Universiteit Utrecht

A Comparative Study on Hydrogen Production and Storage Using an Offshore Wind Farm in The Netherlands

Master's Thesis-Energy Science
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Abbreviations

Alkaline Water Electrolysis	AWE
Capital Expenditures	CAPEX
Carbon Dioxide	CO_2
Capital Recovery Factor	CRF
Direct Current	DC
Electrolyser/Wind capacity ratio	E/W ratio
European Union	EU
Exclusive Economic Zone	EEZ
Greenhouse Gas Emission	GHG
Hydrogen Evolution Reaction	HER
High Voltage Alternating Current	HVAC
Internal Return Rate	IRR
Levelized Cost of Hydrogen	LCOH
Levelized Cost of Storage	LCOS
Net Present Value	NPV
Oxygen Evolution Reaction	OER
Operating Expenditures	OPEX
Offshore Wind Farm	OWF
Pay Back Period	PBP
Polymer Electrolyte Membrane	PEM
Solid Oxide Electrolysis	SOE

Abstract

Producing energy with conventional resources like coal, oil, and gas has come under a lot of scrutiny and criticism because of the greenhouse gas that they emit while producing energy. One of the most hazardous ways of producing Hydrogen is by using natural gas. In this process, extreme amounts of carbon dioxide are released. Countries all around the world are pushing for the production of energy using renewable resources. Energy can be easily produced by using non-conventional resources but storing that energy for future purposes poses a challenge as it has to be sent to the electrical grid or stored in batteries. Hydrogen, in that case, proves to be beneficial as it can be stored for comparatively longer durations and as and when required it can be used for combustion, heat generation, and chemical industry. The focus of this research is to analyse the combination of the wind farm, electrolyser, and hydrogen storage which results in the lowest LCOH and LCOS, and the sensitive factors that affect the LCOH result in the most.

One of the preferred processes for electrolysis is the Polymer Electrolyte Membrane (PEM) process due to its intermittent nature in the balancing of renewable energy sources that makes it alluring for industrial applications. As hydrogen production on offshore as well as onshore is the first part then now storage of the hydrogen produced is the second part of this research. The ways to store hydrogen which are considered in this study are pressurised tanks and underground caverns. By far, storing hydrogen in underground caverns has proven to be advantageous worldwide. In this study, three different scenarios for production and storage of hydrogen are created namely On-Site Centralized Electrolyser with onshore storage, Off-site Electrolyser with onshore storage, and On-Site Distributed Electrolyser with onshore storage. Comparisons are made between these three scenarios based on various parameters like CAPEX, OPEX, increase in cost with distance, and amount of hydrogen produced. By using these parameters, the LCOH is calculated. After developing a base model for all the three scenarios, the scenario with the most cost-effective and practical solution is chosen. This scenario is then subjected to a sensitivity analysis wherein various parameters under consideration are subject to varying load conditions. Sensitivity analysis is necessary to be performed as the supply and production of hydrogen will never be uniform at all times and the chosen system must be able to handle different kinds of situations such as more losses in conversion or transmission, the electrolyser efficiency, and the amount of water needed to ensure optimal performance throughout its commissioned life. Results are drawn from this analysis and a conclusion regarding the best-case scenario for the hydrogen-producing offshore wind farm has been made.

Preface

Fossil fuels when burned emit carbon dioxide and other high-level greenhouse gases which trap heat in our atmosphere, making them a primary contributor to climate change and global warming, one of the devastating challenges of the present era. Besides this, excessive dependence of world's dependence on fossil fuels as an energy resource has resulted in the depletion of fossil fuels as it is a non-renewable resource. Therefore, alternative sources of energy have become very important and relevant to today's world to address the issue of continuous rise in demand for energy resources such as the sun and wind that can never be exhausted and therefore are called renewable. They emit fewer emissions and are available locally. Their use can, to a large extent, reduce chemical, radioactive, and thermal pollution.

In the present study offshore wind farm is selected as a source of renewable energy and its electricity is converted to Hydrogen. After studying various scenarios, a way to store hydrogen is studied in order to fulfil the demand for a renewable resource. The present project is undertaken under the Utrecht University of the Netherland.

1. Introduction

The temperature of Earth is increasing for the last few decades, and the only way to reduce this is by reducing greenhouse gas (GHG) emissions. The main contributors to GHG emissions are energy production and transportation (Olivier & Peters, 2020). In 2018 total GHG emissions were 55.6 Gt CO_2 equivalent in which the 2.0% (1.0 Gt CO_2 equivalent) increase was mainly due to carbon dioxide (CO_2) emissions from fossil-fuel combustion and industrial non-combustion processes (Olivier & Peters, 2020). The fossil CO_2 emissions have the highest source of GHG emissions, which accounts for 72%. Currently, GHG emissions are about 63.35% higher than in 1990 and 43% higher than in 2000 (IEA, 2020a). Since 1880 an average rate of 0.07°C (0.13°F) per decade the temperature is increased combining the ocean and land temperature but since 1981 the average rate of increase is more than twice (0.18°C / 0.32°F) (Dahlman, LuAnn Lindsey, 2021). The mean annual temperature for Europe from 2009 to 2018 was 1.6 °C to 1.7 °C which is higher than the pre-industrial period and this is more than the increase in global average temperature (Morice et al., 2012). In order to reach the carbon-neutral goal, it aims to reduce emissions by 49% by 2030 and by 95% by 2050 compared with 1990 levels (IEA, 2020b). This can be achieved by using renewable energy sources. Electricity generation by renewable sources is expected to be 33% by 2025, surpassing the coal-fired generation (International Energy Agency, 2020). The Dutch government aims to have at least 27% of energy through sustainable sources by 2030 (The National Government. For the Netherlands, 2020).

Among all the renewable energy sources, the generation of energy from offshore wind farms represents one of the most attractive alternatives. The reason for this is the offshore wind turbines have a better exposure to winds which contributes to having fewer irregularities as compared to onshore wind turbines, assuring a good performance on the energy production. Other advantages like the flexibility of locations compared to an onshore wind farm, and fewer concerns of noise, but at the same time drawbacks to be taken into account are installation and maintenance. (Snyder & Kaiser, 2009).

Nonetheless, the transmission of energy from wind farms that are more than 100 km away requires an expensive setup (using HVDC rather than AC transmission) to avoid transportation losses (Peters et al., 2020). One way to compensate for such losses and optimize the energy production for OWF is by combining them with hydrogen production. This is one of the challenges faced by the EU's Energy System that is managing variable renewables, meeting customer preferences, and achieving deep decarbonization, and for which hydrogen is considered the best option (Fuel Cells and Hydrogen JU, 2019). Hydrogen has the potential to cover up the energy deficit as it can be stored for a long time and can be easily connected to more distant demand centres (European; Commission n.d.). In November 2018, the EU published a vision for climate-neutrality, and in that the share of hydrogen in Europe's energy mix is projected to grow to 13-14% by 2050 (Energy Intelligence Group., 2020). By 2050 hydrogen can provide up to 24% of total energy demand in the EU (Fuel Cells and Hydrogen JU, 2019). Hydrogen has numerous uses across various sectors like industry, transport, power, and construction sectors. At the same time, it can also be used as feedstock, fuel, or as an energy carrier and for storage as well (European; Commission n.d.).

Currently, around 96% of the hydrogen worldwide is produced by fossil resources such as natural gas, oil, and coal (Evers, 2010), this is not considered clean energy because there are GHG emissions during the production of hydrogen. Around 70 to 100 million tonnes of CO_2 has been released annually in the EU notably from natural gas or coal (European; Commission n.d.). As hydrogen is used in many sectors like transport, heat generation, and chemical industries, hydrogen is going to be one of the main energy carriers so it is necessary to produce it on a large scale (Dincer, 2012). As it is necessary to reach the climate goal the production of hydrogen should be clean, by using renewable energy sources. Water electrolysis is one of the most basic methods of hydrogen production and it needs only water and electricity in this case electricity is obtained from the OWF. Another reason for focusing on hydrogen is that it does not emit CO_2 when used for electricity production (European; Commission n.d.). According to the global investments, market analysis list conducted between November 2019 and March 2020; around 3.2GW to 8.2GW of electrolysers will be installed by 2030 among which 57% will be in Europe, and also 81 companies have joined the International Hydrogen Council till date (European; Commission n.d.).

Back in the 1970s, The United States coined the term "hydrogen economy". This describes an approach that solves the famous problems associated with the use of fossil fuels by using hydrogen as a secondary energy resource, an energy carrier, and a storage medium (Crotogino, 2016). Hydrogen plays a crucial role in overcoming the energy deficit created by fluctuating wind and solar power as it can be stored for longer periods.

When the hydrogen is produced from wind energy, not only do the production rates fluctuate due to uncertain weather conditions but also the requirement for the demand fluctuates. The gap that has been created due to variation in supply and demand can be resolved using hydrogen storage. The hydrogen produced can be stored in two ways: above the ground in sealed tanks or underground salt caverns. Both of these storage options have their corresponding advantages and disadvantages. The use of energy storage technologies has many benefits in the heat and chemical industries, load shifting, and bulk power management (Wang et al., 2018). By using storage technologies to store energy during overproduction and reusing during its shortage reduces the need for flexible fossil-based energy generation and thus indirectly reduces carbon emission (Gabrielli et al., 2020).

Numerous projects have been implemented on offshore hydrogen production within the Netherlands, Norway (Lindtvedt, 2019), etc. Some of these projects are shown in Table 1:

Table 1: Offshore hydrogen projects

Name of the Company	Name of the project	Country
TNO	HY3	The Netherlands, Germany
Neptune, TNO, Nexstep, Total	PosHYdon	The Netherlands
Orsted	SeaH2Land	The Netherlands
Orsted	H2RES	Denmark
RWE Renewables	AquaVentus	Germany
TechnipFMC	Deep Purple	Norway

This research aims to fill this gap by examining the hydrogen production and storage, together with offshore wind farms in the Dutch area of the North Sea (the Exclusive Economic Zone). This research also analyses and highlights the overall cost and energy production.

This research is an attempt to answer the subsequent question:

"What is the technical and economic potential of hydrogen production and storage from a typical offshore wind farm in the Netherlands part of North Sea by 2030?"

The project will compare three alternative scenarios:

1. Centralized onsite electrolyser platform i.e., with offshore wind energy facility and onshore storage
2. Offsite electrolyser platform i.e., onshore production and storage of hydrogen onshore.
3. Integrated electrolyser i.e., with each offshore wind turbine and onshore storage (no electric cables).

To answer the main research questions, the subsequent sub-questions are identified.

- Which technology of electrolyser and storage is suitable for the scenarios?
- What equipment's would be necessary to place on the offshore platform for hydrogen production?
- What is the overall cost of the three alternative scenarios compared with each other and the most effective choice according to LCOH?
- Finding the parameters that greatly affect the sensitivity analysis for LCOH.

The first two sub-questions are answered by analysing existing literature whereas the last two sub-questions are answered in a quantitative manner, by building a model in Excel.

2. Theoretical Background

2.1. Offshore Wind farm

There are different applications to generate energy from wind, this research focuses on offshore wind farms because of two reasons; one that there is currently high development of technologies in wind farms, second in the Netherlands, the number of offshore wind farms is increasing drastically as it can be seen from Figure 1. In 2020, out of 13.9 TWh total wind energy produced, 5TWh is produced from offshore (CBS, 2021). In order to match the supply and demand as stated in the introduction, hydrogen will be produced from an offshore wind farm in the North Sea that can be stored for a longer duration of time.

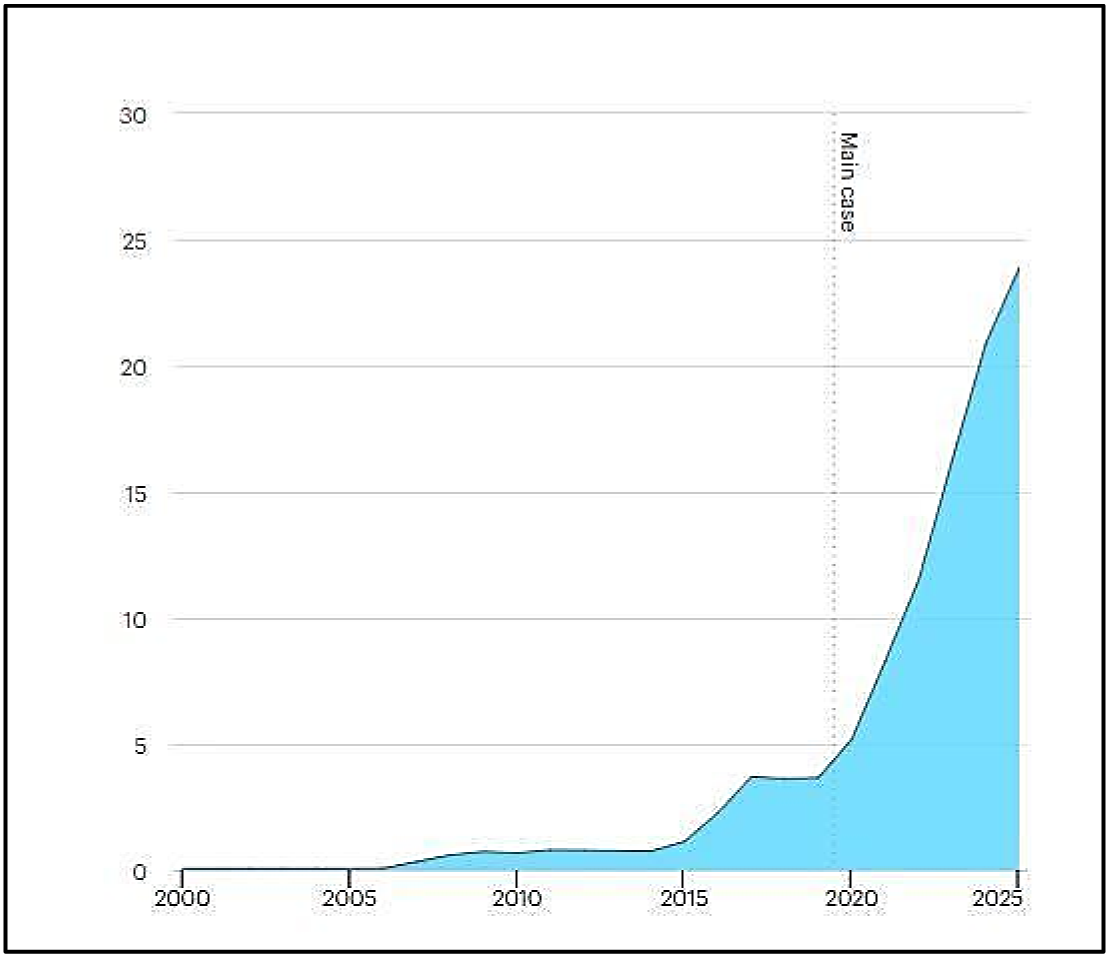


Figure 1: Offshore Wind generation (Unit Terawatt-hr) (IEA, 2020b)

The OWF which is selected is Hollandse Kust (Zuid) sites III and IV. The reason for this selection is that it is newly constructed. There are 74 wind turbines of Siemens Gamesa 10 MW-193 DD, specifications are explained in Table 2. The total installed capacity of this wind farm is 740 MW (Netherland Enterprise Agency, 2020). The size of these wind farms, sites 3 and 4, are 71.4 km^2 and 74.6 km^2 respectively (Netherlands Enterprise Agency, 2014). The basic function of a wind turbine in a wind farm is that it generates electricity when the rotor of a turbine rotates with the help of wind. The rotor spins when there is a difference in air pressure across the two sides of the blade. The rotor is internally connected to the generator. This spinning motion of the rotor makes the copper coil in the generator rotate between the magnets which makes current flow in the conductor. The rotor is connected to the generator. This conversion of the air force to the rotation of a generator creates electricity (Energy gov, 2018)

Table 2: Specification of 10 MW wind turbine (Wind Turbine Models, n.d.)

Parameters	Value	Unit
Diameter	193	m
Swept area	29255.29619	m^2
Cut-in wind speed	3	m/s
Nominal wind speed	11.5	m/s
Cut-out wind speed	25	m/s
Nominal output	10	MW

2.2. Electrolysis

The majority of the hydrogen that is produced and used in the world is acquired from fossil fuels that emit carbon dioxide. Carbon dioxide should be trapped and prevented from emitting into the atmosphere. A sustainable system that produces hydrogen using low carbon energy sources such as renewable and nuclear should be prioritised (Wiley, 2019). The process of electrolysis which is carried out using these energies produces only hydrogen and oxygen. It is certainly sustainable for the future but it is not yet economically effective (Wiley, 2019).

As discussed above the hydrogen can be produced in many ways and currently, it is mainly produced by Natural gas, and this hydrogen from natural gas, can be more cost-effective, but it has high carbon dioxide emission and has limited availability. As now it is required to reduce emission this is not a good way of producing hydrogen. In Figure 2 the different sources of hydrogen production from the year 2015 are shown.

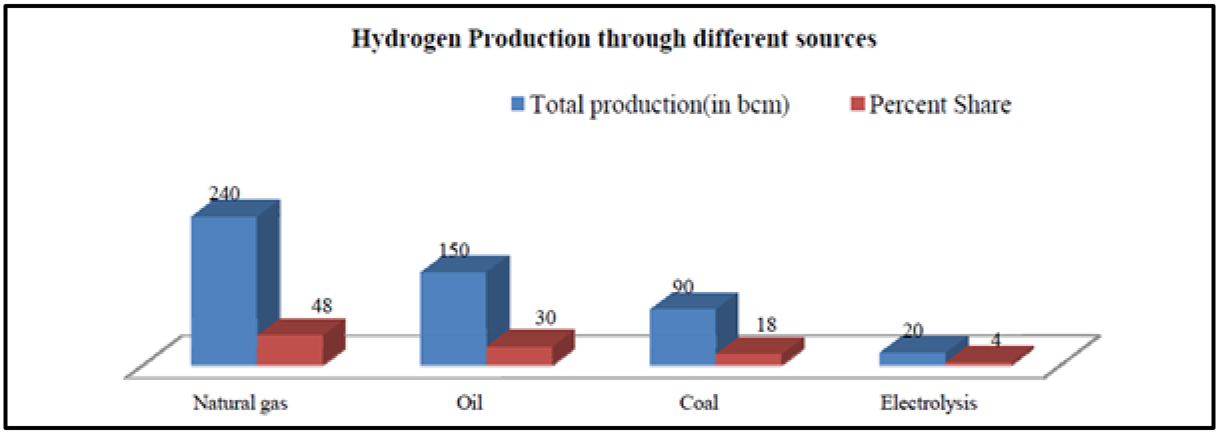
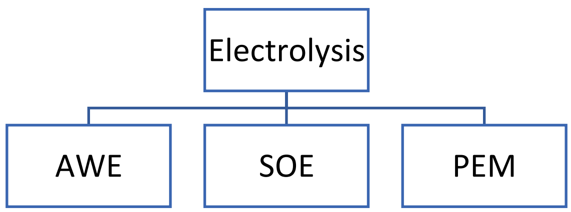


Figure 2: Hydrogen Production (Rashid et al., 2015)

From Figure 2, it is clear that there is a very little percentage of hydrogen production by electrolysis, so there is a good scope for this method and also it is a pollution-free method for the production of 'Green' hydrogen. There are 3 types of electrolysis methods as shown in the flow chart.



Electrolysis uses only water and electricity as input and it is from a DC power source, all the 3 types are explained below.

1) Alkaline Water Electrolysis (AWE)

In this process, when electricity is supplied to the cathode, two molecules of alkaline solution (KOH/NaOH) are reduced to one molecule of hydrogen (H_2) and two hydroxyl ions (OH^-). The H_2 that is deposited at the surface of the cathode gets recombined with H_2 gas and the hydroxyl ions (OH^-) at the anode are released to ½ molecule of oxygen (O_2) and one molecule of water (H_2O). AWE operates in the temperatures range of 343K and 363K (Rashid et al., 2015). The concentration of the KOH/NaOH aqueous solution is generally in the range of 20% to 30% (Shiva Kumar & Himabindu, 2019). There are certain disadvantages of this process. There are limited current densities (lower than 400 mA/cm^2), low operating pressure, and low energy efficiency.

2) Solid Oxide Electrolysis (SOE)

This process of electrolysis generally operates at high pressure and high temperatures 500˚C – 850˚C conditions and it makes use of steam which is derived from water. Typically, this process uses the O_2^- conductors which are made from nickel/yttria-stabilized zirconia. The advantages as well as the major attributes of the SOE technology are higher operating temperature and low-temperature electrolysis. Lack of stability and degradation are the principal disadvantages of the SOE technology (Shiva Kumar & Himabindu, 2019).

3) Polymer Electrolyte Membrane (PEM)

PEM essentially comprises of an electrolyser stack that uses electricity to obtain hydrogen and oxygen after splitting water into its constituent elements. A good cooling system and additional heat removal steps are needed to remove the residual heat from the process. The oxygen which is split from water is taken out from the electrolyte and the water used for this process is passed through an air cooler before returning it to the stack. Oxygen is vented to the atmosphere safely after the separation is completed (Peters et al., 2020). The disadvantages of alkaline water electrolysis are overcome by PEM water electrolysis. The electrolyte in the form of solid poly-sulfonated membranes is used in this process. Lower gas permeability, high proton conductivity, lower thickness, and high-pressure operations are some of the numerous advantages of proton exchange membranes. PEM water electrolysis is a convenient technique to convert renewable energy to the hydrogen of high purity. PEM has various advantages some of which are compact design, high current density, higher efficiency, quick response, small carbon footprint, ability to operate under low temperature, capable of producing pure hydrogen, and also produces oxygen as a by-product (Shiva Kumar & Himabindu, 2019). The simplicity in the balancing of the PEM electrolysis plant makes it appealing for industrial applications. The disadvantage of PEM is that it becomes expensive as compared to AWE because, at the cathode, high chemical activity of noble metals such as Pt/Pd as the Hydrogen Evolution Reaction (HER) is noted, and at the anode, IrO_2/RuO_2 as the Oxygen Evolution Reaction (OER) (Shiva Kumar & Himabindu, 2019). As PEM has a compact design, offshore installation of this process is quite easy. At the same time, being a comparatively cleaner process, its impact on the environment and aquatic wildlife is minimal. This process can be operated at a lower temperature which in turn will help to keep the temperature of water in the ocean under control by not affecting it drastically.

The chemical equation of water electrolysis is written as:

$$H_2O_{(liquid)} + \text{Energy} = H_{2(g)} + \tfrac{1}{2}\, O_{2(g)}$$

According to (van der Burg, 2020) Table 3 shows a comparison of the technologies from several viewpoints.

Table 3: Comparison of three Technologies

	1st	2nd	3rd
Maturity	AEC	PEM	SOE
Efficiency	SOE	AEC	PEM
Stack lifetime	AEC	PEM	SOE
Simplicity	PEM	AEC	SOE
Response time	PEM	AEC	SOE
Safety	PEM/AEC		SOE
Footprint	PEM	AEC	SOE
CAPEX	AEC	PEM	SOE
Peak Power	PEM	AEC	-
Min. Power	PEM	AEC	-

As seen from the table above, using PEM results in the best results for the majority of the parameters considered. Hence, with an overall analysis, the PEM electrolyser is selected for further study, and for offshore as well as onshore PEM electrolyser was used.

The technical parameters which are considered are the stack capacity, efficiency, and hydrogen production per energy input. The economical parameters which are considered are the OPEX (operational expenditures) and CAPEX (capital expenditures) of the electrolysers.

2.3. Hydrogen Storage

The major difference between the electricity grid and the gas grid is that in the case of the electricity grid, the production and consumption have to match at all times because the electricity grid does not have a storage capacity of its own while this is not the case in gas grid. Few of the energy systems that are mainly based upon renewable energy resources are highly dependent on fluctuating wind and solar power. The resulting power production is essentially dependant on time and the weather. It does not correlate with the power consumption which fluctuates daily and weekly (Crotogino, 2016). The major advantage of storing hydrogen is that in large amounts it can be stored for a longer period than electricity. Due to this, hydrogen production on an industrial scale can play an important part in the energy transition (The Florida Solar Energy Center (FSEC), 2014). Hydrogen is one of the most reactive chemical elements. It gets easily diffused into cracks. Small masses of hydrogen will occupy large volumes under normal conditions. Hence, this must be compressed or liquefied (Wiley, 2019).

Hydrogen can be stored in three ways (The Florida Solar Energy Center (FSEC), 2014):

- As a compressed gas in high-pressure tanks/ underground storage (Energy Systems Research Unit, n.d.).

Hydrogen can be compressed and stored in high-pressure tanks in the form of gas. Energy in the form of electricity is required to drive the compressor which is used to compress the gas. This compressed gas occupies a large space and directly results in a reduction in energy density. The compression vessel needs to be tested on regular basis to ensure that there is no leakage in the vessel. The capital cost associated with technology adoption involves the cost needed for building the pressure vessel and purchasing the compressor. Post-installation, the only cost incurred is the electricity consumption cost which is required to drive the compressor.

- As a liquid in tanks (Energy Systems Research Unit, n.d.)

Hydrogen can be stored in the form of liquid at extremely lower temperatures i.e., at 20K or -253˚C. To safely store this liquid hydrogen, cryogenic tanks are needed. The initial process involves compressing the hydrogen gas using a compressor. Almost 30% of the energy that the liquid hydrogen stores within, is lost in the cooling and compression as the process consumes a high amount of electricity. The storage tanks need to be internally reinforced and insulated to withstand the pressure of the stored liquid hydrogen and also to ensure the maintenance of lower temperatures. Cryogenic storage tanks can store a volume of hydrogen almost 1000 times more as compared to compressed gas storage and this is achieved through the liquefaction of the hydrogen. Combining the total energy needed to convert hydrogen into its liquid state and the sustenance of the temperature in cryogenic tanks eventually results in a very expensive process as compared to any other methods of hydrogen storage. Storing hydrogen in compressed gas form is cheaper as compared to this process, this is a disadvantage. Research is being carried out to focus on the development of improved composite tank materials and improved liquefaction methods.

- As a solid by either absorbing or reacting with metals or chemical compounds or storing in an alternative chemical form. Different forms in which hydrogen can be stored are:

A. Chemically stored hydrogen (Energy Systems Research Unit, n.d.)

Hydrogen can be easily found in its elemental form in various chemical compounds and can be considered as a method of hydrogen storage. Combination of hydrogen with other elements during a chemical reaction can create a stable compound and can act as a medium to store the hydrogen. A secondary reaction takes place which aims to release the stored hydrogen and this released hydrogen is then stored in fuel cells. Ammonia cracking, partial oxidation, and methanol cracking are some of the chemical reactions which are used to release hydrogen. The major benefit of using this technique is that it eliminates the need of using a storage unit as hydrogen can be produced by this process on demand. This process has small-scale applications, as it is still under development.

B. Carbon Nanotubes (Energy Systems Research Unit, n.d.)

Carbon nanotubes are capable of storing hydrogen in their microscopic pores and also within their tube structure. They possess the ability to release the stored hydrogen upon application of heating the nanotubes. The main advantage of using a carbon nanotube to store hydrogen is that it can store almost 4.2-65% hydrogen as compared to its own weight. Carbon nanotube has the highest hydrogen storing capacity as compared to a percentage of its own weight. This process of hydrogen storage is still under the research and development phase with an expectation that it will be fully operational in the next 15 years approx.

C. Glass microspheres (Energy Systems Research Unit, n.d.)

In this process, hydrogen is safely stored in a different configuration of tiny glass spheres. The process of absorbing hydrogen in the glass spheres is very complex and the first step is to heat up the glass spheres to increase the permeability of the thin sphere walls. The second step is to immerse the heated glass spheres in high-pressure hydrogen gas. The hydrogen gas is then absorbed into these spheres because of the increased wall permeability. The spheres are then cooled which results in trapping the hydrogen gas. A subsequent temperature increase will let the trapped hydrogen to get released from these glass spheres. The advantage of this process is that it is extremely safe, prevents any contamination of the hydrogen gas, and performs satisfactorily under a high-pressure environment which proves that this process has a high potential in the future.

This is still in the research phase as the commercialization of the process at this point of time is considered to be extremely expensive because of the complex steps involved in the process.

Considering all three possibilities discussed above, compressed gas has a realistic possibility for hydrogen storage on a large scale and a salt cavern can be used if the hydrogen needs to be stored for a longer duration. As the processes discussed above are still under the R&D phase, this study is proposed considering the hydrogen storage in salt caverns and tanks. Storage of hydrogen as a gas typically requires high-pressure tanks (300–700 bar tank pressure) (Energy Systems Research Unit, n.d.). Normally, stainless steel is used as the material to build the hydrogen storage tanks which are expected to withstand a pressure of at least 200 bar but are over-designed to withstand almost double the required pressure to avoid any unexpected accidents as hydrogen is an explosive gas and the above-ground tanks are in direct contact with external factors. So, underground storage attracts a good amount of attention because it is one of the most reliable technologies that can be used to store an extensive amount of energy over long periods of time (Tichler & Bauer, 2016). In Europe, the storage potential considering offshore and onshore for salt caverns constitutes about 84.8 PWh_{H2}, among this 42% belongs to Germany later followed by the Netherlands and the United Kingdom, with 10.4 and 9.0 PWh_{H2} (Caglayan et al., 2020), respectively. Salt caverns are a good option because they have operational safety, low cost, and sealing capacity. The capacity of salt caverns facility to accommodate hydrogen ranges for approximately 50,000-150,000m^3. Salt caverns also need to withstand an internal pressure of around 200 bar.

The EU-funded a project named HyUnder in 2013 to assess the geological storage of hydrogen in:

- Salt caverns
- Depleted oil and gas fields
- Aquifers
- Conventionally mined rock caverns

Currently, salt caverns are used for the short-term storage of natural gas. For hydrogen storage salt caverns is the only technology which is a proven form of geological hydrogen storage, which has several sites operational in the US and UK (Stone et al., 2009). The salt caverns need to be insulated correctly to prevent any seepage of the gas from the cavern. To provide proper insulation, construction in and around the salt cavern is needed to be done.

Figure 3 shows the distribution of salt caverns in Europe. It can be seen that the Netherlands has all types of salt caverns and they are about 212.5 TWh, 350 TWh, and 9437.5 TWh for onshore (within 50km of shore), onshore, and offshore respectively. From Figure 4 the distribution of salt caverns near the Netherlands is seen.

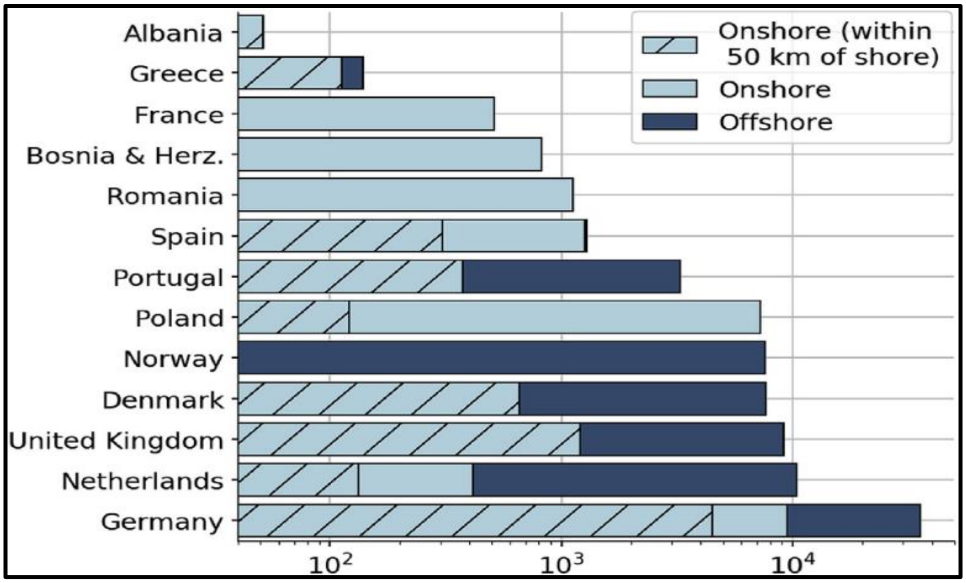


Figure 3: Total Cavern Storage Capacity (Unit TWh) (Caglayan et al., 2020))

Besides salt caverns, old offshore gas fields are also a good option for storing hydrogen underground. But no relevant data was found for offshore gas fields and digging underground salt caverns offshore so not considered.

The main criteria for storage primarily involve the compression of gas up to maximum pressure. The withdrawal is permitted down to a minimum permissible pressure. The capacity available in storage operations between these maximum and minimum pressures is called the working gas. Whereas the volume which cannot be extracted below the minimum pressure is called the cushion gas. Hence, the standard for salt cavern is a working-gas-to-cushion-gas capacity ratio. This ratio is generally 2/1 for caverns and 1/1 for reservoirs (Crotogino, 2016). This ratio is used to find the total required volume of the salt cavern.

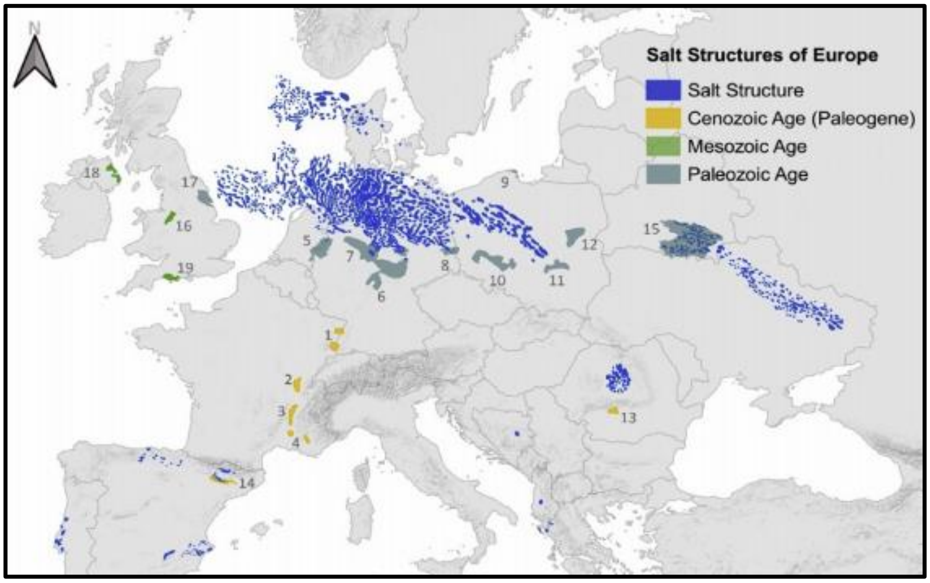


Figure 4: Distribution of Salt Cavern (Caglayan et al., 2020))

Advantages of salt cavern over other types of storage (Caglayan et al., 2020):

- Minimal effects on the environment
- Low investment costs compared to on surface gas storage
- Relatively large storage capacities because of large geometrical volumes and high pressures
- Large sealing capacity of rock salt
- Low cushion gas requirement
- Inert nature of salt structure prevents contamination of hydrogen
- Flexible operation with high injection rate and withdrawal cycles
- Fewer surface footprints
- Good level of safety and security against external influences as well as direct contact with salt cavern because of its deep location under the surface (Crotogino, 2016)

2.4. Platform and Transport

A centralized platform can be constructed in the sea for placing the electrolyser which can be then connected to the wind farm grid. This platform should have an HVAC unit installed that will provide processed air to electrical and living rooms. HVAC will also be used to supply air to the electrolyser system. This results in the prevention of corrosive air entering the chamber and maintaining temperature under control (Peters et al., 2020). The platform can be constructed at a specific distance from shore in order to have a less total cost, the effect of change in the distance on LCOH is shown in section 4.2. And to transport the hydrogen produced on this platform to the storage facility new pipelines will be constructed.

The gas that is most frequently transported by pipelines is natural gas. In France, the estimated total length of pipes in the distribution is 165,000 km. In comparison to this, Europe and the United States have a hydrogen network that has only 2400 km of hydrogen distribution. This demonstrates that the transport of hydrogen is very much feasible even though its associated cost is approximately 50% higher than that of transporting natural gas (Wiley, 2019). As hydrogen has a low volumetric mass (0.0899 kg/Nm^3) which means it has high volatilization of the medium. This can be unfavourable for the existing pipeline material because of seal issues and steel embrittlement. If using existing pipelines, then the following factors should be considered and required changes need to be done.

- The energy density of Hydrogen is 120 MJ/kg and of natural gas is 53.6MJ/kg. Thus Hydrogen density is almost 2.5 times of natural gas which makes it more economical to use as a source of energy.
- Steel pipes and fittings: Due to low-quality Steel (which is suitable for natural gas), embrittlement can occur due to the presence of Hydrogen. The material should be changed by using the right materials (Adam & Engelshove, 2020, Wiley, 2019).

In order to prevent embrittlement and have a stable long life, ‘dedicated’ new hydrogen pipelines are used which are made of stainless or austenitic steels. So, for the analysis in this study, the assumption has been made that new ‘dedicated’ pipelines are used for the transport of hydrogen.

3. Methodology

This section describes the suggested methodology to answer the above-mentioned research questions. Various input parameters and different scenarios of the techno-economic analysis are presented in this study. This section comprises of four steps: 1) Qualitative research 2) Quantitative assessment 3) Process design construction and 4) Analysis of results and recommendations.

The first phase involves a literature review in order to describe the offshore wind sector in the Netherlands and build a database. This will serve as input for the next steps. The comparison will be done by selecting the technical and economic indicators that will be obtained using a model (Excel). Finally, the techno-economic indicators such as Levelized cost, NPV (Net Present Value), PBP (Pay Back Period) results will be analysed in order to formulate concrete recommendations for the application in the Netherlands. Each step of the methodology is further explained in the following subsections.

3.1. Qualitative Research

The fundamental step of this project consists of gathering data regarding the OWF in the Netherlands for a specific plant and various technologies are gathered later; like for Electrolyser, Storage, Transport, etc. While researching the technologies, data gathered is of wind speed profile, turbine power profile, cost, and efficiencies. The data is collected through a literature review. During the proposal phase, the researcher observed that there are few published papers on this matter that provide the relevant data and the majority of them are confidential. The sources for the literature review are collected mainly from scientific papers which are found on Scopus or Google Scholar, reports from research institutions (e.g., NREL), reports from governmental organizations (e.g., PBL), and websites.

Discussion with concerned stakeholders was held with HYGRO Company and TNO to understand the current situation statement. The inferences were then used for a better understanding of the technologies, provided that they were integrated with OWF.

The information collected regarding the technologies has been saved in an Excel spreadsheet. This has been used in the next steps of the methodology to define input data for the modelling stage.

3.2. Quantitative Assessment

This assessment contains comparisons made between the cost data obtained from the literature and the calculations done for each scenario. A detailed explanation of different scenarios has been mentioned in section 3.3.

3.2.1.Input Parameters

The methodology used for the techno-economic model has been explained in this section. Also, to gain further insight into the economic and technical parameters of the research, the quantified data has been presented. A description of the various scenarios under consideration along with the input values used for the calculations has been explained below.

In this research, some modified assumptions were made for simplification. The technical and economic values were based on presumed values in the year 2030. This year has been particularly selected because many companies have estimated their aim for the year 2030. Also, expecting that there will be large-scale hydrogen production development by then (North Sea Energy, 2020). Below is the list of the different cost components used for analysis.

Components CAPEX and OPEX considered for the techno-economic model were:

- CAPEX and OPEX of Electrolyser
- CAPEX and OPEX of Desalination Unit
- CAPEX and OPEX of Compressor
- CAPEX and OPEX of Construction an Offshore Platform/Onshore Base
- CAPEX and OPEX of Pipelines/Electric Cables
- CAPEX and OPEX of Storage (Salt Caverns/Tanks)

3.2.1.1. Technical Parameters

The technical analysis conducted comprises of parameters i.e., amount of hydrogen produced, storage of hydrogen capacity & pressure, and functional parameters of all the equipment's used. Technical performance indicators related to the process, which helped to calculate various CAPEX and OPEX components are mentioned in Table 4. The input data required for the technical assessment is also specified below, based on the most common parameters used for hydrogen production and storage and has been discussed in the literatures (Jepma & Van Schot, 2017; The Scottish Government, 2020) (Van Schot & Jepma, 2020).

The following parameter were selected for the calculations.

Table 4: Technical performance indicator

Indicator	Definition
Wind farm capacity	The total farm capacity (MW)
Percentage Curtailed	Percentage of energy not used due to maintenance or electrolyser capacity limitation
Electrolyser/wind farm capacity ratio	The optimal ratio of electrolyser/wind farm capacity is considered for maximum hydrogen production and minimum LCOH.
Water required	Amount of water required by desalination unit per hour at maximum capacity (L/hr)
Electrolyser specification	Electrolyser capacity, efficiency, and operating conditions of electrolyser
Losses	Only losses related to conversion and transmission of electricity has been considered
Hydrogen produced	Amount of hydrogen produced by electrolyser (kg)
Distance	Distance of platform from shore (km)
Pressure	Pressure for optimal storage considering the discharge cycles (bar)
Storage Capacity for Hydrogen	The total volume of hydrogen stored, at an appropriate pressure (m3)

Table 5: Technical assessment of wind farm

Parameters	Unit	Value	References
Farm Capacity	MW	740	(Lensink et al., 2018)
Electrolyser/wind capacity ratio	%	80%	Calculated refer Appendix B: Hydrogen production calculation
Energy Produced by wind farm	MWh/year	2662432	Refer Equation 1

- **Energy Produced by wind farm:**

Various factors are important for the assessment of the performance of a wind turbine. Most important is the wind speed because it has an exponent of 3. This shows that even a small increase in wind speed leads to a large increase in power.

Equation 1

$$Energy\ Produced\ by\ wind\ farm = \sum_{0}^{n=8760} \left[\left(0.5 * \rho_{air} * A_s * {V_{W_n}}^{3}\right) * \eta_{T_n} * N_t\right]$$

Where ρ_{air} is the density of air at working temperature and pressure in kg/m^3
A_s is Swept Area of Turbine blade in m^2
V_{W_n} is the velocity of wind in the nth hour in m/s
η_{T_n} is Efficiency of the turbine at V_{W_n}
N_t is the Number of Turbine in OWF
Refer to Appendix B: Hydrogen production calculation, for detailed calculation.

- **Electricity supplied to electrolyser:**

Equation 2

$$Electricity\ supplied\ to\ electrolyser = Energy\ Produced\ by\ wind\ farm *\ Losses$$

The electricity that is produced by the wind farm is then supplied to the electrolysers for the electrolysis process after losses, losses are explained below.

Electrolyser capacity:

It is the optimal capacity of electrolyser for a particular OWF and is calculated using Equation 3.

Equation 3

$$Electrolyser\ capacity = Farm\ capacity * E/W\ ratio$$

One stack of electrolyser is of 3 MW. So, the total electrolyser capacity output should be in multiple of 3 (Thomas, 2019). The selection of electrolyser capacity is a crucial factor because the three major parameters, i.e., hydrogen production, electricity curtailed by OWF, and capital cost are equally dependent on electrolyser capacity. Decreasing one parameter will increase another parameter and vice-versa. So, the optimal selection of electrolyser capacity balancing this parameter should be considered.

- **Electrolyser/wind capacity ratio (E/W ratio):**

Electrolyser/wind capacity ratio (E/W ratio) signifies the electrolyser capacity required for a particular OWF capacity which ultimately provides the maximum hydrogen production at the minimum LCOH.

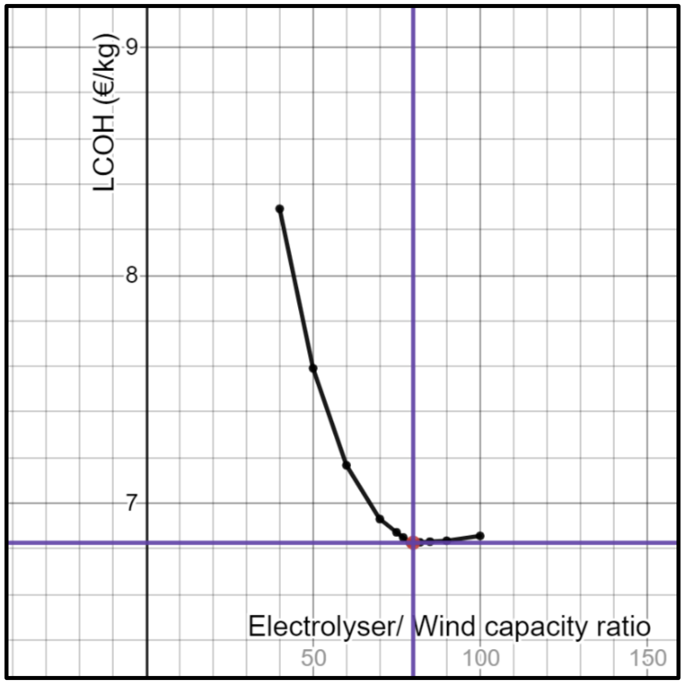


Figure 5: LCOH vs Electrolyser/Wind capacity ratio

Figure 5 indicates that LCOH is lowest at 80%.

If the E/W ratio is 100%, the electrolysers will be in an idle state for 49.3% in a year and no energy will be curtailed, as it is idle for most of the time this will unnecessarily increase the initial investment cost which results in the increase of LCOH. If the E/W ratio is 50%, the electrolysers will be in an idle state for 15.4% in a year but 30.3% of energy will be curtailed. So, the minimum LCOH is at 80% of the E/W ratio as seen from Figure 5. At 80% E/W ratio idle state for 33.6% in a year and 8.7 % of energy will be curtailed. This is the optimal possible E/W ratio.

Refer to Appendix B: Hydrogen production calculation for detailed calculation.

- **Water required for electrolysis at full load capacity:**

The total amount of water required for determining the number of desalination units is calculated by Equation 4.

Equation 4

$$Water\ required = Electrolyser\ capacity * Water\ required\ per\ MW\ at\ full\ load$$

CAPEX of the desalination unit is calculated by multiplying the number of desalination units required with the per-unit cost.

Refer to Appendix B: Hydrogen production calculation, for detailed calculation on the desalination unit.

- **Electrolyser specification**

Electrolyser has an efficiency of 80% with a lifetime of 10 years and an outlet pressure of 30 bar, for specification of electrolyser refer Table 6.

Table 6: Electrolyser specification

Data	Unit	Value	References
The capacity of a single Stack of Electrolyser	MW	3	(Thomas, 2019)
Electrolyser Capacity	MW installed	591	Refer Equation 3
Hydrogen Production per unit electrical power	kg/kWh	0.02	(The Scottish Government, 2020)
Lifetime	year	10	(van Leeuwen & Zauner, 2018)

- **Losses:**

The losses considered are due to conversion & transmission of electricity and due to losses of hydrogen in pipelines.

In order to transport electricity from the OWF to the shore via the transmission cables, two AC-DC conversion steps to be followed:

1. Firstly, the DC power is generated in the wind turbine, and then converted to AC, for feeding the array cables (Papadopoulos et al., 2015).
2. Then the AC power is converted to DC again to fed an onshore electrolyser, as the electrolyser works on DC power input.

Transmission losses are 3% (Cory, 1996)
AC-DC losses are 4% (Energy central, 2013)

For Scenario 1- Centralized Electrolyser; as there is no requirement for transmission of electricity to onshore base because hydrogen is transported only conversion losses are considered and transmission losses in pipelines are negligible.
For Scenario 2- Onshore Electrolyser; the electricity has to be transported to an onshore base for hydrogen production therefore transmission losses and conversion losses both are considered.
For Scenario 3- Integrated Electrolyser; as electrolyser is integrated, both losses do not occur (conversion and transmission) because the DC power is directly supplied to electrolyser in a wind turbine.
Hydrogen when transported through pipes, transmission losses are negligible when compared to

the average losses of e-grid transport (AC/DC and voltage conversion and heat losses) (Koornneef, 2020).

- **Hydrogen production:**

The revenue factor in this case is the amount of hydrogen produced and it is calculated using Equation 5.

Equation 5

$$Hydrogen\,produced = \frac{Energy\ supplied\ to\ electrolyser * Effiency\ of\ electrolyser}{Specific\ energy\ of\ hydrogen}$$

The specific energy of hydrogen is 0.04 MWh/kg[1].

- **Compressor:**

As the hydrogen needs to be transported through pipelines, a pressure difference is needed. This pressure difference is created by the compressor during the injection phase of gas inside the pipeline on the platform and while storing the hydrogen in a salt cavern or tanks. During transport, additional losses are expected to come into the picture, and hence, an intermediate compressor might be required to compensate for the effect of these additional losses. For simplicity, these losses are not considered.

Compressors with different capacity needs to be installed according to preferred scenarios. The selection of these compressors depends on the pressure difference (pipelines and storage) and the flow rate of the hydrogen from the electrolyser. The cost of compressors varies according to the prerequisites of the installed system. Ideally, the flow rate factor affects the value, but for comparing the results the flow rate is kept constant. Equation 6 calculates the input power of the compressor (André et al., 2014).

Equation 6

$$P = Q * \frac{ZTR}{M_{H_2} * \eta} * \frac{\gamma}{\gamma - 1} * \left[\left(\frac{P_{out}}{P_{in}} \right)^{\frac{\gamma-1}{N\gamma}} - 1 \right]$$

Where Q is the flow rate in kg/s,
Z is the hydrogen compressibility factor: 1.
T is the temperature at the inlet of the compressor: 317 K
R is the ideal gas constant: 8.314 J K-1 mol-1
M_{H_2} is the molecular mass of hydrogen: 2.016 g mol-1
η is the compressor efficiency: 75%
γ is the diatomic constant factor: 1.4

[1] Source: (Bruce Lin thesis, n.d.) (http://brucelin.ca/scooters/thumb.html)

P_{in} the inlet pressure of the compressor in the bar
P_{out} the outlet pressure of the compressor in the bar
P is the power in KW

For calculation of flow rate refer to Appendix B: Hydrogen production calculation
The energy consumption of a compressor is given by Equation 7 (André et al., 2014).

Equation 7

$$\text{Energy consumption of a compressor (MWh)} = \frac{Hours/year}{DTE} * P$$

where P is the power of the compressor in MW
DTE is the Driver Thermal Efficiency 90%.
This input energy needed to drive the compressor is provided when produced energy is curtailed from electrolyser and in a similar way, energy is provided to all other equipment's on the platform. At the particular hour when there is no energy curtailed the energy can be used from energy supplied to electrolyser. As energy required to drive the compressor is much lesser overall energy generated so, loss of hydrogen production will be negligible.

CAPEX of the compressor is given by Equation 8 (André et al., 2014).

Equation 8

$$CAPEX = 2545 * P$$

Where P is power in KW.
OPEX of the compressor is 3% CAPEX of the compressor (André et al., 2014).

- **Pipeline:**

Pipelines are used to transport the hydrogen gas from the production facility to the storage facility. The inlet pressure in the pipeline is 30 bar, which is the output from electrolyser. The outlet pressure when hydrogen gas reaches the shore is considered as 75 bar[2].

Equation 9

$$CAPEX\ (\$^{3}/\text{km}) = 418869 + 762.8 * D + 2.306 * D^2$$

Where D is the diameter in mm
Note that when pressure ranges between 30 to 75 bar, the pipe diameter is evaluated as 372 mm. Whereas when pressure raises beyond 75 bar and lies below 120 bar, the pipe diameter is evaluated

[2] Outlet pressure from pipeline at shore is considered by evaluating an average of inlet and outlet pressure at electrolyser and salt cavern respectively. Outlet pressure from electrolyser is 30 bar and inlet pressure at storage facility is 120 bar. For storage pressure refer storage section 3.3.5.
[3] Dollar exchange is 0.83 on 19th April 2021.

as 277 mm. For further calculations, a higher value of pipe diameter, i.e., 372 mm (15 inches) is considered, as this will maintain consistency while considering the hydrogen production scenario and storage scenario.

For calculation of Diameter refer to Appendix B: Hydrogen production calculation.

- **Storage capacity for hydrogen**

As mentioned in the theoretical background, two types of storages are considered.

Pressure and temperature are calculated by considering various plants in the salt cavern. The amount of hydrogen stored inside a salt cavern depends on the hydrogen production between every discharge cycle. This is explained further in section 3.3.5.

3.2.1.2. Economical Parameters

During the economic assessment, capital budgeting methods were used to estimate the hydrogen production capacity; and storage throughout the investment period of 20 years considering each scenario and then compared their economic performance using the indicators shown in Table 7

Table 7: Economic Performance Indicator

Indicator	**Definition**
Total costs	Summation of capital cost, operating & maintenance cost.
Pay Back Period (PBP)	The PBP of the project is formulated as the initial investment cost divided by the average annual net cash flow (Blok & Nieuwlaar, 2016), i.e., the time required to recover the initial investment cost.
Net Present Value (NPV)	NPV is calculated by considering the difference between the present value of cash inflow and the present value of cash outflow for the decided period of time, i.e., 20 years. (Blok & Nieuwlaar, 2016)
Internal Rate of Return (IRR)	The internal rate of return is the discount rate at which the net present value equals zero (Blok & Nieuwlaar, 2016)

The **PBP** is calculated using Equation 10.

Equation 10

$$PBP = \frac{Total\ CAPEX}{Hydrogen\ Selling\ Cost - Total\ OPEX}$$

The required cost of the equipment's is calculated using Equation 11. The final value is obtained by considering the scaling factor as unity. The initial costs that are scaled up, are identified using the literatures.

Equation 11

$$C = C_{ref}\left(\frac{P}{P_{ref}}\right)^{R}$$

Where C is the cost of the equipments in euros.
C_{ref} is the cost of the equipment's with the capacity P_{ref} in MW.
P is the capacity of the equipments, in MW.
R is the scaling factor for all equipment's.

After calculating all annual cash inflows and outflow for every single scenario, this cash flow is then calculated for the entire lifetime of the project and then discounted to their present value. The lifetime is considered as 20 years. After this NPV is calculated.

NPV is calculated using Equation 12.

Equation 12

$$NPV = \sum_{0}^{n=Lifetime} \frac{Revenue - (\ OPEX)}{(1+r)^{n}} - CAPEX$$

As explained in Table 7, by setting NPV equal to 0 and isolating the discount rate, **IRR** is calculated using Equation 13.

Equation 13

$$IRR\ when\ NPV = 0 = \sum_{0}^{n=Lifetime} \frac{Revenue - (OPEX)}{(1+IRR)^{n}} - CAPEX$$

3.2.2. Output Parameters

In this section, the output parameters from the techno-economic model, i.e., Levelized cost of hydrogen (LCOH) and Levelized cost of storage (LCOS) for all three scenarios are identified. The LCOH is defined as the ratio of total investment (CAPEX) and maintenance (OPEX) costs divided by the actual amount of hydrogen produced. These costs are shown in section 4.1. The formula used for calculating the LCOH is Equation 14 (Viktorsson et al., 2017), and the unit is €/kg.

Equation 14

$$LCOH = \frac{Sum\ of\ CAPEX * CRF + Sum\ of\ OPEX}{Hydrogen\ produced}$$

The capital recovery factor (CRF) is calculated using Equation 15 (Viktorsson et al., 2017).

Equation 15

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

Where i = discount rate
n = years of operation.

The discount rate is assumed as 5%.

The formula used for calculating the LCOS is the same as LCOH, and the unit is €/kg. For CRF calculations in LCOH, years of operation is considered as 10 years and the discount rate is considered as 5%. For CRF calculations in LCOS, years of operation is considered as 30 years and the discount rate is considered as 10% (van Leeuwen & Zauner, 2018). For evaluating LCOH, the amount of hydrogen produced is considered whereas for evaluating LCOS, the amount of hydrogen stored is considered.

3.3. Process Design Construction

Three alternative scenarios have been described below and the results are evaluated. These results will help to make a sound decision while selecting the viable scenario. The alternative scenarios will be used as a base for modelling steps in an Excel spreadsheet. These three scenarios are described starting from OWF and up to the onshore hydrogen storage phase in this study. Finally, the input parameters for each of the three scenarios are explained.

3.3.1.Existing (Reference) Scenario

Figure 6 Resembles Existing Scenario: This scenario consists of an offshore wind farm in the North Sea that is directly connected to the onshore grid by electricity cables. Considering this as a base scenario, three different scenarios have been described in this section. Numerous changes have been made with respect to the placement of some of the mandatory systems with an aim to make the overall system cost-effective and to integrate it as much as possible to reduce the LCOH costs.

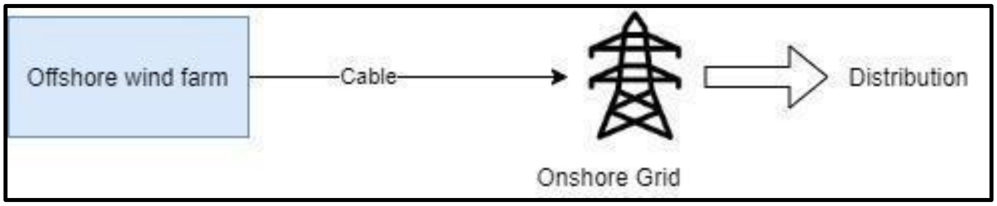


Figure 6: Existing Scenario

3.3.2. On-Site Centralized Electrolyser with Onshore Storage

Figure 7 resembles Scenario 1- Centralized Electrolyser: This scenario focuses on offshore hydrogen production technique on the platform, where the electricity from the offshore wind farm is brought by electric cables to a centralized electrolyser which is placed on a platform built on the sea. The electric cable is shown in red. The sea water is pumped into a desalination system shown in blue. Post sea water treatment in the desalination unit, the water is demineralized and then fed to the electrolyser shown in blue. The electrolyser then uses electricity to split water into oxygen and hydrogen. The hydrogen gas is then transported to onshore storage salt cavern/tanks through pipelines, shown in green and the oxygen is either simultaneously emitted to the atmosphere or is captured, shown in pink.

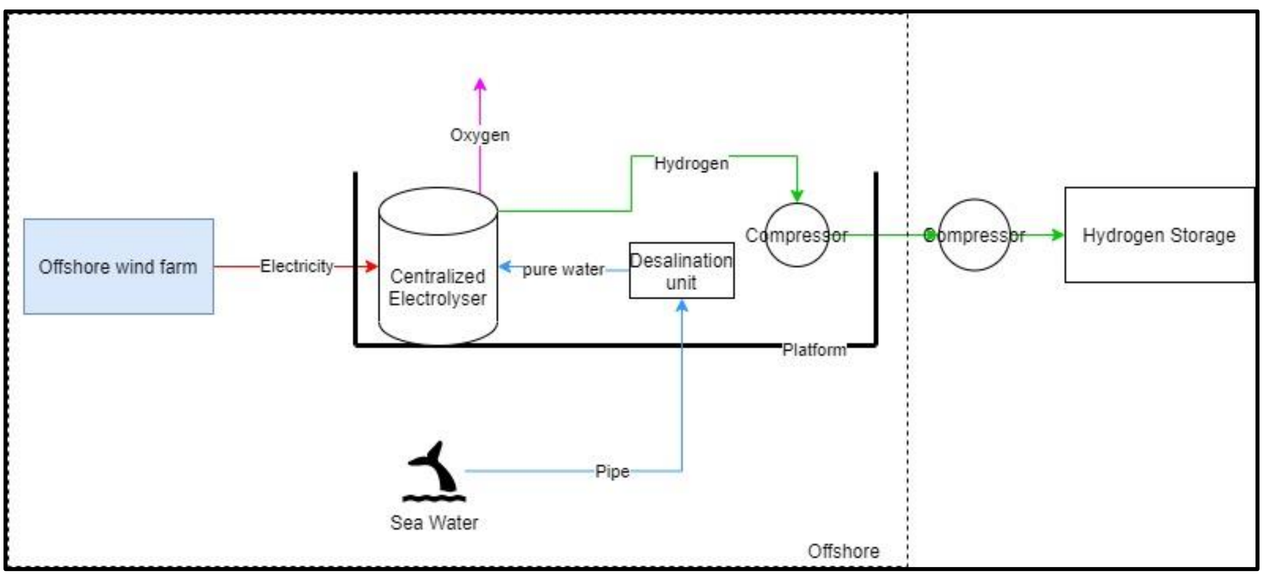


Figure 7: Scenario 1- Centralized Electrolyser

Table 8: Parameters for Scenario 1-Centralized Electrolyser

Parameters	**Unit**	**Value**
Number of Electrolyser Stacks	-	197
Electrolyser capacity actual	MW	591
Number of desalination units (2000L/hr)	-	81
Water needed per hour at max cap	(L/hr)	160062
Transportation Type	Pipeline	

In this scenario, the OWF supplies electricity to an electrolyser, note that only AC-DC conversion losses are considered. Also, as the platform is close to the wind farm grid, the transmission losses are considered negligible. Table 8 shows the number of electrolyser stacks and desalination units required. Note that the number of electrolyser stacks is nearly kept constant for all three scenarios.

3.3.3.Off-Site Electrolyser with Onshore Storage

Figure 8 resembles Scenario 2- Onshore Electrolyser. This scenario focuses on the onshore hydrogen production technique, where the electricity is brought to the onshore grid by cables and then it is fed to the electrolyser as shown in red. Hydrogen which is produced is then transported by pipelines to onshore storage in salt caverns/tanks as shown in green. The oxygen produced can be emitted/captured and used for other purposes, shown in pink. In this scenario, as such, there is no need for an additional desalination unit as the electrolyser is placed onshore and also that the Netherlands' water supply grid is directly used as feedwater for the electrolyser.

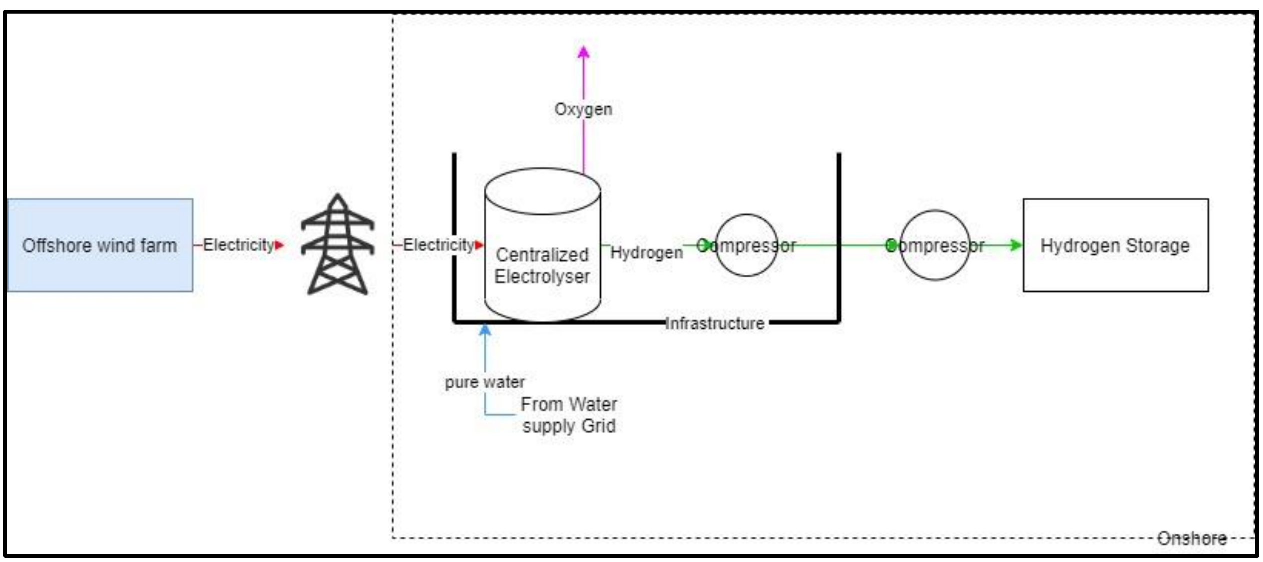


Figure 8: Scenario 2- Onshore Electrolyser

Table 9: Parameters for scenario 2-Onshore Electrolyser

Parameters	Unit	Value
Number of Electrolyser Stacks	-	197
Electrolyser capacity actual	MW	591
Number of desalination units (2000L/hr)	-	0
Water needed at full load per year	m^3/year	679250
Transportation type	Electric Cable	

In this scenario, the electricity supplied by a wind farm to electrolyser carries both the AC-DC conversion losses and the transmission losses. Table 9 shows the number of electrolyser stacks that are considered in this scenario.

3.3.4. On-Site Distributed Electrolyser with Storage

Figure 9 resembles Scenario 3- Integrated Electrolyser. This is similar to scenario 1-Centralized Electrolyser: The only difference between the scenarios is that the electrolyser is not centralized but evenly distributed and installed in every single wind turbine i.e., integrated wind turbine. The output delivered by the wind turbine is the only hydrogen. Figure 7 shows that electricity within the wind turbine is directly taken to the electrolyser in a single step and without the intervention of AC-DC conversion, as shown using a big thick dotted rectangle. This hydrogen from different wind turbines is then transported through pipelines and stored onshore in salt cavern/tanks, as shown in green. Oxygen produced can be emitted/captured, shown in pink.

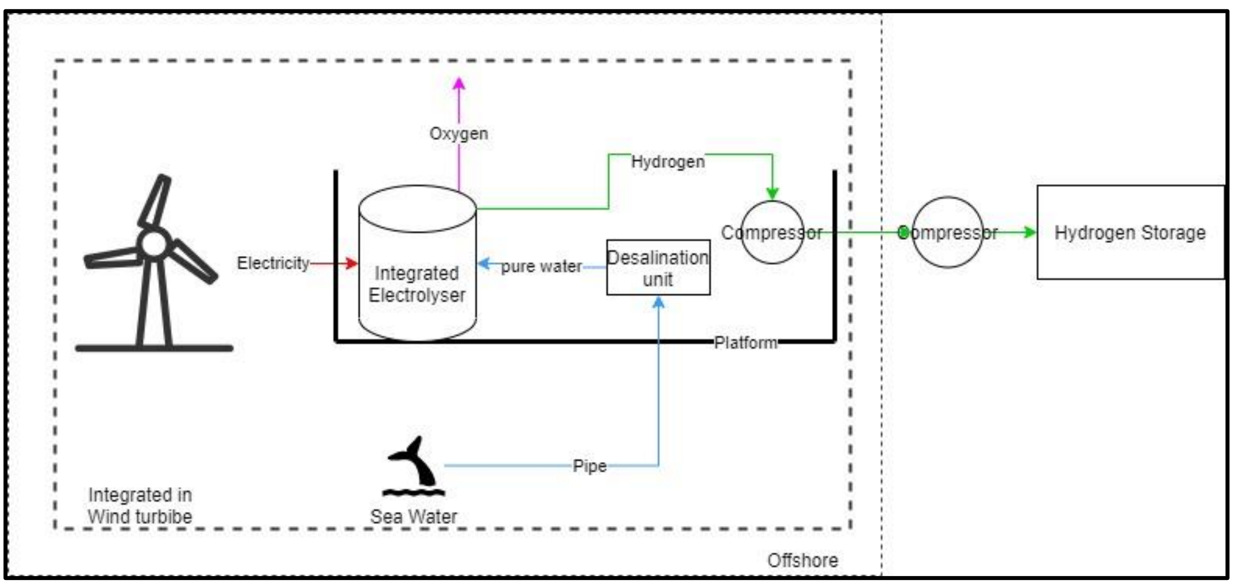


Figure 9: Scenario 3- Integrated Electrolyser

Table 10: Parameters for scenario 3- Integrated Electrolyser

Parameters (Per Turbine)	Unit	Value
Electrolyser capacity	MW	8
Number of Electrolyser Stacks	-	5
Number of desalination units (2000L/hr)	-	2
Transportation Type	Pipeline	

Adding further, the electrolyser is integrated inside the wind turbine leading to a short distance transmission and hence there is no need for the AC-DC conversion. Table 10 shows the number of electrolyser stacks and the number of desalination units required for scenario 3- Integrated Electrolyser smaller electrolyser capacity is used. The values shown in the same table are considered for a single wind turbine. Later, during the final analysis, as the wind farm consists of 74 wind turbines, the obtained value of all parameters is then multiplied by 74. Also, in this scenario, the desalination unit, and the compressor are fitted inside every single wind turbine. While calculating the CAPEX and OPEX, the parameter values are considered to be the same as scenario 1-Centralized Electrolyser. The reason being the final value that scenario 1-Centralized Electrolyser displays is the same when compared with the final value displayed by scenario 3- Integrated Electrolyser considering the work output of each of the 74 wind turbines. Practically, this assumption is not appropriate considering the cost factor, because the installation cost of 74 wind turbines along with their equipment's will be extreme. Hence, the installation costs are not being considered in this study, as these installation costs are directly involved in the manufacturing process. Even if installation cost is considered scenario 3- Integrated Electrolyser will be the best option because the difference between CAPEX of scenario 1-Centralized Electrolyser and scenario 3- Integrated Electrolyser is very huge.

In this scenario, all the wind turbines are connected to each other through pipelines and the total distance of the pipeline is calculated by considering it an approximately square-shaped wind farm having land of area 74.6 km^2.

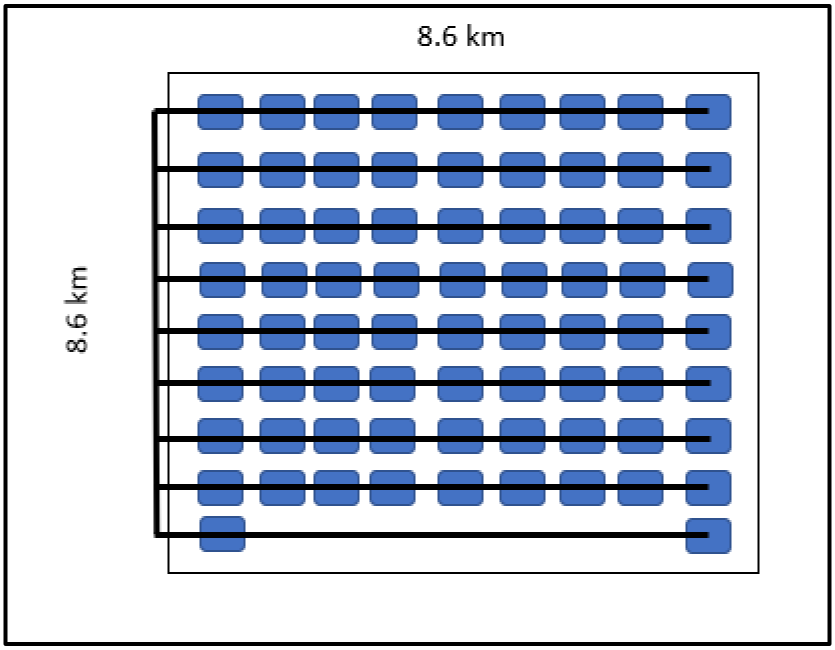


Figure 10: Layout of OWT

$Distance\ of\ Pipelines\ connected\ throughout\ the\ OWF\ (km) = (8.6 * 9) + 8.6 \ = \ 86$ km. Apart from this, the distance of OWF from shore is added separately.

3.3.5. Storage

Two types of storage are considered as explained above, in section 2.3. i.e., salt caverns and tanks.

The hydrogen which is produced can be either on an offshore platform or on an onshore base. The complete hydrogen gas produced is then transported to the compressor inside the storage facility through pipelines, followed by the injection of the hydrogen gas into a salt cavern or in compressed tanks. The transportation cost of hydrogen gas from the shore to the storage facility has been already considered in the Levelized cost of storage. In order to find the operating pressure inside the salt cavern, the following calculation is done.

From $P = Z\varrho RT$, the specific volume if calculated, as shown in equation 16

Equation 16

$$Specific\ volume = \frac{[(6.67 * 10^{-4})P + 1]RT}{P * 10^5}$$

where ϱ is density (kg/m^3)
P is Pressure in the bar
R is a specific gas constant in Nm/kgK
T is the temperature in K.

Z is the compressibility factor
Refer to Appendix D: Storage for detailed calculation of specific volume.

By using Equation 16 graph of pressure vs specific volume is plotted keeping the temperature constant, as shown in Figure 11**.**

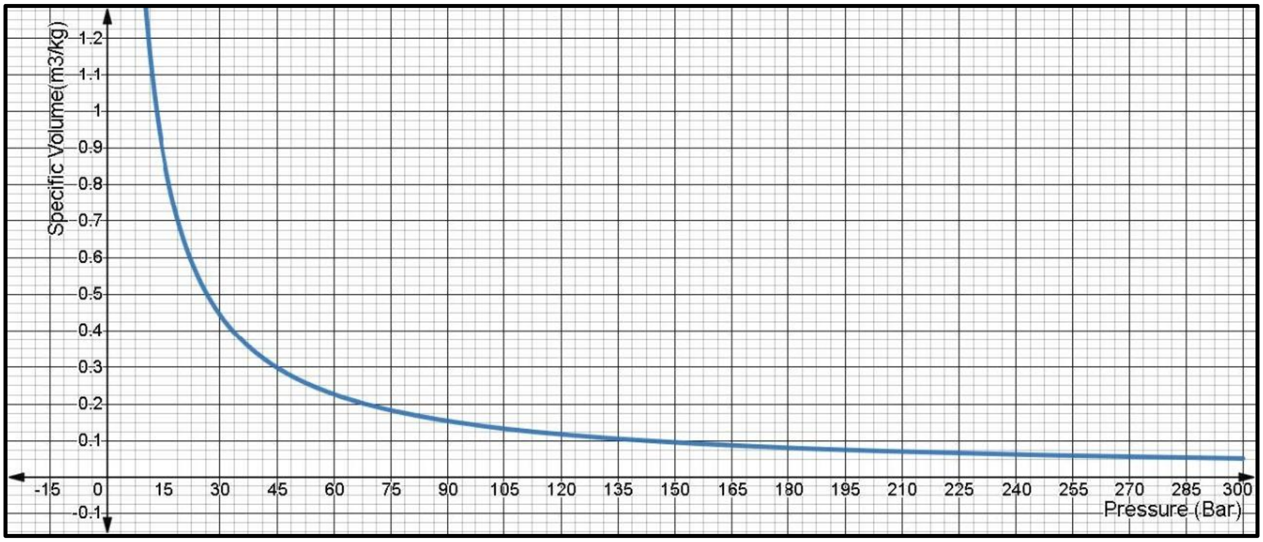


Figure 11: Pressure vs Specific volume

Table 11: Existing 3 scenarios of Salt Cavern (Crotogino, 2016)

Name	Pressure range (bar)	Geometric volume (m^3)
Clemens Dome, Texas	70-137	580000
Moss Bluff, Texas	55-152	566000
Spindletop, Texas	68-202	906000

At high pressures, the maximum amount of hydrogen can be stored. Corresponding values of the required working volume at maximum operating pressure inside the salt cavern are calculated and tabulated in Table 12. Required working volume for hydrogen production on annual basis is calculated by multiplying the specific volumes by the amount of hydrogen produced[4] annually. The specific volumes are obtained from Figure 11, at corresponding pressures.

The frequency of the discharge cycle is considered 14 times in a year, because the LCOS obtained at this pressure and discharge cycle is optimal, as visible from Figure 12. Accordingly, the required

[4] Hydrogen produced in scenario 3- Integrated Electrolyser

working volume per month is calculated by dividing the required total volume for annual hydrogen production by 14.

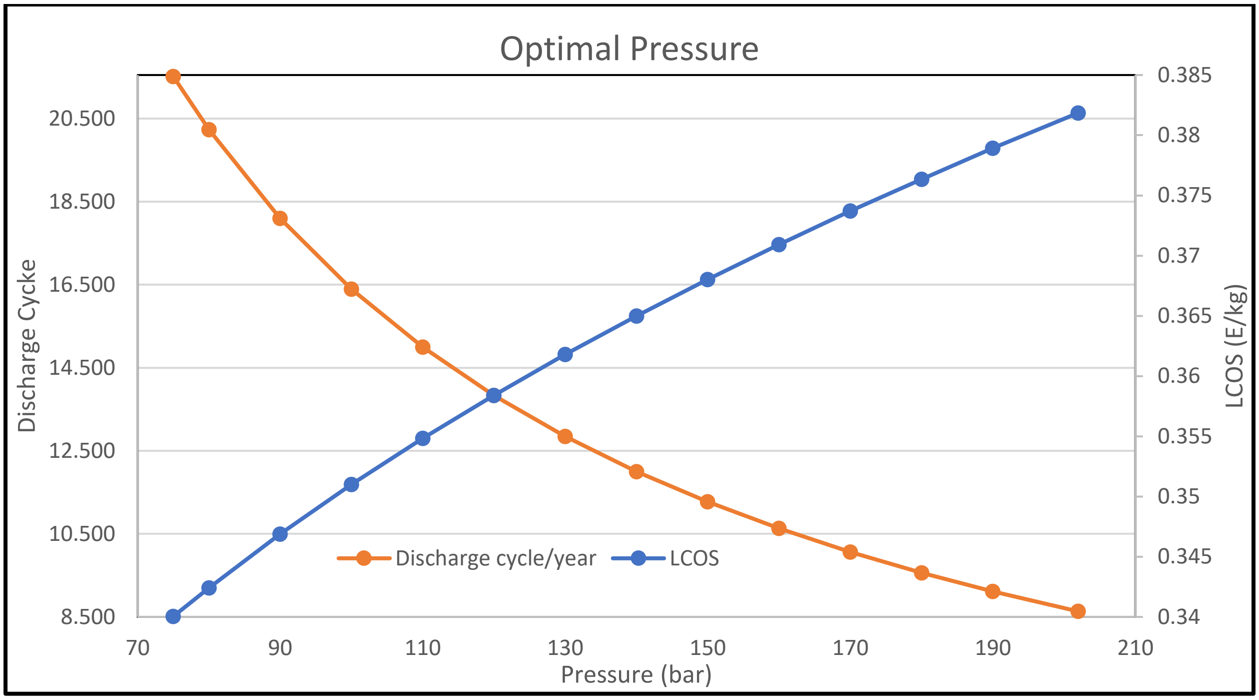


Figure 12: Discharge cycle at Optimal Pressure

Table 12: 3 scenarios of Salt Cavern at various pressure

Density (kg/m^3)	**Specific volume**	**Pressure (bar)**	**Required Working volume (m3)**	**Required Total volume (m^3)**
9.6	0.1041	137	396125.212	792250.423
10.5	0.0947	152	360306.945	720613.890
13.62	0.0734	202	279331.656	558663.313

Table 11 and Table 12 reveals clearly that Spindletop is the only case in which the geometric volume exceeds the required total volume and hence this case is selected. Here, the pressure reduction is possible and the extent to which the pressure can be minimized in this case is 120 bar. For detailed calculation, refer to Appendix D: Storage. Practically, pressure decrease eventually leads to the decrease in CAPEX cost of the compressor, lower losses, and less frequent maintenance.

Table 13: Mining and Compressor cost

Pressure (bar)	**Volume of hydrogen stored (m3)**	**Compressor (M€)**
202	906000	15.24
120	447545	6.69

From Table 13, it is visible that the compressor cost is reduced by 56%. Considerably, using a large salt cavern at 120 bar pressure is economical.

For the CAPEX of the onshore salt cavern, three major costs are considered i.e., mining cost, leaching cost, and well costs. The values are shown in Appendix D: Storage. In order to inject hydrogen gas in the cavern, a compressor is being used working at an operating pressure of 120 bar.

For compressed tanks, only CAPEX of tank and compressor is used because these tanks can be manufactured as per the requirements and can be directly taken to their final destination by trucks or pipelines. The pressure is 300 bar refer to section 2.3.

4. Data Analysis

The methodology section displays, analyses, and presents the extensive results of the techno-economic analysis. The main results out of this quantitative assessment and a concluding statement on the techno-economic potential have been presented and analysed in this section. Also, the cost division of the different scenarios are mentioned in section 3.3.

4.1. Cost Comparison

This section shows the comparison of CAPEX and OPEX values for all three scenarios and the results are briefly explained after analysing this comparison chart. CAPEX is defined as the total cost incurred while setting up a new project. OPEX is defined as the total cost of maintaining and running the whole project post-installation. Note that the lower value of CAPEX and OPEX are always better. This model has only considered the cost drivers for green hydrogen production, and hence it cannot be used for actual business cases.

4.1.1. CAPEX Comparison

Table 14: CAPEX Comparison of Scenarios

CAPEX (Million €) Components/Equipment's	Scenario 1-Centralized Electrolyser	Scenario 2-Onshore Electrolyser	Scenario 3-Integrated Electrolyser
Wind farm	1184	1184	1184.00
Electrolyser	568.23	568.23	569.19
Platform/Infrastructure	177.30	56.97	0.00
Transmission Equipment's	33.47	58.00	91.03
Compressor	13.94	13.94	13.94
Desalination unit/Water Charges	4.96	0.47	9.06
Total	**1981.8**	**1881.61**	**1867.21**

Table 14 shows the comparison of CAPEX for each of the three scenarios. As tabulated, the CAPEX for scenario 1-Centralized Electrolyser is the highest; making it the most expensive scenario among all three scenarios, as it consists of the cost required for both the platform and desalination unit. While in the case of the other two scenarios, only one desalination unit/water charges or platform is present. The CAPEX of scenario 3- Integrated Electrolyser is comparatively cheaper by almost €114 million, making scenario 3- Integrated Electrolyser the most affordable option.

Figure 13 represents the investment for all scenarios. The total investment costs are significantly influenced by the wind farm CAPEX, followed by electrolyser CAPEX.

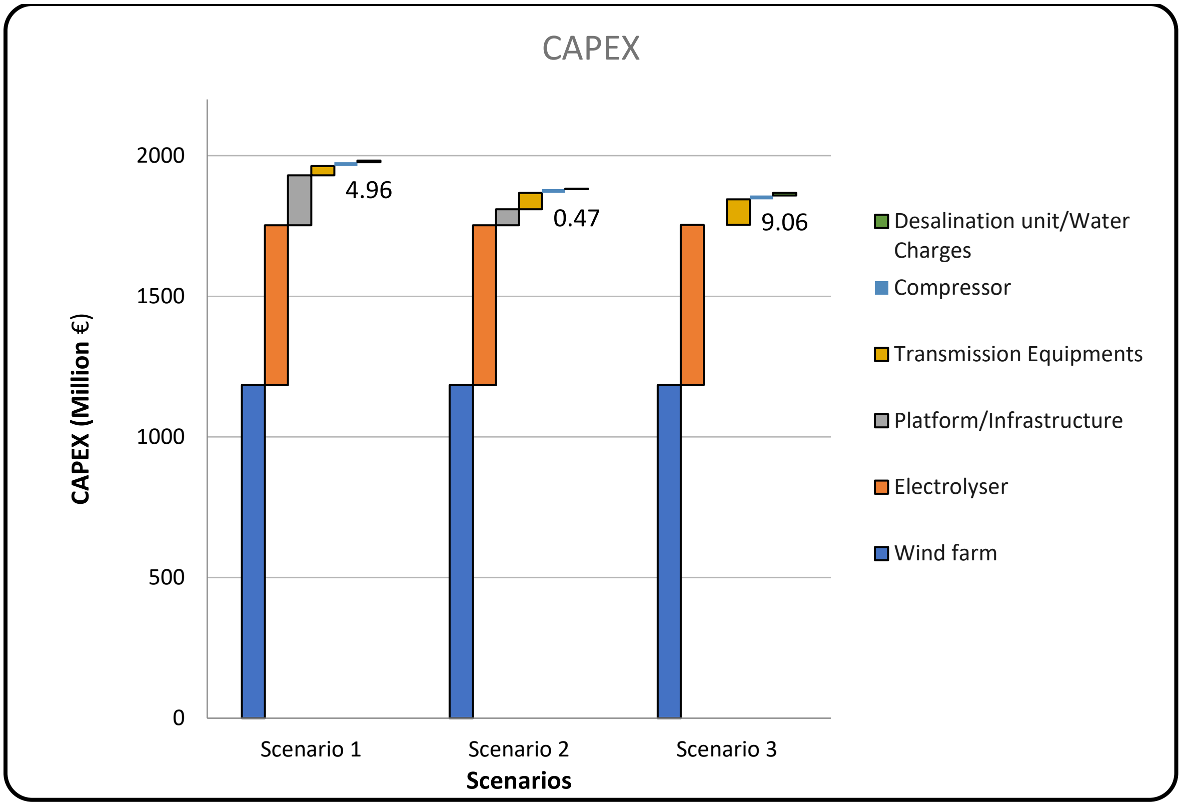


Figure 13: CAPEX of scenarios in Million €

1. While calculating the CAPEX of individual components, the CAPEX values for the wind farm and electrolyser are considered to be the same throughout this study (except for electrolyser in 3- Integrated Electrolyser), as the same components will be used for all three scenarios.
2. The other components that were considered while calculating CAPEX are platform/infrastructure, transmission equipment's required for transfer i.e., pipelines for scenario 1- Centralized Electrolyser and scenario 3- Integrated Electrolyser; and electric cables for scenario 2-Onshore Electrolyser; compressor, and the desalination units/ water charges.
3. Proportionately, the CAPEX cost of platform/infrastructure in scenario 1-Centralized Electrolyser is the highest. In the case of scenario 3- Integrated Electrolyser, the platform/infrastructure cost is not involved because all the components are integrated within the wind turbine.
4. As the flow rate of hydrogen gas from electrolyser is the same, the same compressor has been used in all three scenarios. Hence, the CAPEX value of the compressor for all three scenarios is the same.
5. The CAPEX of transmission equipment's is the lowest for scenario 1-Centralized Electrolyser and highest for 2-Onshore Electrolyser because the cost of cables is higher as compared to pipelines.
6. The CAPEX of desalination unit for scenario 1-Centralized Electrolyser and scenario 3- Integrated Electrolyser; and water charges for scenario 2-Onshore Electrolyser is very low when

compared with the individual total CAPEX cost for each of the scenarios, as visible from the Table 14**.**

4.1.2. OPEX Comparison

Table 15: OPEX Comparison of Scenarios

OPEX (Million €) Components/ Equipment's	Scenario 1- Centralized Electrolyser	Scenario 2- Onshore Electrolyser	Scenario 3- Integrated Electrolyser
Wind farm	30.34	30.34	30.34
Electrolyser	17.05	17.05	17.08
Platform/Infrastructure	8.87	2.85	0.00
Transmission Equipment's	0.02	0.00	1.82
Compressor	0.56	0.56	0.56
Desalination unit/Water Charges	0.12	0.00	0.23
Total	56.95	50.79	50.02

Table 15 shows the comparison of OPEX for each of the three scenarios.

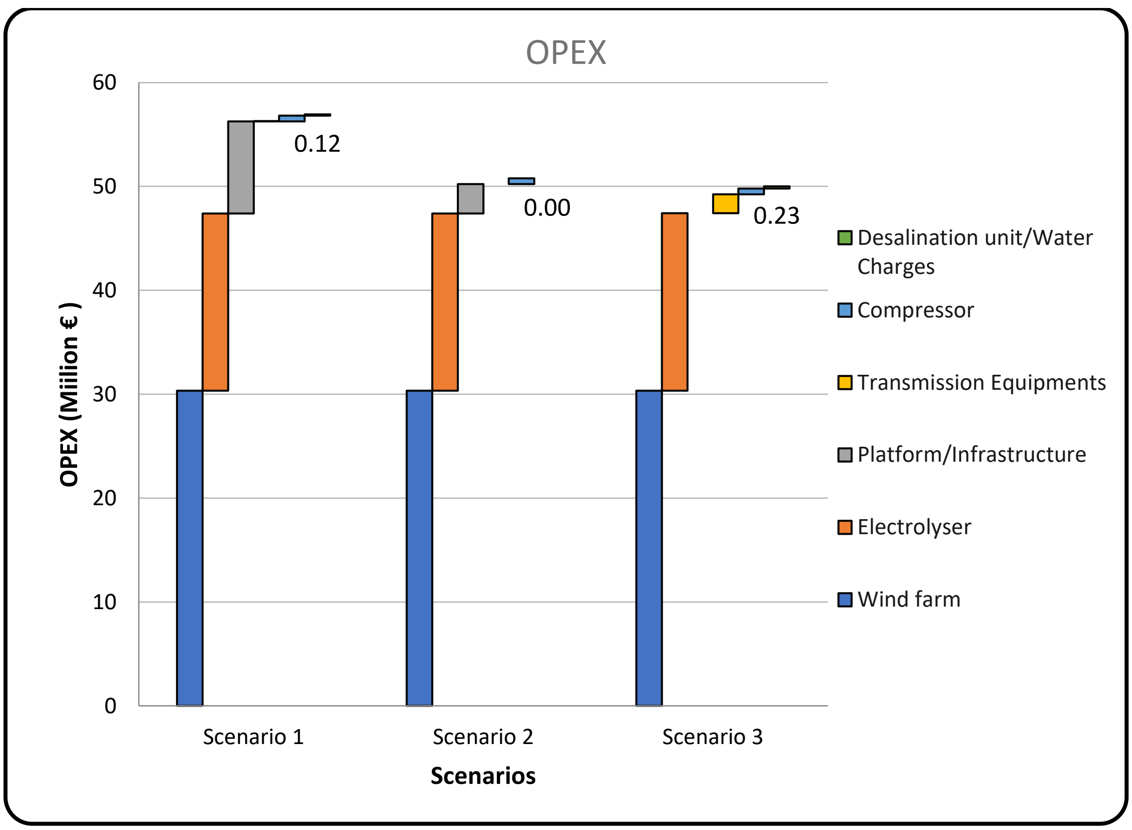


Figure 14: OPEX in value

1. The OPEX value of the wind farm, electrolyser, and compressor is considered to be the same for all three scenarios, as discussed in section 4.2.1.
2. The OPEX value in scenario 2-Onshore Electrolyser for cables needed to transmit electricity is considered to be negligible, as the maintenance activities involved post-cable-laying phase are rare.
3. The OPEX value of platform/infrastructure and equipment's needed for the transfer of hydrogen and electricity is the factor that causes variance in the total OPEX cost of the system. The OPEX value of platform/infrastructure in scenario 1-Centralized Electrolyser is the highest. In the case of scenario 2-Onshore Electrolyser, it is comparatively lower as the infrastructure is built onshore. In scenario 3- Integrated Electrolyser, there is no OPEX cost involved as the equipment's are altogether equipped in the wind turbines.

4.1.3. CAPEX And OPEX Of Hydrogen Storage

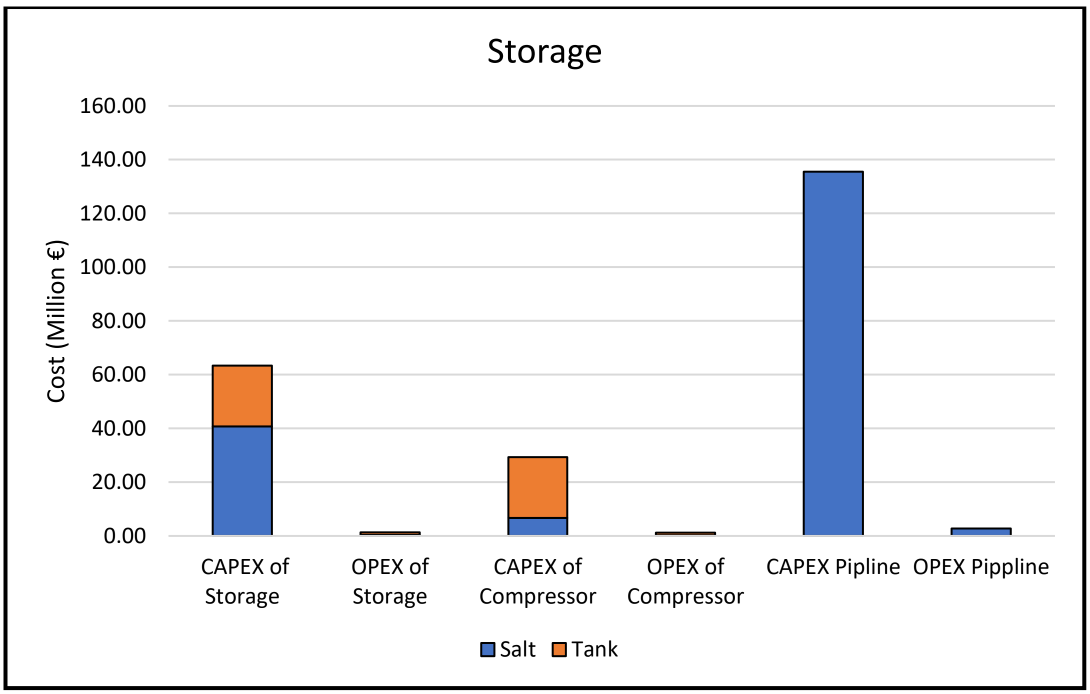


Figure 15: Storage Cost

As explained in section 2.3 the CAPEX cost of the salt cavern involves well cost, mining cost, leaching cost, and cushion gas cost. In salt caverns, the hydrogen is transported from shore to the storage facility using pipelines. In the case of tanks, there is no need for additional transport facilities as the hydrogen gas can be compressed at shore itself and delivered to the required destination by trucks/pipelines. This is the major difference in both the salt cavern and tank storage options available. The compressor cost considering tank storage is higher as compared to the salt cavern storage because the pressure needed in tanks is higher than in salt caverns.

Comparison of Economic Performance indicator for all 3 scenarios:

The economic indicators NPV, IRR, and PBP are shown in Table 16, Table 17, and Table 18 respectively.

Table 16: NPV

Scenario	Hydrogen production (M€)	With Salt Cavern (M€)	With Tanks (M€)
Scenario 1-Centralized Electrolyser	**3127**	**2902**	**2985**
Scenario 2-Onshore Electrolyser	**3071**	**2846**	**2929**
Scenario 3-Integrated Electrolyser	**4145**	**5016**	**5016**

NPV for 3- Integrated Electrolyser is the highest because it produces more hydrogen, and the losses are also very less as compared to the other two scenarios. The same trend is seen in salt caverns and tanks. The major factor contributing to Scenario 3- Integrated Electrolyser is the high value of cash inflows. In between Scenario 1- Centralized Electrolyser and Scenario 2- Onshore Electrolyser, Scenario 2-Onshore Electrolyser has the lowest value because the OPEX of is lowest as compared to other scenarios. Also, there is no requirement for electrical cable maintenance, no desalination unit is needed, and the OPEX value of onshore infrastructure is less as compared to the offshore platform.

Table 17: IRR

Scenario	Hydrogen production	With Salt Cavern	With Tanks
Scenario 1-Centralized Electrolyser	**20%**	**18%**	**19%**
Scenario 2-Onshore Electrolyser	**21%**	**18%**	**19%**
Scenario 3-Integrated Electrolyser	**26%**	**23%**	**24%**

IRR for Scenario 3- Integrated Electrolyser is the highest, as per Table 17. It is important to note that when viewing the IRR, the NPV should be considered every time because the economic performance is mainly dependant on the financial aspects of the project. A successful scenario should have a high IRR with a corresponding high NPV.

Table 18: PBP

Scenario	Hydrogen production (year)	With Salt Cavern (year)	With Tanks (year)
Scenario 1-Centralized Electrolyser	**5**	**6**	**6**
Scenario 2-Onshore Electrolyser	**5**	**6**	**6**
Scenario 3- Integrated Electrolyser	**4**	**5**	**5**

Scenario 3- Integrated Electrolyser is having the lowest PBP because it produces more hydrogen as compared to Scenario 1- Centralized Electrolyser and Scenario 2- Onshore Electrolyser; and also, it has the lowest CAPEX and OPEX values. The number of years remains the same in Scenario 1- Centralized and Scenario 2- Onshore Electrolyser because the amount of hydrogen produced is almost constant. As mentioned in NPV, Scenario 3- Integrated Electrolyser has a high value of cash inflows which contributes towards the low PBP value.

4.2. LCOH And LCOS Comparison

- **LCOH**

  By using Equation 14, LCOH is calculated. The distance is considered as 50 km. CRF is evaluated using Equation 15, where the lifetime is considered as 10 years and the discount rate is considered as 5%.

Table 19: LCOH (€/kg) at 50km

Scenarios	LCOH (€/kg)
Scenario 1-Centralized Electrolyser	6.72
Scenario 2-Onshore Electrolyser	6.57
Scenario 3- Integrated Electrolyser	5.48

From Table 19, it is clear that Scenario 3- Integrated Electrolyser is comparatively the best scenario. As there were no losses, more hydrogen was produced which ultimately led to a lower value of LCOH.

- **LCOS**

  By using Equation 14, LCOS is calculated. CRF is evaluated using Equation 15, where the lifetime is considered as 30 years for the salt cavern and 20 years for the tank. The discount rate is commonly considered as 10%.

Table 20: LCOS (€/kg)

Scenarios	LCOS (€/kg)
Salt Cavern	0.42
Tank	0.33

As per Table 20, the tank has lower values of LCOS, as pipelines were not considered. If the salt cavern storage and the production facilities are located nearby, then salt cavern storage is the best option, the storage facility is considered to be at a distance of 200 km (from Hague to Friesland).

- **LCOH comparison by varying the distances.**

Table 21: LCOH at various distance

LCOH			
Distance (km)	**Scenario 1- Centralized Electrolyser**	**Scenario 2- Onshore Electrolyser**	**Scenario 3- Integrated Electrolyser**
25	6.67	6.49	5.43
50	6.72	6.57	5.48
75	6.76	6.65	5.53
100	6.81	6.74	5.57
150	6.90	6.90	5.67
175	6.95	6.99	5.72
200	7.00	7.07	5.76
225	7.04	7.16	5.81

As observed from Table 21 and Figure 16, it is clear that at a distance close to 150 km, the LCOH values of Scenario 1-Centralized Electrolyser and Scenario 2- Onshore Electrolyser overlap. Scenario 2-Onshore Electrolyser is a better option if the distance between the wind farm and shore is less than 150 km. Beyond 150 km, Scenario 1-Centralized Electrolyser is the better option, because the cost of the pipeline at an increased distance is less compared to the cost of electric cables. LCOH cost of Scenario 3- Integrated Electrolyser is less for all ranges of distances when compared with the other two scenarios. This proves that implementing Scenario 3- Integrated Electrolyser will be beneficial in maintaining lower LCOH costs even if the distance increases.

Note that, in Scenario 1- Centralized Electrolyser and Scenario 2- Onshore Electrolyser, all the wind turbines in the wind farm are connected internally through cables. The cost of laying these cables linearly increases till the distance of 100 km. Once the distance exceeds 100 km, the cost increases rapidly. This is the reason that at large distances, the preference is given to pipelines than electric cables.

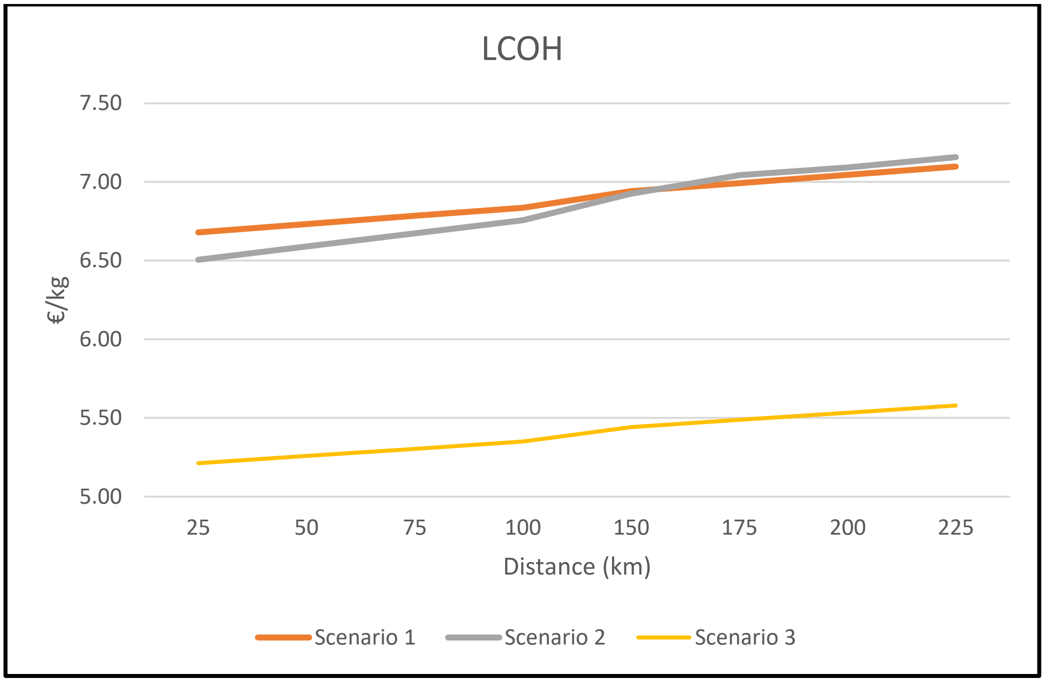


Figure 16: LCOH at various distance

LCOH values of scenarios 1- Centralized Electrolyser and - Onshore Electrolyser are close to each other and are far away from the LCOH values of 3- Integrated Electrolyser. This is because 1- Centralized Electrolyser and 2- Onshore Electrolyser are considered to have wind turbine conversion losses. Scenarios 2-Onshore Electrolyser is also considered to have additional transmission losses. As there are no losses in scenarios 3- Integrated Electrolyser, the resulting LCOH values are lower.

Another reason for the LCOH values of scenarios 1- Centralized Electrolyser and scenarios 2- Onshore Electrolyser to be far away from the LCOH values of 3- Integrated Electrolyser is that in scenarios 1-Centralized Electrolyser, a platform is involved and in scenarios 2-Onshore Electrolyser, onshore infrastructure is involved, whereas, in scenarios 3- Integrated Electrolyser, there is no platform involved as such. Ultimately, the LCOH values are comparatively lower for scenarios 3- Integrated Electrolyser.

4.3. Hydrogen Production

Hydrogen produced from electrolyser depends on the amount of electricity supplied to it.
The amount of electricity supplied to electrolyser on yearly basis is shown in Table 22, inclusive of optimal E/W ratio and losses.

Table 22: Electricity supplied to electrolyser (MWh)

Scenarios	Electricity supplied to electrolyser (MWh)
Scenarios 1-Centralized Electrolyser	2334520.45
Scenarios 2-Onshore Electrolyser	2241139.63
Scenarios 3- Integrated Electrolyser	2662432.61

The electricity supplied to electrolyser in scenarios 2-Onshore Electrolyser is the lowest as compared to the other two scenarios because it consists of both the losses i.e., conversion and transmission losses. In scenarios 3- Integrated Electrolyser, the value is highest because there are no losses as the electrolyser is directly fitted inside the wind turbine.

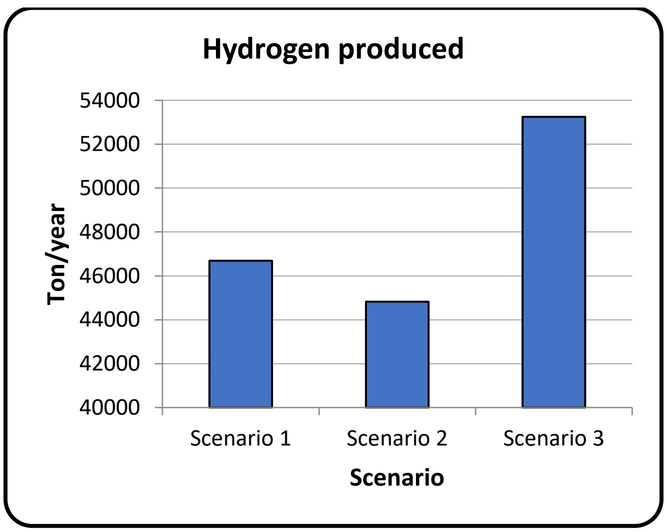


Figure 17: Hydrogen Production

Figure 17 shows the amount of hydrogen produced in tons on yearly basis by each of the three scenarios. Scenarios 3- Integrated Electrolyser produces the highest amount of hydrogen whereas scenarios 2-Onshore Electrolyser produces the lowest amount of hydrogen. This shows that the electricity supply to electrolyser exactly proportionate with the hydrogen production.

- **Total earnings received from selling Hydrogen.**

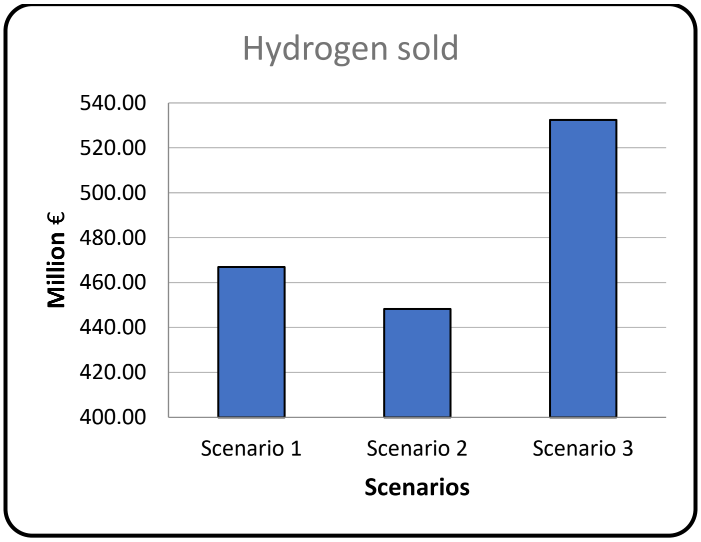


Figure 18: Total Hydrogen selling price

Figure 18 shows the total earnings received after selling the hydrogen produced using these scenarios. The selling price of hydrogen is €10/kg i.e. €0.01/ton (Jovan & Dolanc, 2020). As scenarios 3- Integrated Electrolyser produced the highest amount of hydrogen, the revenue generated is also the highest and stands at approximately €532 million/year. It is evident from the chart that implementing scenarios 3- Integrated Electrolyser will lead to higher revenue generation.

4.4. Sensitivity Analysis

A sensitivity analysis is carried out to analyse the effects caused by uncertainties related to various input parameters, during LCOH calculations. To analyse the effects, the parameters were varied using a triangular probabilistic distribution function limited by the maximum and minimum ranges obtained from the literature.

Table 23: Parameters for sensitivity analysis

Parameters	Unit	Most likely	Minimum	Maximum
Electrolyser/wind capacity ratio	%	80.00%	20%	100%
Electrolyser cost	(€/MW)	961470	300850	1622090
Losses		8%	0%	10%
Hydrogen production per unit of power	kg/kWh	0.02	0.018	0.021
At full load water needed for 1MW	(L/hr)	270.83	250	300

Figure 19 reveals the results obtained from the LCOH sensitivity analysis. The parameter that majorly contributes is wind farm capacity. The most important thing that needs to be considered is the E/W ratio, as the electrolyser cost and hydrogen production values directly depend on it. The price of electrolyser will be in a range of 300,850-16,22,090 €/MW by 2030 (ICCT, 2020). Electrolyser efficiency i.e., Hydrogen production per unit of power has a big effect on LCOH.

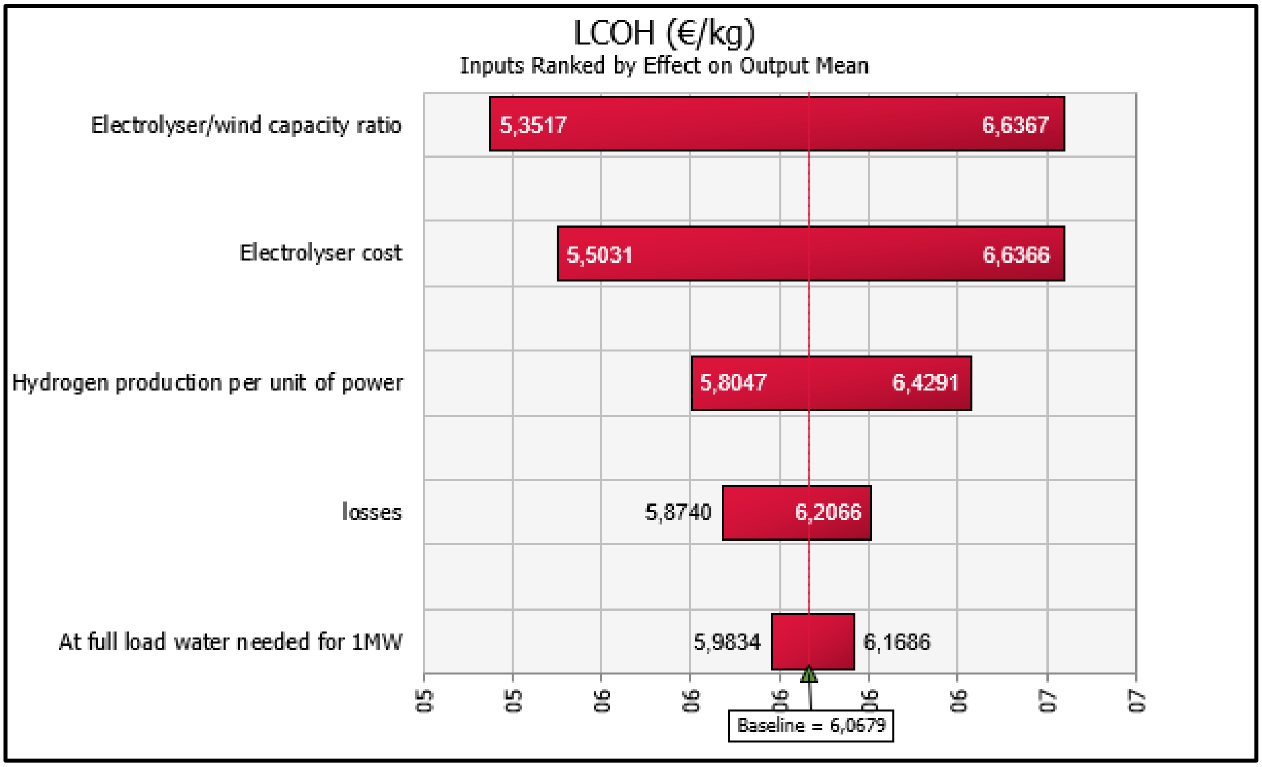


Figure 19: Sensitivity analysis for LCOH

5. Discussion and Interpretation

This section discusses and interprets the challenges related to usage and utility of hydrogen and oxygen and also possibility of suing existing platform. This also covers the limitations and the scope area where this study can be further improvised and also outlines the situation statement of the industries currently working on similar projects.

- **Using Existing platform:**
  Taking into consideration, the existence of redundant or soon-to-be dismantled offshore oil and gas platforms if an offshore wind farm and a redundant oil and gas platform work together, it leads to the creation of an integrated system working together in harmony. The use of an integrated system would eliminate the cost of setting up the platforms and installation of pipelines as the redundant oil and gas platform being used will suffice the needs. Using an integrated system will further reduce the LCOH. But need to focus on:
  - The prerequisite for using an existing redundant offshore installation is that it has to be electrified to ensure regular availability of electricity as equipment's onboard consumes electricity.
  - Regular maintenance of the existing platforms is required to ensure the soundness of the operation to avoid any mishaps.
  - So far, the renovation cost and maintenance costs have not been considered in the calculations as this topic is only for discussion, but if an existing platform was to be used, these renovation costs and maintenance costs will have to be considered for OPEX calculations.

- **Requirements:**
  The three scenarios under consideration have some requirements. Those requirements are:
  - If assuming that an existing redundant platform is used, the pipeline already installed would have aged quite a bit and if the same is used for transporting hydrogen from the wind farms to the onshore storage caverns, it should be made sure through proper inspection that the pipeline is compatible in performing the required function.
  - Adequate checks need to be done to ensure that the existing pipeline does not leak the gas into the surrounding.
  - The cables used to connect wind farms array must be 25kV and the cables used to connect the wind farm to the electrical grid onshore must be around 110-115kV (TenneT, 2021).

- **Oxygen:**

  While producing hydrogen from water using electrolysis, oxygen is the useful by-product obtained during electrolysis, i.e., an approximate of 8 kg of oxygen for 1 kg of hydrogen (van Leeuwen & Zauner, 2018). The oxygen is 95% pure in quality and can be further transported to onshore platform where it can be utilized for medical and industrial applications. This can be considered as a future scope for windfarm expansion to obtain oxygen and distribute it wherever needed (Layman's, 2010).

  The cost involved for capturing and transporting after direct exposure of oxygen to atmosphere will be higher and it will not be an economical option because the cost of equipment's involved and other expenses will altogether exceed the selling price. Hence this option has not been considered, pertaining to this study. With time and by implementation of technological advancements, the whole system will then become beneficial and will help reduce the LOCH costs further. This is because, as the cost of the equipment and other things depreciate, there is a significant increase in production and sale of the captured oxygen. For 2-Onshore Electrolyser, this system can be implemented only if it is situated nearby a region where there is a demand for high purity oxygen, further leading to reduced transportation cost.

- **Hydrogen:**

  Literature review states that the potential effects of a hydrogen-based system are less than that of a fossil fuel-based system. But this depends majorly on the leakage rate of hydrogen during production, storage, transport, and other phases. Hydrogen reacts in the atmosphere with tropospheric OH^- radicals, further leading to ozone depletion and increased global warming. If the hydrogen leakage rate is 1% then the resulting impact will be the emission of 0.6% fossil fuels (Derwent et al., 2006). Hence, one can conclude that hydrogen is not pollution-free and create undesired risky situations, unless it is carefully inspected and ensured that there is no leakage.

- **Storage in the pipeline:**

  As the hydrogen gas is transported through the pipelines, always there will be a gap in the amount of hydrogen gas while entering inside and leaving out, i.e., the amount of hydrogen gas that stays inside the pipes. Further research can be done on this which will ultimately reduce the cost involved in hydrogen storage.

- **Situation Statement** (J.W. Langeraar, HYGRO, personal communication):

  As agreed with the stakeholder's perspective while discussing with HYGRO Company, it was found that from the viewpoint of technological development, the status of 3- Integrated Electrolyser seems good but economically it isn't a good option. Also, the rules and regulations are obstructing development. This is because when a plant is constructed it has high uncertainties and it needs some subsidy. This being a hydrogen plant, it seems difficult to gain subsidy because, presently, the hydrogen is not considered as an energy carrier by any law.

The stakeholder has also claimed that they are currently working on Scenario 3- Integrated Electrolyser. Theoretical observations pertaining to this study also reveals that Scenario 3-Integrated Electrolyser is the best option.

- **Limitation:**
  - In Scenario 3- Integrated Electrolyser, as explained in section 3.3.4, as the electrolyser is integrated inside the wind turbine, the installation cost and the equipment costs will be higher because the cost of manufacturing and installation of small equipment's compared to one big equipment is always higher. The CAPEX of Scenario 1- Centralized Electrolyser is costlier than the CAPEX of Scenario 3-Integrated Electrolyser by an approximate of 100 Million €, mainly because of platform cost. If manufacturing and installation costs are also considered, still scenario 3-Integrated Electrolyser will be the best option. No proper literature is available related to Scenario 3- Integrated Electrolyser. Hence, same values for OWF, electrolyser, desalination unit and compressor are used for calculations as Scenario 1- Centralized Electrolyser. These characteristics can set limitations while analysing the outcomes of hydrogen production prices.
  - Pipeline diameter is considered same thought this study. In reality, the pipe diameter can vary because when pressure changes diameter changes as both these parameters are inversely related. For pipelines at storage facility, the pipe diameter is less as the pressure difference is more and by using this pipe diameter at storage facility, the CAPEX of pipelines can be reduced; but at junction of pipes near offshore, the assembly cost will be considered.
  - For hydrogen storage using salt cavern, it is assumed that whole new cavern is constructed through mining process. In case of offshore salt cavern, the mining cost will differ; at present no relevant data is available for proving the statement.
  - The plan was also to cover the details of offshore hydrogen storage in depleted gas field or salt cavern. Due to lack of information and insufficient data availability, this part is skipped, pertaining to this study.
  - Many projects related to energy island in North Sea are under implementation phase, where the energy will be produced by combining two or more renewable energy sources i.e., wind, solar and wave generation. The outcomes can be compared with the outcomes obtained from the three scenarios considered and accordingly the best situation can be selected.
  - The detailed analysis on discharge cycle has not been considered in this study. Also, the effect of storage injection pressure and withdrawal pressure on storage facility has been avoided due to time constraints.

This study can be extended further by performing and analysing the direct and indirect environmental impacts of hydrogen production, storage and distribution, for the different scenarios discussed. This will negatively impact the marine ecosystem. The study should take into account the mechanical factors (noise and vibrations), electromagnetic factors and other undesirable factors.

6. Conclusion

The main objective of the present study was to develop various scenarios of hydrogen production using OWF and select the best scenario with the lowest Levelized cost for hydrogen production. The study initially explains various electrolysis technologies and selects PEM because of its advantages over other technologies. Later various storage technologies are explained among those salt cavern and tanks are selected and are compared with each other by LCOS. Equipment that is used for hydrogen production on offshore or onshore production are explained by considering the major equipment for simplicity are considering while desalination unit, transport, and compressor are analysed on the basis of their CAPEX and OPEX.

Three scenarios were designed to determine the lowest LCOH and LCOS using the techno-economic analysis. In the first scenario, hydrogen is produced offshore on a new platform and the pure water required for electrolysis is taken from seawater. In order to get pure water from seawater, a desalination unit is considered. The produced hydrogen is transported to shore by new pipelines, and a compressor is used to create the pressure difference. From shore, the hydrogen is transported to storage facility by pipelines.

In the second scenario, hydrogen is produced onshore; instead of the platform, a new infrastructure is considered. The water required for electrolysis is directly taken from the national water grid at industrial water cost, so in this scenario, there is no need for a desalination unit. And later it's transported to a storage facility.

In the third scenario, hydrogen is produced inside the wind turbine called an Integrated Wind Turbine and all the equipment like desalination and compressor are installed inside the wind turbine. As the wind farm is installed offshore to convert seawater to pure water desalination unit is required.

The LOCH ranges between 5.26 €/kg to 6.73 €/kg. A higher amount of hydrogen produced coupled with lower CAPEX and OPEX works in favour of using scenarios 3- Integrated Electrolyser as it is proven to be the more efficient out of all the three scenarios. Scenarios 1-Centralized Electrolyser is better if it is further in the sea and scenarios 2-Onshore Electrolyser is better if it is close to shore. This happens mainly because of cost and losses in transport and conversion. Reducing the length of cables laid and utilizing the existing oil and gas pipelines to transport the hydrogen from the offshore wind farms to onshore storage facilities help to reduce the LCOH drastically and uses the hydrogen to produce energy more affordable. For storage, a salt cavern should be a better option because of the quantity and span of duration to be stored. The present study concludes that the LCOS for salt cavern is more than that of tanks because for salt cavern the transport cost to the storage location is considered and assumed to be 200 km.

For future studies can be undertaken in the field of the Energy Island concept where various renewable energy sources can be combined. It is possible to store hydrogen in pipelines so the future study can be done on hydrogen storage in pipelines. The present study concludes that hydrogen production by using the electrolysis process and electricity from OWF is still not competitive with the price of grey hydrogen production i.e., 1.24-2.4 €/kg (IEA, 2019). The use of Integrated wind turbines in the Netherlands, Norway, Denmark, etc., has a better future and can be achieved in the next few decades. However, as environmental pressures increase it will be one of the most efficient solutions to tackle these pressures and achieve the necessary targets.

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8. References

Adam, P., & Engelshove, S. (2020). *Hydrogen infrastructure – the pillar of energy transition gas networks to hydrogen operation*.

André, J., Auray, S., Brac, J., De Wolf, D., Maisonnier, G., Ould-Sidi, M. M., & Simonnet, A. (2013). Design and dimensioning of hydrogen transmission pipeline networks. *European Journal of Operational Research*, *229*(1), 239–251. https://doi.org/10.1016/j.ejor.2013.02.036

André, J., Auray, S., De Wolf, D., Memmah, M.-M., & Simonnet, A. (2014). *Time development of new hydrogen transmission pipeline networks for France*. https://doi.org/10.1016/j.ijhydene.2014.04.190

Blok, K., & Nieuwlaar, E. (2016). *Introduction to Energy Analysis - Kornelis Blok, Evert Nieuwlaar - Google Books*. https://books.google.nl/books?id=aCslDwAAQBAJ&pg=PR1&lpg=PP1&focus=viewport&dq=blok+and&lr=&hl=nl#v=onepage&q=blok and&f=false

Bruce Lin thesis. (n.d.). *Rules of Thumb*. Retrieved April 20, 2021, from http://brucelin.ca/scooters/thumb.html

Caglayan, D. G., Weber, N., Heinrichs, H. U., Linßen, J., Robinius, M., Kukla, P. A., & Stolten, D. (2020). Technical potential of salt caverns for hydrogen storage in Europe. *International Journal of Hydrogen Energy*, *45*(11), 6793–6805. https://doi.org/10.1016/j.ijhydene.2019.12.161

CBS. (2021). *Renewable electricity; production and power*. CBS. https://www.cbs.nl/nl-nl/cijfers/detail/82610NED?q=windenergie

Cory, B. (1996). Pricing in electricity transmission and distribution. *Proceedings of the Mediterranean Electrotechnical Conference - MELECON*, *1*(April), 19–25. https://doi.org/10.1109/melcon.1996.550955

Crotogino, F. (2016). Larger Scale Hydrogen Storage. In *Storing Energy: With Special Reference to Renewable Energy Sources*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-803440-8.00020-8

Dahlman, LuAnn Lindsey, R. (2021). *Climate Change: Global Temperature | NOAA Climate.gov*. https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature

Derwent, R., Simmonds, P., O'Doherty, S., Manning, A., Collins, W., & Stevenson, D. (2006). Global environmental impacts of the hydrogen economy. *International Journal of Nuclear Hydrogen Production and Applications*, *1*(1), 57. https://doi.org/10.1504/ijnhpa.2006.009869

Dincer, I. (2012). Green methods for hydrogen production. *International Journal of Hydrogen Energy*, *37*(2), 1954–1971. https://doi.org/10.1016/j.ijhydene.2011.03.173

Energy central. (2013). *Energy From Wind Turbines Actually Less Than Estimated? | Energy Central*. https://energycentral.com/c/ec/energy-wind-turbines-actually-less-estimated

Energy gov. (2018). *How Do Wind Turbines Work? | Department of Energy*. https://www.energy.gov/eere/wind/how-do-wind-turbines-work

Energy Intelligence Group. (2020). *EIG Article : EU Hydrogen Plans Spell Trouble for Gas*. http://www.energyintel.com/pages/eig_article.aspx?DocId=1078270

Energy Systems Research Unit. (n.d.). *Hydrogen Economy Storage*. University of Strathclyde Glasgow. Retrieved April 25, 2021, from http://www.esru.strath.ac.uk/EandE/Web_sites/02-03/hydrogen_economy/Storage.htm

European Commision. (2020). *COMMITTEE AND THE COMMITTEE OF THE REGIONS A hydrogen strategy for a climate-neutral Europe*. https://www.eu2018.at/calendar-events/political-events/BMNT-

Evers, A. A. 2010. (2010). *The Hydrogen Society*.

Fuel Cells and Hydrogen JU. (2019). *HYDROGEN ROADMAP EUROPE A sustainable pathway for the European energy transition*.

Gabrielli, P., Poluzzi, A., Kramer, G. J., Spiers, C., Mazzotti, M., & Gazzani, M. (2020). Seasonal energy storage for zero-emissions multi-energy systems via underground hydrogen storage. *Renewable and Sustainable Energy Reviews*, *121*, 109629. https://doi.org/10.1016/j.rser.2019.109629

ICCT. (2020). Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe. *International Council on Clean Transportation (ICCT)*, 1–73. https://theicct.org/sites/default/files/publications/final_icct2020_assessment_of _hydrogen_production_costs v2.pdf

IEA. (2019). *The Future of Hydrogen*.

IEA. (2020a). *IEA – International Energy Agency*. https://www.iea.org/

IEA. (2020b). *The Netherlands 2020 - Energy Policy Review*. www.iea.org/t&c/

International Energy Agency. (2020). *Renewables 2020 - Analysis and forecast to 2025*. https://www.iea.org/reports/renewables-2020

Jepma, C., & Van Schot, M. (2017). On the economics of offshore energy conversion: smart combinations_Converting offshore wind energy into green hydrogen on existing oil and gas platforms in the North Sea. *Energy Delta Institute*, *February*, 1–54. https://www.gasmeetswind.eu/wp-content/uploads/2017/05/EDI-North-Sea-smart-combinations-final-report-2017.pdf

Jovan, D. J., & Dolanc, G. (2020). Can Green Hydrogen Production Be Economically Viable under Current Market Conditions. *Energies*, *13*(24), 6599. https://doi.org/10.3390/en13246599

Khzouz, M., Gkanas, E. I., Shao, J., Sher, F., Beherskyi, D., El-Kharouf, A., & Qubeissi, M. Al. (2020). Life Cycle Costing Analysis: Tools and Applications for Determining Hydrogen Production Cost for Fuel Cell Vehicle Technology. *Energies*, *13*(15). https://doi.org/10.3390/en13153783

Koornneef, J. (2020). *North Sea Energy Technical assessment of Hydrogen transport , compression , processing offshore As part of Topsector Energy :*

Layman's. (2010). *Hydrogen and Oxygen production via electrolysis powered by renewable energies to reduce environmental footprint of a WWTP Layman's Report*. www.life-greenlysis.eu

Lensink, S., Pisca, I., & PBL. (2018). *Costs of offshore wind energy 2018*. *February*, 6. www.pbl.nl/en.

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

Lord, A. S., Kobos, P. H., Klise, G. T., & Borns, D. J. (2011). A Life Cycle Cost Analysis Framework for Geological Storage of Hydrogen: A User's Tool. *Sandia National Laboratories*, *September*, 1–60. http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online%0Ahttp://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online%0Ahttps://prod-ng.sandia.gov/techlib-noauth/access-control.cgi/2011/116221.pdf

Makridis, S. S. (n.d.). *Hydrogen storage and compression*.

Morice, C. P., Kennedy, J. J., Rayner, N. A., & Jones, P. D. (2012). Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set. *Journal of Geophysical Research Atmospheres*, *117*(8). https://doi.org/10.1029/2011JD017187

Netherland Enterprise Agency. (2020). *Hollandse Kust (zuid)*. https://offshorewind.rvo.nl/generalzh

Netherlands Enterprise Agency. (2014). Borssele Wind Farm Zone. *Wind Energy*, *August*.

North Sea Energy. (2020). *Unlocking potential of the North Sea Interim Program Findings* (Issue June).

Olivier, J. G. J., & Peters, J. A. H. W. (2020). *TRENDS IN GLOBAL CO 2 AND TOTAL GREENHOUSE GAS EMISSIONS 2019 Report*. https://www.pbl.nl/sites/default/files/downloads/pbl-2020-trends-in-global-

Papadopoulos, A., Rodrigues, S., Kontos, E., Todorcevic, T., & Bauer, P. (2015). *Modeling of Collection and Transmission Losses of Offshore Wind Farms for Optimization Purposes Declaration of Authorship*. *February*, 6724–6732.

Peters, R., Vaessen, J., & Van Der Meer, R. (2020). Offshore hydrogen production in the north sea enables far offshore wind development. *Proceedings of the Annual Offshore Technology Conference*, *2020-May*, 1–14. https://doi.org/10.4043/30698-ms

Rashid, M. M., Mesfer, M. K. Al, Naseem, H., & Danish, M. (2015). Hydrogen Production by Water Electrolysis: A Review of Alkaline Water Electrolysis, PEM Water Electrolysis and High Temperature Water Electrolysis. *International Journal of Engineering and Advanced Technology*, *3*, 2249–8958.

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

Snyder, B., & Kaiser, M. J. (2009). Ecological and economic cost-benefit analysis of offshore wind energy. *Renewable Energy*, *34*(6), 1567–1578. https://doi.org/10.1016/j.renene.2008.11.015

Stone, H. B. J., Veldhuis, I., & Richardson, R. N. (2009). Underground hydrogen storage in the UK. *Geological Society Special Publication*, *313*, 217–226. https://doi.org/10.1144/SP313.13

TenneT. (2021). *Our high-voltage grid - TenneT*. TenneT. https://www.tennet.eu/our-grid/our-high-voltage-grid/our-high-voltage-grid/

The Florida Solar Energy Center (FSEC). (2014). *Hydrogen Basics - Storage*. University of Central Florida. http://www.fsec.ucf.edu/en/consumer/hydrogen/basics/storage.htm

The National Government. For the Netherlands. (2020). *Windenergie op zee | Duurzame energie | Rijksoverheid.nl*. https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/windenergie-op-zee

The Scottish Government. (2020). *Scottish Offshore Wind To Green Hydrogen Opportunity Assessment*. *44*(December), 1–11.

Thomas, D. (2019). Large scale PEM electrolysis : technology status and upscaling strategies. *Hydrogenics*, *October*, 20. http://hybalance.eu/wp-content/uploads/2019/10/Large-scale-PEM-electrolysis.pdf

Tichler, R., & Bauer, S. (2016). Power-to-Gas. In *Storing Energy*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-803440-8/00018-X

van der Burg, L. (2020). *Hydrogen webinar 2: Next generation electrolysers [Vedio]*.

van Leeuwen, C., & Zauner, A. (2018). *Innovative large-scale energy storage technologies and Power-to-Gas concepts after optimisa tion Real time implementation of grid models*. *691797*.

Van Schot, M., & Jepma, C. (2020). *North Sea Energy A vision on hydrogen potential from the North As part of Topsector Energy*.

Viktorsson, L., Heinonen, J. T., Skulason, J. B., & Unnthorsson, R. (2017). A step towards the hydrogen economy - A life cycle cost analysis of a hydrogen refueling station. *Energies*, *10*(6), 1–15. https://doi.org/10.3390/en10060763

Wang, X., Li, L., Palazoglu, A., El-Farra, N. H., & Shah, N. (2018). Optimization and control of offshore wind farms with energy storage systems. *IFAC-PapersOnLine*, *51*(18), 862–867. https://doi.org/10.1016/j.ifacol.2018.09.245

Wiley, J. (2019). *CHAPTER 17 Hydrogen*.

Wind Turbine Models. (n.d.). *Siemens Gamesa SG 10.0-193 DD - 10,00 MW - Wind turbine*. Retrieved April 26, 2021, from https://en.wind-turbine-models.com/turbines/1969-siemens-gamesa-sg-10.0-193-dd

9 Appendix

9.1. Appendix A: Input data

Input data of CAPEX and OPEX are shown below for all scenarios.

Table 24: Input data for scenarios

Components	Unit	Value	References
CAPEX wind farm	(€/MW)	16,00,000	(Lensink et al., 2018)
OPEX wind farm	(€/MW)	41,000	(Lensink et al., 2018)
CAPEX of electrolyser low	(€/MW)	3,00,850	(ICCT, 2020)
CAPEX of electrolyser base	(€/MW)	9,61,470	(ICCT, 2020)
CAPEX of electrolyser high	(€/MW)	16,22,090	(ICCT, 2020)
OPEX of electrolyser (3% of capex)	(€/MW)	28,844.1	(ICCT, 2020)
CAPEX of platform(100MW)	M€	30	(Van Schot & Jepma, 2020)
OPEX of the platform (5% of CAPEX)	M€	1.5	(Van Schot & Jepma, 2020)
CAPEX of hydrogen pipeline	$/km	806,444	Calculated refer Appendix B: Hydrogen production
OPEX of hydrogen pipeline (2% of CAPEX)	$/km	16,128	Calculated
CAPEX of Desalination Unit (2000L/h capacity unit)	€	61,200	(Jepma & Van Schot, 2017)
OPEX of Desalination Unit (2.5%)	€	1,530	(Jepma & Van Schot, 2017)
CAPEX of hydrogen compressor	M€	13.9	Calculated refer Appendix B: Hydrogen production calculation
OPEX of hydrogen compressor (4%of CAPEX)	M€	0.56	Calculated
CAPEX of Export cable	£[5]/m	1,000	(The Scottish Government, 2020)
CAPEX of land	$/(kg/day)	558.96	(Khzouz et al., 2020)
OPEX of land (5% of capex)	$/(kg/day)	27.94	(Khzouz et al., 2020)
Water Cost	€/m3	0.67	(van Leeuwen & Zauner, 2018)

[5] Pound exchange is 1.16 on 19th April 2021.

9.2 Appendix B: Hydrogen production calculation

Renewable energy availability at the chosen location is determined by using the wind profile at location and turbine power profile (for 8 MW wind turbine capacity). In order to project a turbine power profile for a 10 MW turbine, various efficiencies with respect to wind speed are calculated that are shown in Table 25, and considering the same efficiencies, the turbine profile for 10 MW is calculated. At 80% electrolyser/wind capacity ratio, electrolyser capacity is identified. This optimal value is determined considering the range of electrolyser capacities and using hourly data of available wind energy, turbine energy, and electrolyser energy. Practically, the actual energy used for hydrogen production is the minimum value of the turbine energy and electrolyser energy. By substituting total actual energy in Equation 5, total hydrogen produced annually is obtained. For detailed figures, refer Table 27.

Table 25: Efficiency of 8MW wind turbine with respective to velocity

V_s	0-3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
η	0	0.12	0.29	0.34	0.43	0.43	0.40	0.37	0.33	0.32	0.27	0.21	0.17	0.14	0.12	0.10	0.09	0.07	0.06	0.06	0.05	0.04	0

Electrolyser/wind capacity ratio ranges between 40% and 100%. Accordingly, corresponding values of E/W ratio and LCOH (€/kg) are plotted. The E/W ratio for the minimum value of LCOH is then selected. Refer to the graph in Figure 5.

Finally, by using this data, various other parameters such as the amount of curtailed energy and idle time for electrolyser can be evaluated and analysed. Refer Table 26.M

Table 26: Parameters for Electrolyser/wind capacity ratio

Parameters	Definition
% of Energy Actual Used	It is a ratio of total actual energy used by electrolyser to the OWF energy achieved throughout the year.
% of time electrolyser Idle	It is a ratio of total idle time of electrolyser to total working hours of OWF.
% of electricity curtailed	It is a ratio of total energy curtailed to the OWF energy achieved throughout the year.
Cost due to curtailment (M€)	It is wasted cost due to unproduced hydrogen[6].

[6] The amount of unproduced hydrogen is calculated by substituting total energy curtailed in Equation 5

Plant Capacity	740 MW	E/W ratio	80	No of turbine	74	Electrolyser Capacity used	591 MW		
Wind speed	**Hours**	**10MW**	**10kW**	**Energy per turbine**	**Energy from OWF**	**Electrolyser Capacity**	**Actual Energy Used**	**Idle time of electrolyser**	**Energy Curtailed**
(m/s)		Wind power (MW)	Turbine Power (MW)	MWh	MWh	MWh	MWh	hr	MWh
0	2	0	0	0	0	0	0	0	0
1	122	0	0	0	0	0	0	0	0
2	338	0	0	0	0	0	0	0	0
3	540	0	0	0	0	0	0	0	0
4	740	1.15	0.13	97.66	7227.02	437340.00	7227.02	581.23	0
5	871	2.24	0.66	574.76	42532.01	514761.00	42532.01	542.17	0
6	938	3.87	1.32	1237.94	91607.41	554358.00	91607.41	493.34	0
7	883	6.15	2.64	2330.70	172471.95	521853.00	172471.95	395.68	0
8	801	9.17	3.96	3171.39	234682.95	473391.00	234682.95	298.01	0
9	696	13.06	5.28	3674.22	271892.36	411336.00	271892.36	200.35	0
10	692	17.92	6.60	4566.38	337912.20	408972.00	337912.20	102.69	0
11	582	23.85	7.92	4608.61	341037.40	343962.00	341037.40	5.03	0
12	421	30.96	9.90	4167.15	308369.30	248811.00	248811.00	0	59558.30
13	329	39.37	10.00	3290.00	243460.00	194439.00	194439.00	0	49021.00
14	266	49.17	10.00	2660.00	196840.00	157206.00	157206.00	0	39634.00
15	179	60.48	10.00	1790.00	132460.00	105789.00	105789.00	0	26671.00
16	131	73.40	10.00	1310.00	96940.00	77421.00	77421.00	0	19519.00
17	79	88.04	10.00	790.00	58460.00	46689.00	46689.00	0	11771.00
18	44	104.50	10.00	440.00	32560.00	26004.00	26004.00	0	6556.00
19	44	122.91	10.00	440.00	32560.00	26004.00	26004.00	0	6556.00
20	49	143.35	10.00	490.00	36260.00	28959.00	28959.00	0	7301.00
21	21	165.95	10.00	210.00	15540.00	12411.00	12411.00	0	3129.00
22	8	190.80	10.00	80.00	5920.00	4728.00	4728.00	0	1192.00
23	3	218.02	10.00	30.00	2220.00	1773.00	1773.00	0	447.00
24	2	247.71	10.00	20.00	1480.00	1182.00	1182.00	0	298.00
25	3	279.98	0.00	0	0	0	0	0	0
	8784			**35978.81**	**2662432.6**	**4597389.0**	**2430779.3**	**2618.5**	**231653.3**

Table 27: Electrolyser/Wind capacity ratio

The number of Electrolyser Stacks:

$$\text{Number of Electrolyser Stacks} = \frac{\text{Electrolyser capacity}}{Electrolyser\ capacity\ of\ one\ stack}$$

The value obtained is 197 (refer to previous calculations).

Desalination unit:

At the full load capacity of the selected electrolyser, 6,500 litres of water per MW per day is required (Jepma & Van Schot, 2017). The resulting flow rate is 270.83 litres/hr. The capacity of desalination units is 2000L/hr.

The Number of desalination units is found by dividing Water needed per hour at max capacity by the capacity of the desalination unit that is 2000L/hr.

$$Number\ of\ desalination\ units = \frac{Water\ needed\ per\ hour\ at\ max\ capacity}{Capacity\ of\ desalination\ units}$$

Water needed per hour at max capacity is shown in section **3.2.1**.

Compressor:

The compressor should be capable of handling the maximum flow rate throughout the year. From the hourly data of hydrogen produced, the flow rate is calculated as follows:

$$Q = \frac{Maximum\ Hydrogen\ productiom\ per\ hour\ in\ a\ year}{3600}$$

Maximum hydrogen production per hour is 10800 kg.
Flow rate is 3 kg/sec.

Pipelines:

To calculate the diameter of the pipe, Equation 17 is used (André et al., 2013)

Equation 17

$$Q = K\sqrt{P_1^2 - P_2^2}$$

Where Q is the flow rate in m^3/hr,
K is coefficient
P_1 is the inlet pressure, in bar.
P_2 is the outlet pressure, in bar.

K is calculated using Equation 18 (André et al., 2013)

Equation 18

$$K = 0.0129\sqrt{\frac{D^5}{\lambda * Z * T * L * d}}$$

Where D is the diameter in mm
λ is the dimensionless coefficient of friction
Z is dimensionless compressibility factor
T is the gas temperature in Kelvin
L is the length of pipe as the distance between OWF and Shore. L=50km
d is the relative density of the gas in regard to the air.

The coefficient of friction λ is calculated by $\lambda = \frac{16*\mu}{d*V*\rho}$

V i.e., velocity (m/s) it is found by $Q = Av$

where A is the cross-sectional area of pipe (m^2).
So, $\lambda = \frac{1.15945*10-4*D}{Q*\rho}$

Standardized values of parameters are considered for calculation purposes. Pressure values are assumed in section 3.2.1.1 in the pipeline. Flow rate is similar to the compressor as calculated above, the only difference is the density and is considered at its average pressure.

By using Equation 17 and 18
For pressure range from 30-75 bar
Density at average pressure i.e., 42.5 bar is 3.16 kg/m^3
Q=3kg/s= 2783.61 m^3/hr
So, the diameter is 371.69 mm

For pressure range from 75-120 bar
Density at average pressure i.e., 42.5 bar is 6.66 kg/m3
Q=3kg/s= 1542.34 m^3/hr
So, the diameter is 276.67 mm

Finally selecting a larger diameter from the above two cases, for simpler assembly.
The diameter is 15 inches

Table 28: Input Data for Pipe Selection

Notation	Parameter	Value	Units
Z	Compressibility Factor	$(6.67 * 10^{-4})P + 1$	Refer Equation 20
T	Mean Temp	317	K
L	Length	50	km
$\boldsymbol{\rho_a}$	Density of air	1.127	Kg/m^3
d	Relative Density	ρ/ρ_a	-
$\boldsymbol{\mu}$	Dynamic Viscosity	9.23E-06	Ns/m^2

9.3 Appendix D: Storage

Density calculation

Equation 19

$$P = Z\varrho RT$$

Where
ϱ is density (kg/m^3)
P is Pressure in the bar
R is a specific gas constant in Nm/kgK
T is the temperature in K
Z is the compressibility factor.
Compression factor is almost linear for 317 K range. From Figure 20 at 317 K corresponding values are: at P_1 = 300 bar, Z_1 = 1.2 and P_2 = 600 bar, Z_2 = 1.4.

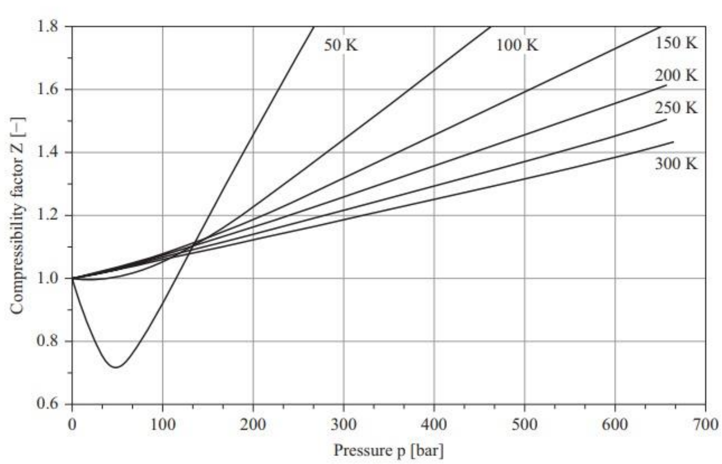

Figure 1.2 Compressibility factor Z of hydrogen [10]

Figure 20: Compressibility factor Z of hydrogen (Makridis, n.d.)

So, using the linear interpolation method following equation is defined.

$$Z = \left(\frac{Z_2 - Z_1}{P_2 - P_1}\right) * P + Constant$$

Equation 20

So,

$$Z = (6.67 * 10^{-4})P + 1$$

From *Equation 19* and Equation 20

Specific volume $= \frac{1}{\varrho} = \frac{[(6.67*10^{-4})P+1]RT}{P*10^5}$

The actual geometric volume of the salt cavern is 906000 m^3. Now to calculate the specific volume of this salt cavern, the geometric volume is divided by the actual working volume calculated considering hydrogen production on monthly basis in kg.

Input data for storage

CAPEX and OPEX for compressor and pipeline for storage are considered as used in hydrogen production.

Table 29: Storage data

Storage (Million €)		**Salt Cavern**	**Tank**	**References**
Storage CAPEX	Well Costs	1.90	22.64	For Salt cavern (Lord et al., 2011) and for tank (van Leeuwen & Zauner, 2018)
	Mining Cost	17.50		
	Leaching Plant Costs	8.40		
	Cushion gas	12.95		
OPEX		0.39	0.91	(van Leeuwen & Zauner, 2018)
Capex of compressor		6.69	22.64	For tank CAPEX of the compressor is calculated at 300 bar
OPEX of compressor		0.27	0.91	
CAPEX Pipeline		135.48	0.00	Calculated similar to Scenario 1-Centralized Electrolyser
OPEX Pipeline		2.71	0.00	

9.4 Appendix E: Discussion

The discussions were held with three stakeholders
TNO: J.M. Koornneef conducted on 22nd February 2021 (https://www.tno.nl/en/)
TNO: R.M. Groenenberg conducted on 15th March 2021 (https://www.tno.nl/en/)
HYGRO: J.W. Langeraar conducted on 27th November 2020 (https://hy-gro.net/en/waterstof-uit-wind)

Questions asked during the interview:

- What is your opinion on an integrated wind turbine?
- Building an energy island is better than or platform in the sea?
- Which scenario is best fitted for the Netherlands?
- What is your opinion on rules and regulations?
- What do you think about the environmental effect?
- What is your opinion on hydrogen storage in pipes?
- What is your opinion on hydrogen storage offshore in the salt cavern or a depleted field?

9.5 Appendix F: Excel sheet

The attached file Excel file "Thesis" has all the calculations required for the qualitative assessment.