.8 \frac{m}{s}$ .. wind velocity at a turbine's

$c_p := 0.45$ .. power coefficient (max)

$P_{turbine} := 0.5 \rho_{air} \cdot A_{swept} \cdot U^3 \cdot c_p = 7.334 \cdot MW$ .. generated power by a single turbine

$i_{turb} := 40$

$P_{turbine} \cdot i_{turb} = 293.378 \cdot MW$

Cost Analysis

$P_{total} := P_{turbine} \cdot i_{turb} = 293 \cdot MW$ .. total power generation of the farm

Pre-installation costs

$c_{eng} := 570000euro = 0.57 \cdot Meuro$ .. engineering analyses cost

$c_{feas} := 100000euro = 0.1 \cdot Meuro$ .. feasibility study costs

$c_{leg} := 475000euro = 0.475 \cdot Meuro$ .. legislative factors cost

$c_{design} := 5141382euro = 5.141 \cdot Meuro$ .. farm layout cost

$IC := c_{design} + c_{leg} + c_{feas} + c_{eng} = 6.286 \cdot Meuro$ .. Initial costs

$c_{viewshed} := 3\% \cdot IC = 0.189 \cdot Meuro$ .. viewshed cost

$c_{permit} := 2\% \cdot IC = 0.126 \cdot Meuro$ .. siting and permits cost

$c_{GHG} := 0.5\% \cdot IC = 0.031 \cdot Meuro$ .. GHG investigation cost

$c_{pre} := IC + c_{viewshed} + c_{permit} + c_{GHG} = 6.632 \cdot Meuro$ .. pre-installation costs

Implementation costs

$c_{transportation} := 220000 \frac{euro}{km} \cdot dis_{shore} = 36.3 \cdot Meuro$ .. installations' transportation cost

$c_{designwind} := 0.24 \cdot 10^{6} euro = 0.24 \cdot Meuro$ .. design of tlb b turbine cost

$c_{buildturb} := \frac{P_{turbine}}{MW} \cdot 1480000.euro \cdot i_{turb} = 434.199 \cdot Meuro$ .. construction costs of the turbines

$c_{mooringturb} := \left(39772euro + 520820euro + \frac{1096 \cdot d}{m} euro\right) \cdot i_{turb} = 24.265 \cdot Meuro$ .. mooring costs for the tlb

$c_{cableinter} := \frac{307euro}{m} \cdot l_{interarray} = 24.56 \, Meuro$ .. interarray costs

$c_{cableexport} := \frac{500Meuro}{50km} \cdot dis_{shore} = 1650 \cdot Meuro$ .. export cables costs

$c_{cable} := c_{cableinter} + c_{cableexport}$

$c_{installation} := 977620euro \cdot (i_{turb}) = 39.105 \cdot Meuro$ .. installation costs

$c_{substation} := 20000 \frac{euro}{MW} \cdot P_{total} + 2000000 euro = 7.868 \cdot Meuro$

$c_{implementation} := c_{designwind} + c_{buildturb} + c_{transportation} + c_{installation} + c_{cable} + c_{mooringturb} + c_{substation} = 2192 \cdot Meuro$ .. implementation phase costs

Operation costs

$c_{omturb} := \frac{P_{turbine}}{MW} \cdot 13300 \cdot \frac{euro}{yr} \cdot \frac{t}{yr} = 1.951 \cdot \frac{Meuro}{yr}$ .. annual operation and maintenace costs for the turbines

$c_{insurance} := \frac{17500euro}{MW \cdot yr} \cdot P_{turbine} \cdot i_{turb} = 5.134 \cdot \frac{Meuro}{yr}$ .. total insurance costs

$c_{adminstarion} := \frac{3Meuro}{yr}$ .. adminstative costs

$c_{operation} := t \cdot c_{omturb} + t \cdot c_{insurance} + c_{adminstarion} \cdot t = 201.702 \cdot Meuro$ .. total operation costs

$t \cdot c_{omturb} = 39.019 \cdot Meuro$

$c_t := c_{pre} + c_{implementation} + c_{operation} = 2400 \cdot Meuro$ .. total costs excluding decomissioning

$t \cdot c_{insurance} = 102.682 \cdot Meuro$

$c_{decomissioning} := 0.03 c_t = 72.009 \cdot Meuro$ .. decomissiong costs

$GW := 10 \cdot 10^9 W$

$P := P_{total} \cdot t \cdot 93.8\% = 4825 \cdot GW \cdot hr$ .. total electricity generated (with taking into account the energy losses in the cables)

$COST := c_t + c_{decomissioning} = 2472 \cdot Meuro$

$$LCOE := \frac{COST \cdot \left[100\% + \frac{1.4\%}{yr} \cdot (4yr + t)\right]}{P} = 68.463 \cdot \frac{euro}{MW \cdot hr}$$

$P_{total} = 257.17 \cdot GW \cdot \frac{hr}{yr}$

APPENDIX IV. 2030 HYDROGEN PRODUCTION APPROACH ANALYSIS

Wind Turbine and WEC Analysis

Site and location characteristics

$dis_{shore} := 165km$ .. distance from the offshore site to the nearest shipyard

$t := 20yr$ .. project's lifetime

$d := 42m$ .. water depth

$\rho_{air} := 1.225 \frac{kg}{m^3}$ .. air density

$\rho_{water} := 1025 \frac{kg}{m^3}$ .. sea water density

$T_e := 5.5s$ .. significant wave period at the site

$H_{mo} := 2.5m$ .. significant wave height at the site

$l_{interarray} := 80km$ .. total inter array cables distances

$l_{export} := 56km$ .. distance to the nearest platform in the decomsioning plan

Wind turbine charactersitcs

wind turbine type: tlb b

$r := \frac{230}{2} m$ .. Rotor radius

$A_{swept} := \pi \cdot r^2 = 4 \times 10^4 m^2$ .. swept area by a turbine's blade

$U := 10.8 \frac{m}{s}$ .. wind velocity at a turbine's

$c_p := 0.45$ .. power coefficient (max)

$P_{turbine} := 0.5 \rho_{air} \cdot A_{swept} \cdot U^3 \cdot c_p = 14.426 \cdot MW$ .. generated power by a single turbine

$i_{turb} := 38$

$P_{turbine} \cdot i_{turb} = 548.175 \cdot MW$

WEC characteristics

WEC type:

$P_{wave} := \frac{\rho_{water} \cdot g^2}{64\pi} \cdot T_e \cdot H_{mo}^2 = 16.853 \frac{1}{m} \cdot kW$ .. wave energy in the location per wave crest

$C_{pelamis} := 44.5m$ .. WEC conversion factor

$P_{wec} := P_{wave} \cdot C_{pelamis} = 749.96 \cdot kW$ .. generated power by a single wecdevice

$i_{wec} := ceil\left(\frac{48}{3}\right) = 16$ .. number of wec devices

$P_{wec} \cdot i_{wec} = 11.999 \cdot MW$

Cost Analysis

$P_{total} := P_{turbine} \cdot i_{turb} + P_{wec} \cdot i_{wec} = 560 \cdot MW$ .. total power generation of the farm

Pre-installation costs

$c_{eng} := 570000 euro = 0.57 \cdot Meuro$ .. engineering analyses cost

$c_{feas} := 100000 euro = 0.1 \cdot Meuro$ .. feasibility study costs

$c_{leg} := 475000 euro = 0.475 \cdot Meuro$ .. legislative factors cost

$c_{design} := 5141382 euro = 5.141 \cdot Meuro$ .. farm layout cost

$IC := c_{design} + c_{leg} + c_{feas} + c_{eng} = 6.286 \cdot Meuro$ .. Initial costs

$c_{viewshed} := 3\% \cdot IC = 0.189 \cdot Meuro$ .. viewshed cost

$c_{permit} := 2\% \cdot IC = 0.126 \cdot Meuro$ .. siting and permits cost

$c_{GHG} := 0.5\% \cdot IC = 0.031 \cdot Meuro$ .. GHG investigation cost

$c_{pre} := IC + c_{viewshed} + c_{permit} + c_{GHG} = 6.632 \cdot Meuro$ .. pre-installation costs

Implementation costs

$c_{transportation} := 220000 \frac{euro}{km} \cdot dis_{shore} = 36.3 \cdot Meuro$ .. installations' transportation cost

$c_{designwec} := 245371 euro = 0.245 \cdot Meuro$ .. design of pelamis wec cost

$c_{designwind} := 0.24 \cdot 10^{6} euro = 0.24 \cdot Meuro$ .. design of tlb b turbine cost

$c_{buildwec} := 5500000 euro \cdot i_{wec} = 88 \cdot Meuro$ .. construction costs of the wec devices

$c_{buildturb} := \frac{P_{turbine}}{MW} \cdot 1480000.euro \cdot i_{turb} = 811.299 \cdot Meuro$ .. construction costs of the turbines

$c_{build} := c_{buildturb} + c_{buildwec}$ .. total construction costs

$c_{mooringturb} := \left(39772 euro + 520820 euro + \frac{1096 \cdot d}{m} euro\right) \cdot i_{turb} = 23.052 \cdot Meuro$ .. mooring costs for the tlb

$c_{installation} := 977620 euro \cdot \left(i_{turb} + i_{wec}\right) = 52.791 \cdot Meuro$ .. installation costs

$c_{cableinter} := \frac{307 euro}{m} \cdot l_{interarray} = 24.56 \, Meuro$ .. interarray costs

$c_{cableexport} := \frac{500 Meuro}{50 km} \cdot l_{export} = 560 \cdot Meuro$ .. export cables costs

$c_{cable} := c_{cableinter} + c_{cableexport}$

$c_{substation} := 20000 euro \cdot \frac{P_{total}}{MW} + 2000000 euro = 13.203 \cdot Meuro$

$c_{implementation} := c_{design} + c_{build} + c_{transportation} + c_{installation} + c_{cable} + c_{mooringturb} + c_{substation} = 1590 \cdot Meuro$ .. implementation phase costs

Operation costs

$c_{omturb} := \frac{P_{turbine}}{MW} \cdot 13300 \cdot \frac{euro}{yr} \cdot \frac{t}{yr} = 3.837 \cdot \frac{Meuro}{yr}$

.. annual operation and maintenace costs for the turbines

$c_{omwec} := \frac{P_{wec}}{MW} \cdot 228564 \cdot \frac{euro}{yr} \cdot \frac{t}{yr} = 3.428 \cdot \frac{Meuro}{yr}$

.. annual operation and maintenace costs for the WEC devices

$c_{om} := c_{omturb} + c_{omwec} = 7.266 \cdot \frac{Meuro}{yr}$

.. total annual operation and maintenace costs

$c_{insurance} := 4020843 \frac{euro}{yr} + \frac{17500 euro}{MW \cdot yr} \cdot P_{turbine} \cdot i_{turb} = 13.614 \cdot \frac{Meuro}{yr}$

.. total insurance costs (wec+ tubines)

$c_{adminstarion} := \frac{3 Meuro}{yr}$

.. adminstative costs

$c_{operation} := (100 - 10.58)\% \cdot (0.82 t \cdot c_{om} + t \cdot c_{insurance} + c_{adminstarion} \cdot t) = 403.671 \cdot Meur$

.. total operation costs

$c_t := c_{pre} + c_{implementation} + c_{operation} = 2 \times 10^3 \cdot Meuro$

.. total costs excluding decomisioning

$c_{decomissioning} := 0.03 c_t = 60.003 \cdot Meur$

.. decomisiong costs

$P := P_{total} \cdot t \cdot 93.8\% = 9.212 \times 10^7 \cdot MW \cdot$

.. total electricity generated (with taking into account the energy losses in the cables)

Hydrogen production Analysis

$C_s := 4.184 \frac{J}{gm \cdot \Delta °C}$

.. water specific heat

$T_{ambient} := 15 °C$

.. water ambient temp

$T_{final} := 110 °C$

.. desired temp in heating

$\rho_{h2} := 0.0649 \frac{kg}{m^3}$

.. hydrogen density at the desired condition

$R := 8.314 \frac{J}{mole \cdot K}$

.. universal molar constat

$P_{ambient} := 1 atm$

.. atmospheric pressure

$P_{final} := 100 bar$

.. desired pressure

$M := 2.015 \frac{gm}{mol}$

.. molar mass of hydrogen

$F := 96485.3329 \frac{C}{mole}$

.. faraday's constant

$V_c := \frac{141860 J \cdot M}{2F \cdot gm} = 1.481 \cdot$

.. SOEC's cell voltage

$\eta := 77.1\%$

.. electrolyzer efficiency

$m_{h2} := \frac{P_{total}}{V_c \cdot 2 \cdot F} \cdot M \cdot \eta = 3 \frac{kg}{s}$

.. amount of hydrogen produced

$M_{h2o} := 18.015 \frac{gm}{mole}$

.. molar mass of water

$\eta_{boiler} := 99\%$

$m_{h2o} := \frac{m_{h2}}{M} \cdot M_{h2o} = 27.219 \frac{kg}{s}$

.. amount of water needed for desalination

$$E_{desalination} := 12\,kW \cdot \frac{hr}{m^3} \cdot \frac{m_{h2o}}{\rho_{water}} = 1.147 \cdot MW$$

. energy required for desalination

$$E_{heating} := \frac{m_{h2o} \cdot C_s \cdot \left(T_{final} - T_{ambient}\right)}{\eta_{boiler}} = 11 \cdot MW$$

.. energy required for heating

$$\eta_{comp} := 70\%$$

$$E_{comp} := \frac{\frac{m_{h2}}{M} \cdot R \cdot T_{ambient} \cdot \ln\left(\frac{P_{final}}{P_{ambient}}\right)}{\eta_{comp}} = 23.745 \cdot MW$$

.. energy required for compression

$$\eta_{h2} := \frac{366.514\,MW}{P_{total}} = 65.429 \cdot \%$$

.. conversion from electricity to hydrogen efficiency

$$m_{h2} := \frac{93.8\% \cdot P_{total} - \left(E_{desalination} + E_{heating} + E_{comp}\right)}{V_c \cdot 2 \cdot F} \cdot M \cdot \eta = 3\,\frac{kg}{s}$$

$$E_{h2} := 33889\,\frac{kcal}{kg} \cdot m_{h2} = 377.569 \cdot MW$$

.. Equivalent electric energy from the produced hydrogen

$$c_{electrolysis} := 1100\,\frac{euro}{kW}$$

.. cost of SOEC electrolyzer per input energy

$$c_{steam} := 1215\,\frac{euro}{kW}$$

.. cost of boilers per needed energy

$$C_{electrolyzers} := c_{electrolysis} \cdot 93.8\% \cdot P_{total} = 577.98764 \cdot Meuro$$

$$c_{omsoec} := \frac{2\% \cdot \left(C_{electrolyzers}\right)}{yr} \cdot t = 231.195 \cdot Meuro$$

.. operation and maintenace costs

$$C_{total} := C_{electrolyzers} + c_{omsoec} = 809.1827 \cdot Meuro$$

.. total hydrogen production costs

$$COST := C_{total} + c_{decomissioning} + c_t = 2869 \cdot Meuro$$

.. total project's costs

$$CAPEX := c_{pre} + c_{implementation} + \left(C_{total} - c_{omsoec}\right) = 2174.40645 \cdot Meuro$$

capital expenditure

$$OPEX := c_{operation} + c_{decomissioning} + c_{omsoec} = 694.868 \cdot Meuro$$

operational expenditure

$$LCOH := \frac{(CAPEX + OPEX) \cdot \left[100\% + \frac{1.4\%}{yr} \cdot (14yr + t)\right]}{m_{h2} \cdot t} = 2.522 \cdot \frac{euro}{kg}$$

.. final price of kilogram of hydrogen

$$LCOE := \frac{COST \cdot \left[100\% + \frac{1.4\%}{yr} \cdot (14yr + t)\right]}{E_{h2} \cdot t} = 63.979 \cdot \frac{eur}{MW}$$

APPENDIX V. 2030 CONVENTIONAL APPROACH ANALYSIS

Wind Turbine and WEC Analysis

Site and location characteristics

$dis_{shore} := 165km$ .. distance from the offshore site to the nearest shipyard

$t := 20yr$ .. project's lifetime

$d := 42m$ .. water depth

$\rho_{air} := 1.225 \frac{kg}{m^3}$ .. air density

$\rho_{water} := 1025 \frac{kg}{m^3}$ .. sea water density

$T_e := 5.5s$ .. significant wave period at the site

$H_{mo} := 2.5m$ .. significant wave height at the site

$I_{interarray} := 80km$ .. total inter array cables distances

$I_{export} := 56km$ .. distance to the nearest platform in the decomsisioning plan

Wind turbine charactersitcs

wind turbine type: tlb b

$r := \frac{230}{2} m$ .. Rotor radius

$A_{swept} := \pi \cdot r^2 = 4 \times 10^4 m^2$ .. swept area by a turbine's blade

$U := 10.8 \frac{m}{s}$ .. wind velocity at a turbine's

$c_p := 0.45$ .. power coefficient (max)

$P_{turbine} := 0.5 \rho_{air} \cdot A_{swept} \cdot U^3 \cdot c_p = 14.426 \cdot MW$ .. generated power by a single turbine

$i_{turb} := 39$

$P_{turbine} \cdot i_{turb} = 562.6 \cdot MW$

Cost Analysis

$P_{total} := P_{turbine} \cdot i_{turb} = 563 \cdot MW$ .. total power generation of the farm

Pre-installation costs

$c_{eng} := 570000 euro = 0.57 \cdot Meuro$ .. engineering analyses cost

$c_{feas} := 100000 euro = 0.1 \cdot Meuro$ .. feasibility study costs

$c_{leg} := 475000 euro = 0.475 \cdot Meuro$ .. legislative factors cost

$c_{design} := 5141382 euro = 5.141 \cdot Meuro$ .. farm layout cost

$IC := c_{design} + c_{leg} + c_{feas} + c_{eng} = 6.286 \cdot Meuro$ .. Initial costs

$c_{viewshed} := 3\% \cdot IC = 0.189 \cdot Meuro$ .. viewshed cost

$c_{permit} := 2\% \cdot IC = 0.126 \cdot Meuro$ .. siting and permits cost

$c_{GHG} := 0.5\% \cdot IC = 0.031 \cdot Meuro$ .. GHG investigation cost

$c_{pre} := IC + c_{viewshed} + c_{permit} + c_{GHG} = 6.632 \cdot Meuro$ .. pre-installation costs

Implementation costs

$c_{transportation} := 220000 \frac{euro}{km} \cdot dis_{shore} = 36.3 \cdot Meuro$ .. installations' transportation cost

$c_{design} := 0.24 \cdot 10^{6} euro = 0.24 \cdot Meuro$ .. design of tlb b turbine cost

$c_{buildturb} := \frac{P_{turbine}}{MW} \cdot 1480000. euro \cdot i_{turb} = 832.649 \cdot Meuro$ .. construction costs of the turbines

$c_{build} := c_{buildturb}$ .. total construction costs

$c_{mooringturb} := \left(39772 euro + 520820 euro + \frac{1096 \cdot d}{m} euro\right) \cdot i_{turb} = 23.658 \cdot Meuro$ .. mooring costs for the tlb

$c_{installation} := 977620 euro \cdot \left(i_{turb}\right) = 38.127 \cdot Meuro$ .. installation costs

$c_{cableinter} := \frac{307 euro}{m} \cdot l_{interarray} = 24.56 \cdot Meuro$ .. interarray costs

$c_{cableexport} := \frac{500 Meuro}{50 km} \cdot dis_{shore} = 1650 \cdot Meuro$ .. export cables costs

$c_{cable} := c_{cableinter} + c_{cableexport}$

$c_{substation} := 20000 \frac{euro}{MW} \cdot P_{total} + 2000000 euro = 13.252 \cdot Meuro$

$c_{implementation} := c_{design} + c_{build} + c_{transportation} + c_{installation} + c_{cable} + c_{mooringturb} + c_{substation} = 2594 \cdot Meuro$ .. implementation phase costs

Operation costs

$c_{omturb} := \frac{P_{turbine}}{MW} \cdot 13300 \frac{euro}{yr} \cdot \frac{t}{yr} = 3.837 \cdot \frac{Meuro}{yr}$

.. annual operation and maintenace costs for the turbines

$c_{om} := c_{omturb} = 3.837 \cdot \frac{Meuro}{yr}$

.. total annual operation and maintenace costs

$c_{insurance} := 4020843 \frac{euro}{yr} + \frac{17500euro}{MW \cdot yr} \cdot P_{turbine} \cdot i_{turb} = 13.866 \cdot \frac{Meuro}{yr}$

.. total insurance costs (wec+ tubines)

$c_{adminstarion} := \frac{3Meuro}{yr}$

.. adminstative costs

$c_{operation} := (100 - 10.58)\% \cdot (t \cdot c_{om} + t \cdot c_{insurance} + c_{adminstarion} \cdot t) = 370.263 \cdot Meuro$

.. total operation costs

$c_t := c_{pre} + c_{implementation} + c_{operation} = 2.971 \times 10^{3} \cdot Meuro$

.. total costs exduding decomisioning

$c_t := c_{pre} + c_{implementation} + c_{operation} = 2.971 \times 10^{3} \cdot Meuro$

.. total costs exduding decomisioning

$c_{decomissioning} := 0.03c_t = 89.134 \cdot Meuro$

.. decomisiong costs

$P := P_{total} \cdot t \cdot 93.8\% = 9.252 \times 10^{7} \cdot MW \cdot hr$

.. total electridty generated (with taking into account the energy losses in the cables)

$COST := c_t + c_{decomissioning} = 3060 \cdot Meuro$

$LCOE := \frac{COST \cdot (100\% + r_{inflation} \cdot 14)}{P} = 40.024 \cdot \frac{euro}{MW \cdot hr}$