Analysing the competitiveness of offshore hydrogen-wind production models

Javier Pollos Ezquerra

Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

Supervisors: Dr. Rui Pedro da Costa Neto

Eng. Sofia Carvalho Ganilha

Examination Committee

Chairperson: Prof. Susana Isabel Carvalho Relvas

Supervisor: Dr. Rui Pedro da Costa Neto

Member of the Committee: Dr. Patrícia de Carvalho Baptista

January 2021

Acknowledgements

I would like to acknowledge those who have contributed through the elaboration of this project by supporting and inspiring me.

I would first like to thank my supervisor Prof. Dr. Rui Pedro da Costa Neto, from IST, and Eng. Sofia Carvalho Ganilha from EDP Innovaçao for their availability and fruitful feedback as well as for sharing their professionalism and commitment, which has definitely inspired me not only for the project but for achieving goals within the energy sector in the future. I am especially grateful given the context of the COVID crisis during this year 2020, which has changed our circumstances and has proved we need to adapt to unexpected changes.

I would also like to thank my family, who has fully supported me for both the project and Masters itself, and has encouraged me to research and work on the field I have found as my life career.

Lastly, I would like to thank all those researchers, engineers, professionals and professors who believe in the power of science and of the importance of sharing knowledge for building a better future, working in private companies, public organizations, agencies, universities and governments in the shake of wellbeing, equality and sustainability of our society.

Resumo

A produção de hidrogénio (H2) está a ganhar muita popularidade em 2020. Todos os atores na cadeia de valor dos sistemas energéticos já reconhecem as aportações deste gás aos objetivos de descarbonização da economia, e isto é refletido nos apoios de governos e empresas ao hidrogénio nos últimos meses através de grandes investimentos. A produção de H2 a partir de energia eólica offshore é um tema que vale a pena ser explorado, uma vez que a energia eólica offshore oferece bons fatores de capacidade e energia elétrica de baixo custo.

Este trabalho estuda a competitividade das diferentes vias de ligar um parque eólico offshore com uma planta de produção de H2, realizando uma avaliação técnico-económica desses casos.

Quatro casos são definidos e comparados. Os resultados para os casos estudados indicam que a adição de oxigénio (O2) na estratégia de venda de gases é necessária para atingir um *Net Present Value* (NPV) positivo com uma representação potencial de quase 65 % das vendas de gases.

Desta forma, o caso escolhido como melhor opção é a produção de H2 de forma offshore, dedicada e centralizada com um Levelized Cost of Hydrogen (LCOH) de 5,98 €/kg. Adicionalmente, com o objetivo de ampliar a avaliação, é realizada uma análise de sensibilidade em relação às variáveis mais influentes que afetam o projeto. Por fim, é apresentado um estudo de caso potencial, cobrindo os fatores que podem surgir no futuro quando o H2 tiver um papel relevante no campo dos sistemas de energia.

Palavras-chave: *Produção de hidrogénio; produção de oxigénio; produção de eletricidade eólica offshore; ligação energia eólica e hidrogénio; análise económica.*

Abstract

Green hydrogen (H_2) production is gaining a lot of popularity in 2020. Its contributions to the energy systems have been recognised by every stakeholder in the field of energy systems. Both governments and companies have announced in the last months massive support to this technology. The combination of offshore wind and H_2 plants for large-scale production of this gas is a topic worth to be studied and with tremendous potential for development. Both technologies present synergies that can leverage the deployment of offshore wind farms (OWFs) and green H_2 plants. This thesis analyses the main options when connecting an OWF to a H_2 production plant and assesses the results based on economic indicators and technical needs.

Four cases are defined and compared. The results for the studied cases indicate that, the addition of oxygen (O_2) in the gases sales strategy is necessary to achieve a positive Net Present Value (NPV) with a potential representation of almost 65% of the gases sales.

As a result, the case selected as the best option is the production of H_2 in an offshore, dedicated and centralized way with a Levelized Cost of Hydrogen (LCOH) of 5.98 €/kg. Additionally, with the aim of broadening the assessment, a sensitivity analysis is performed regarding the more influential variables that affect the project. Lastly, a potential case study is shown, covering the factors that may arise in the future when H_2 plays a relevant role in the field of energy systems.

Keywords: *Hydrogen production; oxygen production; offshore wind electricity production; hydrogen and offshore wind energy coupling concept; economic analysis.*

Index

List of figures

List of tables

Nomenclature

AEL	Alkaline Electrolysis
ATR	Autothermal Reforming
BEV	Battery electric vehicles
BOP	Balance of the plant
CAPEX	Capital expenditures
CCUS	Carbon Capture Sequestration and Utilization
DRI-EAF	Direct Reduced Iron-Electric Arc Furnace
ERM	Environmental Resources Management
EU	European Union
FCEVs	Fuel Cell Electric Vehicles
HER	H_2 Evolution Reaction
HRPC	High Rise Pile Cap
HVAC	High Voltage Alternate Current
HVDC	High Voltage Direct Current
ICE	Internal Combustion Engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal rate of return
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Hydrogen
LHV	Low Heating Value
LOHC	liquid organic H_2 carriers
Mtoe	Million Tonnes of Oil Equivalent
NPV	Net present value
OER	O_2 Evolution Reaction
OPEX	Operational expenditures
OWFs	Offshore Wind farms
PEM	Polymer Electrolyte Membrane Electrolysis
RES	Renewable Energy Sources
SMR	Steam Methane Reforming
SOEL	Solid Oxide Electrolysis
TRL	Technology Readiness Level
WACC	Weighted Average Cost of Capital

Chapter 1.- INTRODUCTION

1.1 Motivation

Being the energy sector as a whole a focus of innovation in recent years, in September 2019 Bloomberg defined Hydrogen (H_2) as the hot topic within the energy sector [1] and this thesis rises as a response to the numerous movements and expressions of interests that individuals, companies and governments have shown for H_2 since last year. The new H_2 trend started in 2019 on a worldwide scale (Australia, South Korea, China, Japan), but only arrived to Europe in 2020 confirmed through the publication of several roadmaps at country-level. Such interest has been spurred by the *EU Hydrogen Strategy* announced in July 8th 2020 [2], which aims to use green H_2 (H_2 produced from renewable energy) to fulfil up to 14 % of its final energy demand by 2050. Many countries have included H_2 targets and roadmaps in their climate plans or stated clear intentions to do so, such as Netherlands, Germany, Portugal, Spain, France and Italy are those who have already stated their intentions in Europe [3] [4] [5] [6] [7]. Other non-European countries such as Australia, with notably high potential to produce green H_2, have also developed their strategies [8]. Moreover, some of the largest energy companies worldwide have made public their intentions to enter in the H_2 market. This fact is especially visible in the growth of the number of associated members to institutions such as *Hydrogen Council* or *Hydrogen Europe* have experienced in the last year. As an example, the former has increased its members from 59 to 92, including not only enterprises but also academia and national organizations in only 6 months [9].

From a point of view of searching for a cleaner production of H_2, two sectors shall be highlighted. On one hand, there are Oil&Gas companies, which advocate for the development of blue H_2, which is the one produced from fossil fuels with Carbon Capture Sequestration and Utilization (CCUS) [10]. On the other hand, there are the utilities, which are pushing for the development of green H_2 from renewable energy. Both sectors aim to make use of their infrastructure in order to improve the efficiency and the competitiveness of their business models [11].

This strong momentum for H_2 comes at a time in which this energy carrier is still not competitive either with the fossil fuel or sustainable alternatives, especially for the case of green H_2, where costs need to be drastically reduced in order to fulfil the abovementioned EU expectations in a competitive way.

Therefore, even when H_2 is still recognized by the different players to have a long path ahead for cost reduction, most of the stakeholders in the energy sector have aligned in the last months to push for the H_2 development, led by the International Energy Agency (IEA). This lies on the fact that H_2 is the only alternative for the decarbonization of the so-called “hard-to-abate sectors”, such as the steel production, high heat production, long-haul transport or the chemical industry. Here, the reach of electrification is limited, both technically and economically. Hence, these H_2 green molecules can provide a solution for decarbonizing all these sectors [12]. H_2 has the ability to support a deep integration of Renewable Energy Sources (RES), powering applications where direct connection to the power sources would not be possible. In addition, H_2 can also act as a long-term storage medium, which is especially interesting when countries face constraints due to intermittent RES along the different seasons in the year which has a positive impact not only from a power system balance perspective, but also supports the stabilization of RES revenues for the owners of the power plants (facilitating the shift from a carbon-powered society towards a sustainable one) or short-term because electrolysers can provide grid services (like batteries) [13].

Currently, and as stated by the IEA, there is a clear opportunity to limit the global CO_2 emissions after the COVID-19 pandemic shock [14] and to point these towards the Paris Agreement goals which aim to limit the temperature increase up to 2 ºC above pre-industrial levels while pursuing efforts to limit it even further to 1.5 ºC. In order to achieve this 1.5 ºC target, the Intergovernmental Panel on Climate Change (IPCC) published in its report “Global Warming of 1.5 ºC” that CO_2 emissions should be cut down to zero by 2050 by providing measures to carry it out [15].

Governments have shown disposition to take this chance and turn the pandemic into a shift to a cleaner future. This will spur the development of H_2 technologies, as recognized by the IEA, which considers that in order to achieve Paris Agreement´s targets, the global capacity of electrolysers will expand to 3,300 GW (in order to produce around 310 Mt of green H_2) by 2070 from 0.2 GW today [14]. These electrolysers will use around 13,750 TWh of electricity per year, 20 % of the global electricity generation by that year, which means almost 800 GW of installed RES capacity [14].

Once the importance of H_2 as a decarbonization agent in order to achieve a sustainable energy system is recognised, it is crucial to determine the possible RES that can be coupled to it, offering abundant energy amounts at low prices in order to produce competitive H_2. Both solar PV and onshore wind are among the considered RES that can power the electrolysers [14]. Also, nuclear energy is expected to be used to generate H_2 due to its high capacity factors, acceptable energy prices and synergies with electrolysis technologies that can take advantage of high temperatures [16]. Another technology that is expanding at fast pace and can couple with H_2 is offshore wind. This is a fast-growing industry with the potential of producing 36,000 TWh/year in installations less than 60 m deep and in a range closer than 60 km from shore [17]. Plus, it is expected that the development of floating wind turbines can take this potential even further to 253,000 TWh/year [17]. Currently, new offshore wind projects have capacity factors of 40 % to 50 % [17]. This characteristic is especially interesting for the combination with electrolysers, since higher capacity factors increases the amount of H_2 produced, increasing the revenues and decreasing the LCOH [12].

Levelized Cost of Electricity (LCOE) were in the order of 126 €/MWh in 2018. However, this LCOE is projected to decline by nearly 60 % by 2040, to around 50 €/MWh [17], from which half of it would belong to the electricity transmission assets, such as substation or cables. This low price combined with its high value to the system (it is considered as a pseudo-baseload source) will make offshore wind one of the most competitive sources of electricity systems of the future [17].

Therefore, offshore wind shall be considered as one of the main RES to produce the large amounts of H_2 that will be needed to achieve the sustainable future that all nations are looking for. The synergies of these two technologies lie on the high-capacity factors with relatively low prices that Offshore Wind farms (OWFs) could offer to produce H_2 in the medium-term. Moreover, as stated by the IEA, H_2 could dramatically increase the market potential for offshore wind. Europe is already looking to developing offshore “hubs” for producing electricity and clean H_2 from offshore wind [17]. In addition, and as explained above, new concepts could erase the costs of the transmission assets by generating the H_2 in offshore platforms that would then export the H_2 to land, avoiding unnecessary costs and complexity.

Hence, the study of OWFs and H_2 production combination arises as an important topic to study. This thesis aims to explore different configurations of the coupling of these two technologies and provides insights about the possible benefits of these, both in economic and technical terms.

1.2 Objectives

The main objective of the thesis is to analyse and select the most optimal design of an H2 - Offshore wind plant, based on different coupling concepts (e.g., onshore/offshore H2 production, centralized/decentralized, dedicated wind farms/curtailed renewable electricity). Some steps are taken for this purpose:

- Analyse the different concepts in terms of technical characteristics and requirements, TRL, commercial market availability, etc.
- Estimate the costs associated to each offshore H_2-wind coupling models (e.g., CAPEX, OPEX, cost breakdown in Levelized Cost of H_2).
- Propose business cases based on the outcomes of the analysis.

1.3 Thesis Outline

Chapter 2. This chapter describes the fundamentals of the H_2-wind coupling concept. First of all, Offshore Wind is explained, secondly H_2 and then both altogether, with principles that serve as basis, current projects and future projection of each technology.

Chapter 3. This chapter specifies the data and figures used in the calculations additionally to the main assumptions taken.

Chapter 4. This chapter describes four different study-cases created by the author, showing H_2-wind coupling to assess their advantages and disadvantages and main features.

Chapter 5. This chapter presents results of the studied cases, combining therefore the data from Chapter 3 and the cases of Chapter 4, with the intention of comparing the different parameters (CAPEX, OPEX, NPV…).

Chapter 6. In this chapter the best scenario is selected based on the results, specifying also and potential ways to improve the system.

Chapter 7. In this chapter a sensitivity analysis is performed in order to evaluate how the most critical parameters (electricity price, electrolyser cost...) affect the figures and results of projects with similar characteristics.

Chapter 2.- H_2-WIND COUPLING

2.1 H_2-wind coupling concept

The combination of offshore wind and H_2 plants for the large-scale production is a topic worth to be studied. Both technologies present synergies that can leverage the deployment of OWFs and green H_2 plants, such as high-capacity factors, affordable electricity, the proximity to water resource needed for the electrolysis and the cost of transporting H_2 to shore vs. cost of transporting electricity. This chapter analyses the main options when connecting an OWF to a H_2 production plant.

2.1.1 Offshore wind energy production

Wind is formed due to a pressure gradient in air, leading to a flow from high pressure regions to low pressure regions. These pressure variations leading to pressure gradients are due to uneven heating of the Earth's land and sea surfaces. Wind is, therefore, like many other sources of energy on Earth, coming directly or indirectly from the Sun. It can be stated thus that the variations of the wind depend on the radiation of the Sun (rotation of the Earth) and its surface (mountains, plains, oceans…) [18].

The power generated by a wind turbine and, as a result, the capacity factor of a wind farm, depends on the availability and speed of the wind, which varies in time and space [19]. Therefore, in order to select a suitable site, maximizing the power output in a selected location and to choose or design the best wind turbine that can produce the maximum power at the lowest cost, it is necessary to understand and examine the variations of the resource, both in its direction and velocity. The spatial and temporal variations of the activity can be studied at different scales. Fortunately, climate models and data from the past compiled over the past few decades provide proper data to understand these alterations [19].

Siting an OWF is a complex process, in which not only the economic feasibility of the project with indicators such as LCOE or net present value (NPV) [19] are taken into consideration, but also the environmental and social sustainability of the farm needs to be addressed by considering its impacts on marine life, the effects on tourism or the visual impact and the possible conflict with other users such as fishing industry or sea and air navigation [18]. Consequently, all these aspects should be carefully investigated. Table 1 summarises some of the main considerations that are needed to be prepared for marine spatial planning:

Table 1 Different aspects to consider when developing marine spatial planning [18]

Technical-related maps/data	– Wind resource (e.g., average wind speed at hub-height) – Water depth (bathymetry) – Geology and foundation
Other users of the ocean	– Navigation areas; shipping lanes – Fishing areas – Recreational/tourism (e.g., sailing race courses, diving sites…) – Other (e.g., cable routes, military, aquaculture, airport buffer zones…)
Marine protected areas and environmental-related maps/data	– Marine mammals and turtles – Birds – Sediments – Other ecological data
Historical and cultural resources maps/data	– Historical and cultural resources maps/data
Statutes, regulations, and policies	– Territorial (state/federal) and international

Wind energy is one of the fastest growing renewable energy sectors along with solar energy and can do similar contributions to the energy system as coal or gas power plants (but in a sustainable and cleaner way) due to similar LCOEs and relative high capacity factors, particularly in the offshore wind case [20]. During last few years, wind energy has experienced an exponential increase in installed wind power capacity, with European countries, North America and China leading the trend, going from the 24 GW installed in 2000 to 650 GW in 2018 [21], out of which 23 GW corresponded to offshore wind energy [17]. However, achieving CO_2 reduction targets will require a total capacity of 560 GW of offshore wind by 2040, compared to 28 GW in 2019 [17], foreseeing thus a rapid growth in this industry with Europe and China as the main leaders [22]. An important aspect to be considered in favour of OWFs is that presently approximately 40 % of the world's population lives within 100 km of the coast [23], therefore, this RES could power a high share of the world economies without long transmission distances.

Despite deeper knowledge and experience in the onshore wind sector, offshore is expected to experience a greater rollout in the upcoming years, as previously mentioned. This development is expected to be spurred by the great value it adds to the energy systems, due to higher capacity factors (33 %) compared to onshore wind (25 %) or solar PV (14 %), although new offshore projects are expected to reach factors of around 50 % [17]. This improvement potential relies on the possibility of taking advantage of better resources in areas where there are no obstacles and wind energy is more constant and also due to tech improvements to benefit from this (e.g., cut-in and cut-out speeds). In addition, turbines size can be much bigger in the sea, where 15 to 20 MW units are forecasted to be installed by 2030. Upcoming improvements are expected to lower the LCOEs offered by this technology, achieving cost reductions that would bring the LCOE from 126 €/MWh of current projects to around 40 €/MWh by 2040 [17] The current high LCOEs are a result of the combination of several factors, such as the initial capital costs (Around 4 M€/MW in 2018), the expensive maintenance, and the interests charged by the financial institutions, which are greatly impacted by the low experience and the high uncertainties associated to this technology (TRL 5 - 9, depending on the design [14]). The interests, commonly reflected in the Weighted Average Cost of Capital (WACC), may have impacts of up to 50 % on the current LCOE [17]. As long as this technology is widely proven, financing entities will lower the interests charged, helping to cut down the LCOE as shown in Figure 1.

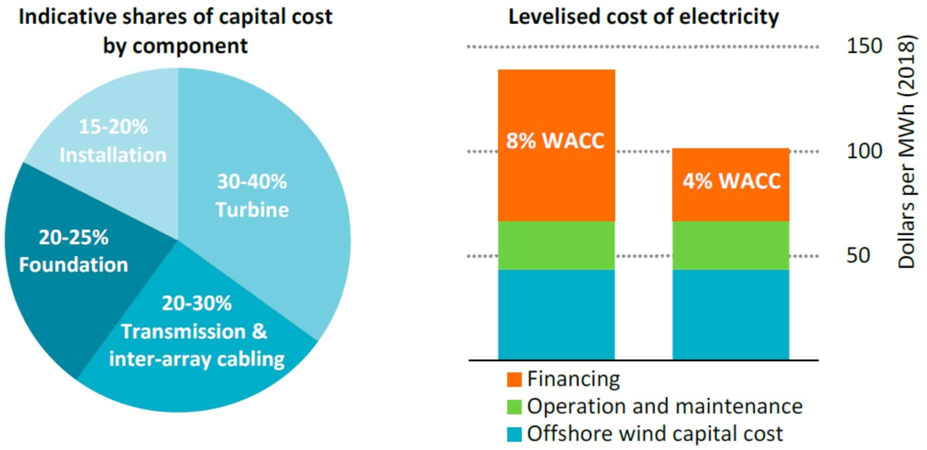


Figure 1 Offshore wind initial investment breakdown by component and LCOE for projects completed in 2018 [17]

These types of installations face several challenges due to their environmental and visual impact. Regarding the environmental effects, long-term implications are still uncertain. Some reports mention negative effects on the wildlife both below and above the water, while others indicate that foundations and structures may attract marine species and create new ecosystems [17]. Despite of this, several projects have been stopped due to the possible impacts on the environment. Conversely, the issue of visual impact is highly subjective. However, compared to onshore wind it is practically negligible and therefore emplacing OWFs far enough from the shore would eliminate possible rejections due to public opposition [22].

In general, OWFs are more expensive and more difficult to build in comparison to onshore, which is a more mature technology and implies less logistics (i.e., weather windows, vessel availability, etc) and specialized workforces. When it comes to upfront costs, as shown in Figure 1, turbines are the main expense of OWFs (40-60 % of the initial investment), followed by the installation (25 % of the investment). Foundations are usually the third largest cost, although new technologies, such as floating wind platforms, may lower these costs in the future, especially for deep waters, particularly when it comes to the installation and decommissioning [24]. Considering the whole lifetime of these OWFs, operation and maintenance also represents a significant expense [25] which combined with the WACC paid along the years incur into more than half of the resulting LCOE of these sort of projects [17]. However, as mentioned before, despite higher investment costs (currently around 4 times compared to onshore [17]) the resource is better offshore and thus the generation will be greater and more stable. In addition, the visual impact and noise of OWFs are much lower than those of onshore projects [25]. As shown in Table 2 below, despite working under the same principles, each technology can offer different contributions to the energy systems.

Table 2 Contribution of onshore and offshore wind

Offshore Wind	Onshore Wind
Good wind resource	Low LCOEs
Minimal visual impact	Simple installation and maintenance
Baseload energy source	Mature technology and business
Further cost reduction potential	Global availability of the resource

One of the factors with the highest impact on costs and complexity in the design and construction of OWFs is the water depth. To date, most OWFs have been built in shallow water with no more than 20 meters deep [17]. But as mentioned above, going into deeper waters provides the opportunity of benefiting from a vast resource. Therefore, the possibility of doing so in a cost-effective and technically possible way is being explored. On Section 2.1.1.2.3, the most common support structures of offshore wind turbines are explained more in deep.

2.1.1.1 Past present and future for the OWFs

In 1991, the world's first OWF was built in Denmark [22], since then, the growth of OWFs has been encouraging and it is expected to increase in the forthcoming years due to its huge potential. In addition to the 112 OWFs currently operational, there are 712 projects in different phases of development and 53 projects in pre- and under-construction as of August 2020 [22, 26].

By the end of 2019, there were 28.3 GW installed worldwide [27]. In Europe, more specifically, wind power is mainly exploited in the North Sea, off the coast of the United Kingdom, Belgium, Netherlands, Germany and Denmark, as shown in Figure 2.

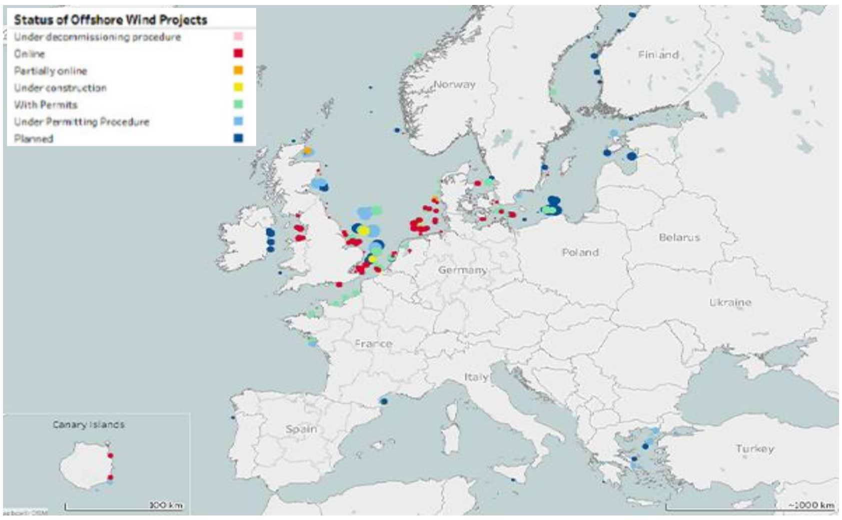


Figure 2 European OWFs map to date [28]

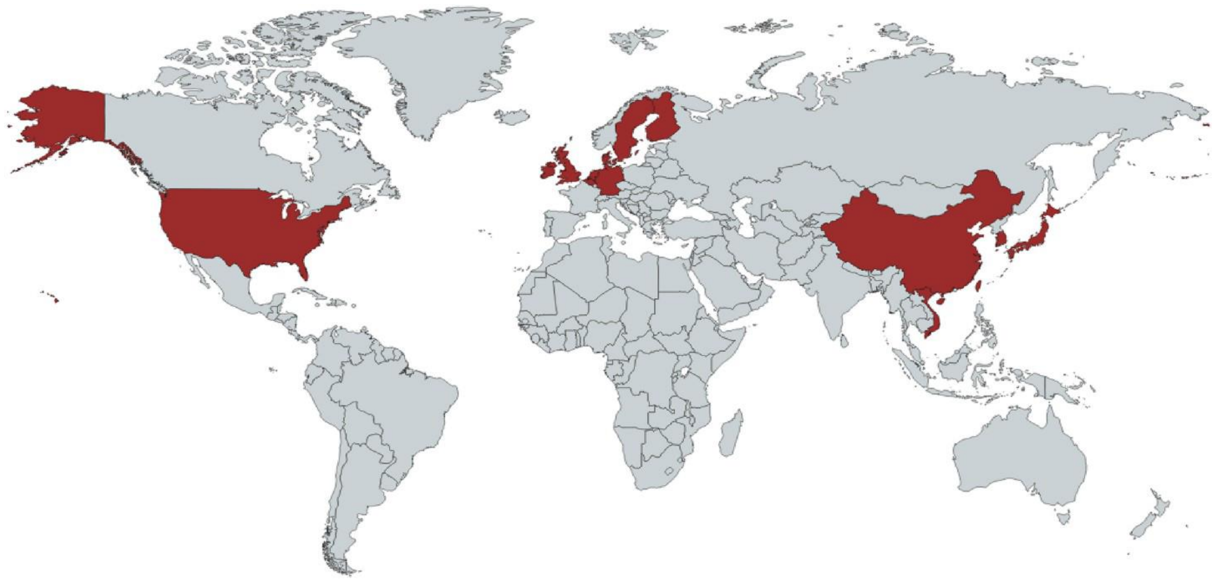


Figure 3 Global distribution of OWFs by countries [22]

Offshore wind has also been expanding significantly in the seas of China, which today is one of the top five wind energy producers in the international market, Figure 3. As it can be observed in Figure 4, the North Sea region and China represent most of the wind offshore capacity added from 2010 to 2018 [17], while they are expected to cope with the highest share of the market in the upcoming years too [22].

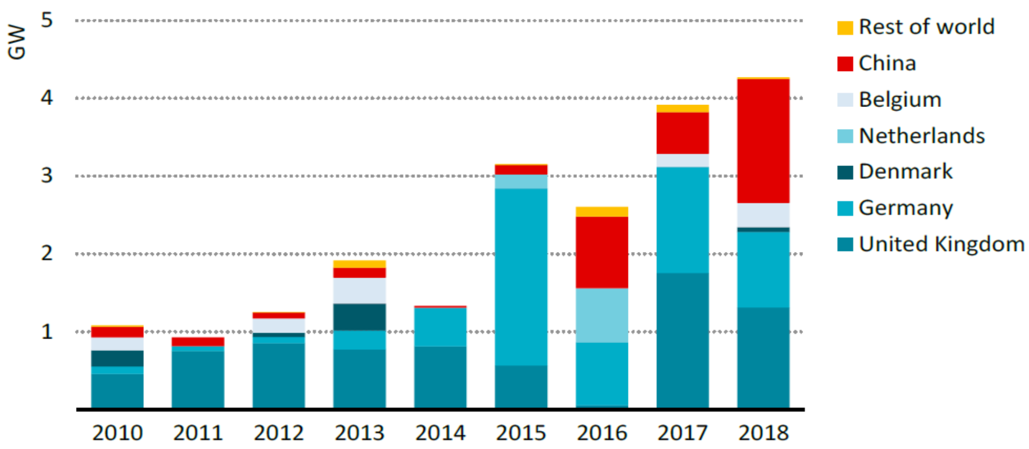


Figure 4 Annual offshore wind capacity additions by region [17]

As indicated by the IEA, global offshore wind market is set to expand significantly over the next two decades, achieving 345 GW of global installed capacity within the stated policies scenario or increasing more than twenty-fold the current capacity in the sustainable scenario to 560 GW [17]. The industry will continue to grow worldwide with a projected share of the global electricity supply between 3 % and 5.5 % by 2040 and between 16 % and 20 % in the EU as shown in Figure 5 [17].

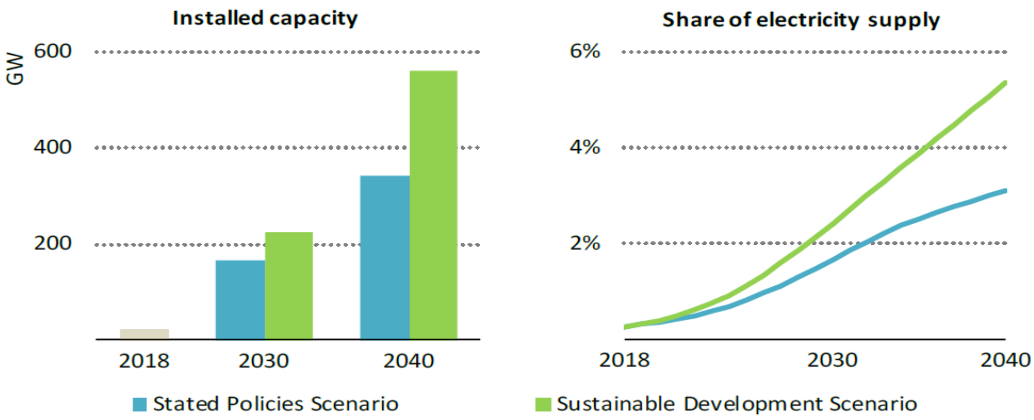


Figure 5 Projected global offshore wind capacity and share of electricity supply [17][1]

The fast development expected for this sector relies not only on the technology improvement, but also in the vast resource it can take advantage of. As shown in Figure 6, wind capacity factors above 50 % are available in areas closer than 60 km from shore. Wind´s technical potential in these areas is around 36,000 TWh, which is x1.5 the current electricity demand [17].

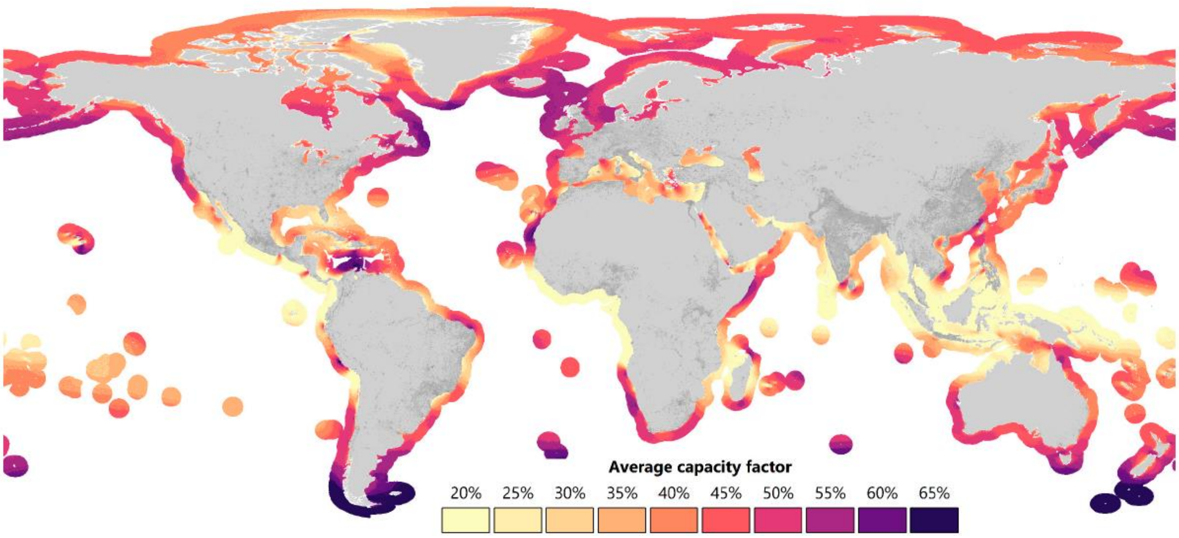
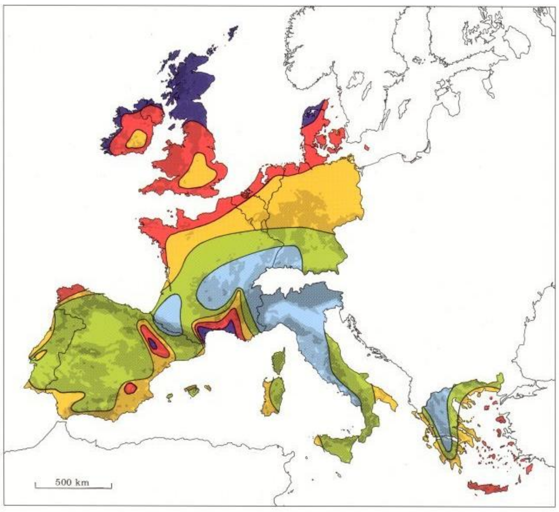


Figure 6 Average simulated capacity factors for offshore wind worldwide [17]

The exploitation of this RES, however, also depends on more factors than the wind availability. As an example, in the case of Europe, it is visible than the already installed OWFs belong to those areas with shallower waters (see Figure 2). This underpins that, to date, even if technologically possible, it is not economically viable to develop OWFs in areas where the wind resource is good, but water depth is prohibitive from a technology and economic deployment perspective (See Figure 7 and Figure 8). Floating wind turbines are expected to lower the costs of developing these projects and open possibilities for an economically feasible exploitation of offshore wind in deeper areas [17].

[1] Sustainable Development Scenario: Scenario which outlines a path to meeting global climate, air quality and universal energy access goals



Wind resources[1] at 50 metres above ground level for five different topographic conditions										
	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Figure 7 European wind resources [29]

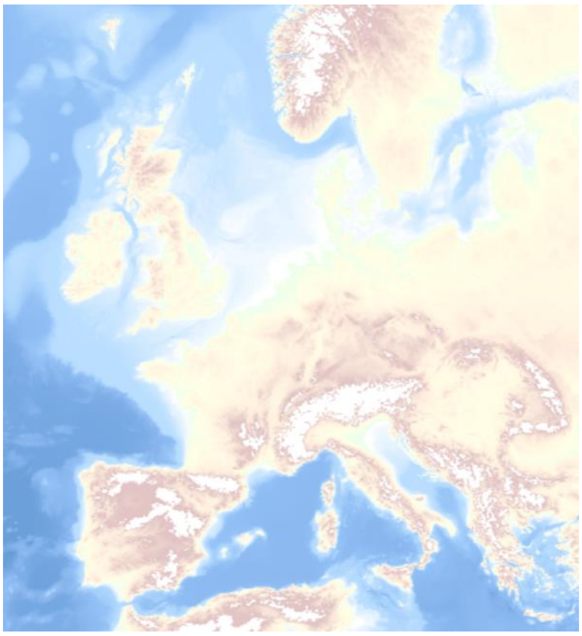


Figure 8 Sea depth in Europe (darker → deeper) [30]

2.1.1.2 OWFs classification

OWFs can be designed in different ways based on their location, the resource availability and the technical or economical requirements. There is no one-fits-all solution for the development of these farms, and therefore the configurations to be deployed have to be optimized based on different parameters. These also allow to classify the OFWs, for instance, in relation to the size, the capacity of the individual turbines, the wind turbine substructures used to attach the turbines or the way electric transmission to land is carried out are ways to sort the OWFs.

2.1.1.2.1 Wind turbine rated capacity

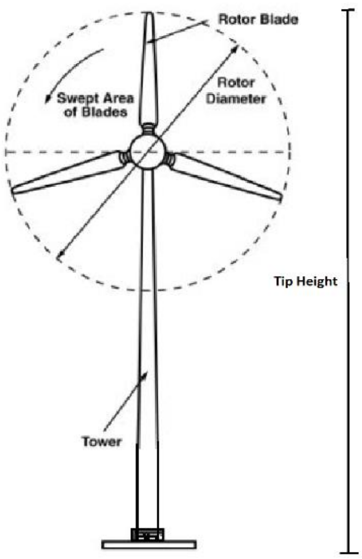


Figure 9 Wind turbine tip height and swept area [33]

Offshore wind turbines continue to gain strength. On average, turbine capacity increased by 16 % each year since 2014 (See Figure 10). The tip height of the turbines increased from over 100 m in 2010 (3 MW) to more than 200 m in 2016 (8 MW) while the swept area increased by 230 %, Figure 9.

The larger swept area allows for more wind to be captured per turbine [17]. A 12 MW turbine by General Electric is now under development and it is expected to reach 260 m [31]. Average rated capacity of turbines installed in 2019 is 7.8 MW, 1 MW more than the previous year [32]. This fact relies mainly on the technology innovation and the possibility of installing big turbines on the ocean, something that remains limited inland.

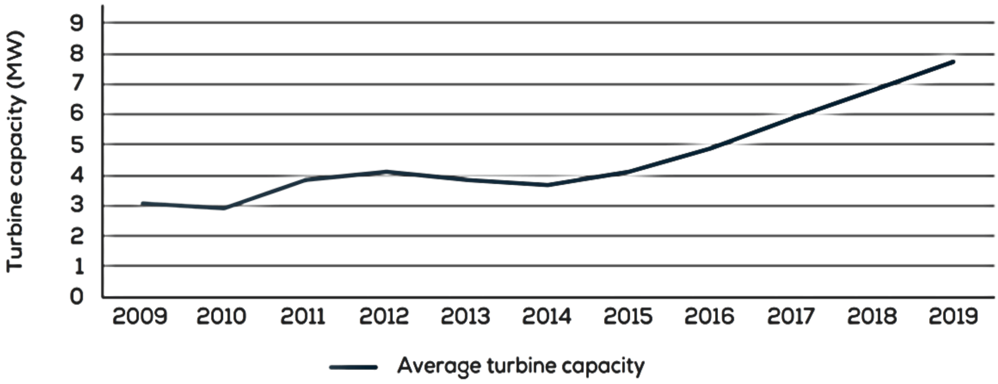


Figure 10 Average capacity per installed turbine [32]

In a very simplistic way, we can divide the wind turbines by 3 different sizes. The already existing size of less than 8 MW, the short-term planned medium size between 8 and 12 MW and the future prototypes with a capacity above 12 MW with a clear upward slope (See Figure 10).

Transportations of the parts of the wind turbines is one of the main barriers of large onshore wind turbines, being it complex to accomplish. This barrier is reduced with offshore installation, given that ships are able to carry larger pieces with reduced obstacles.

2.1.1.2.2 Wind farm size

Very related to the wind turbine capacity is the size of the wind farm. There is an increasing trend in OWFs size, doubling in a decade from 313 MW in 2010 to 621 MW in 2019 and the trend seems to continue in the short term (See Figure 11) [32].

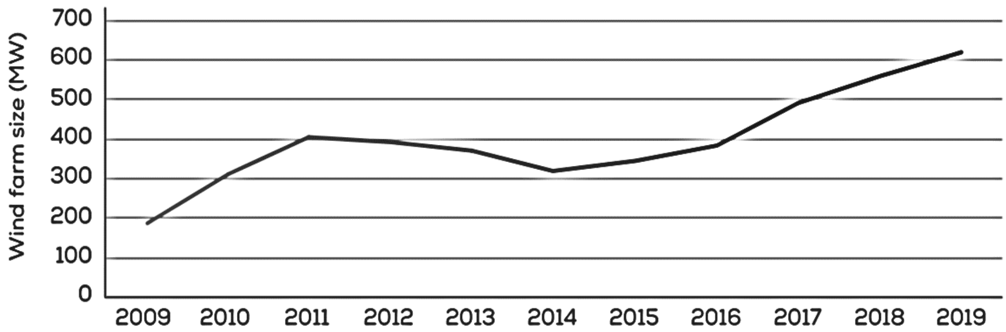


Figure 11 Average wind farm capacity [32]

2.1.1.2.3 Types of foundations

The foundation structures of offshore wind turbines are crucial elements in the development of the OWFs. They oversee anchoring the whole wind turbine and elevating it above the water. High forces and aggressive environments experienced in the sea make the design and installation of foundations a very complex activity [34]. The selection of the foundation will depend on aspects such as water depth or sea and soil conditions [35]. As shown in Figure 1, foundations account currently for 20-25 % of the total cost of the installation for an average wind farm. However, their costs may have great variations, being almost double for depths of 40-50 m compared to 10–20 m [34]. Different structures have been developed in order to adapt to the different depths and conditions (See Figure 12):

- **Monopile structures**: This method offers the simplest manufacturing and installation. The turbine tower sits directly on a pile. Monopile foundations are one of the most widely used supporting structures to date and shallowest water OWFs are monopile structures. They have the advantage of simple design for manufacturing and therefore lower costs, although its installation requires heavy equipment [34], due to the need of hammering hydraulically the monopiles into the seabed. These kinds of structures are suitable for water depths of 0 to 30 m [22].
- **Gravity foundations**: This type of foundation achieves its stability by supplying sufficient dead loads through its own gravity. It is generally a concrete-based structure which consists of sand, rock-filled and iron ore filled inside the base and a central concrete or steel shaft from the transition piece to the turbine tower [34]. It is suited for water depths greater than 20 m. High maturity of this method lowers its costs in construction and installation, while minimizes the risks [22].
- **Tripod structures:** The turbine is directly sited on a tripod which is supported on the pile foundations. The tripod structure is considered to be a relatively lightweight three-legged steel jacket compared to a standard lattice structure. Under the central steel column, which is below the turbines, there is a steel frame that transfers the forces from the tower to the three steel piles. Piles are installed at each leg position to anchor the tripod to the seabed. These structures tripod can be more effective than monopile. In the face of extreme events such as hurricanes or typhoons, the monopolies require greater suction caissons or longer piles. [22].
- **Jacket foundations**: Jacket foundations provide a solution for foundations in OWFs in water depths of 35 m and beyond which is less risky, less expensive, and more reliable than monopiles and gravity-base foundations. These offshore structures are suitable for locations having a water depth between 25 m and 50 m. Currently, there are 220 wind turbines supported by this foundation type [22].
- **High Rise Pile Cap (HRPC)**: The HRPC structure is suitable for low depths (0-20 m). It consists of a concrete bearing platform taller than the sea level and a group of steel pipe piles at the bottom of the bearing platform, wherein the lower end of the steel pipe pile inclines outwards slightly [22].
- **Suction caisson**: This technology works by lowering a sort of upside-down buckets into the seabed to anchor the offshore structures. Water is pumped out of the buckets producing a negative pressure inside the structures [34]. This suction, combined with the weight of the offshore foundation, enables the structure to sink deeper into the seafloor. This technology is best suited for deep waters and large wind turbines, and it does not require seabed preparation. It is also favourable for a quick removal of the structure [22].

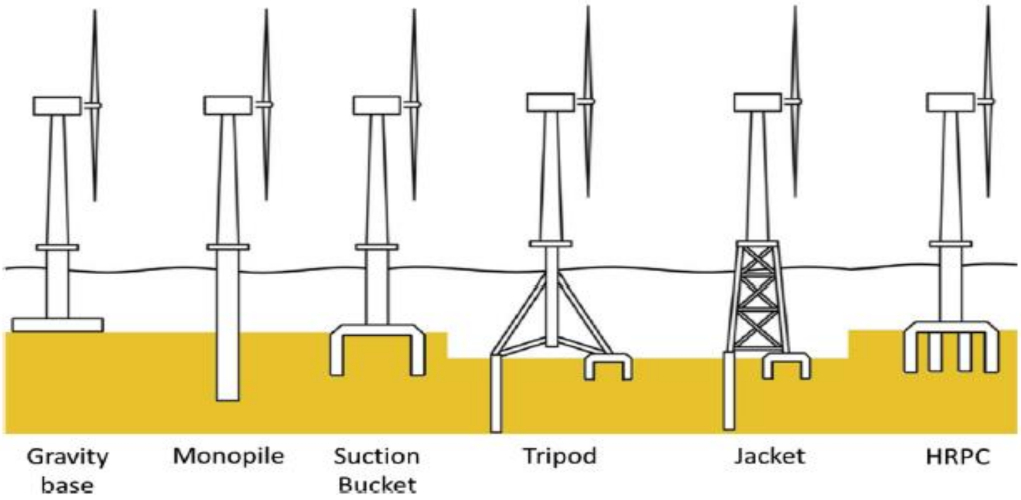


Figure 12 Most common offshore wind turbines structures [22]

- **Floating structures:** Floating structures are especially competitive at large water depths where the depth makes the conventional bottom- supported structures non-competitive. Above 50 meters, fixed bottom structures incur into higher costs and technical complexities, which implies major challenges, providing floating structures many advantages in deep waters such as lower costs and simpler construction, installation, and decommission [34]. This technology is expected to untap vast resources in the medium term [17]. It is classified into three categories in terms of how the design achieves its stability, as shown hereunder: ballast stabilized, mooring line stabilized (tension leg platform), and buoyancy stabilized foundations [34] (See Figure 13).

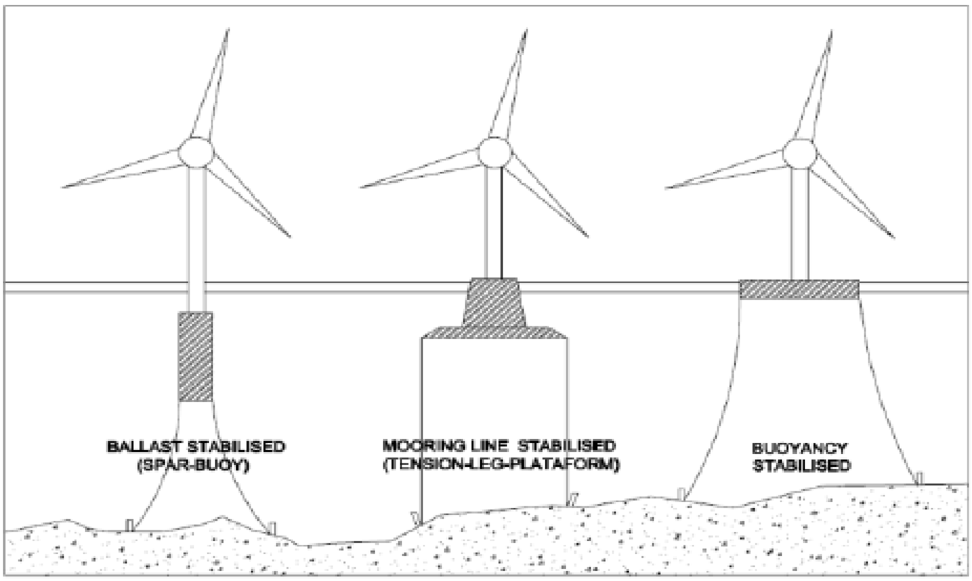


Figure 13 Floating wind structures [36]

Probably, the most popular design and the one taken into account in this thesis is the buoyancy stabilized foundation, consisting on a triangular base of floating tubes with the turbine located on one of the corners (See Figure 14) [37].

Figure 14 Floating wind structures [37]

The major advantage of this configuration in relation with H_2 production is the generation of the triangular base. It would create the required deck area to locate a H_2 production facility without need of extending the footprint of the sub-structure and just protecting it out of the splash zone. Although this change in the standard configuration will increase the cost of the structure, it will be insignificant [38].

2.1.1.2.4 Electricity transmission

As shown in Figure 1, transmission assets account for 20 - 30 % of the total upfront investments. These assets are mainly the cables and the substation. Cables can be either inner array cables, used to collect the power from the turbines and to take it to the substation, or they can also be export cables, which are those that connect the substation with the inland grid [39]. Cables are an element that is always present at the wind farms.

However, offshore substations are an element that may not exist since their presence will depend on the distance to shore and the amount of power to be transferred to land. The function of the substations is to receive the electricity brought by the inner cables from the wind turbines and condition it in order to be exported to land, minimizing costs and losses. This power conditioning consists mainly of converting the voltage with a transformer, generally at 20 or 33 kV from the array cables into 132 kV for its transmission [40]. Higher voltages are expected for the High Voltage Direct Current (HVDC) cases [41].

Offshore substations needed when the installed power of the wind farm is higher than 100 MW and/or when the farm is situated more than 15 km from shore [42]. Substations usually have a maximum power capacity of 500 MW as with higher power it is better to rely on more than one substation in order to guarantee supply in case of failure or operation & maintenance intervention (operation stoppage) [42].

The power conditioning of the substation can convert the electricity either in HVDC or High Voltage Alternate Current (HVAC) [43], being the former the most widely used currently. While HVDC is more costly [44], it has the potential to become more competitive and to present higher value to the system due to less losses and cost-decrease potential [43]. This is not only applicable at the substation level, but also taking into consideration the whole installation.

The selection of the export cables depends completely on this. The advantage of the HVDC transmission in terms of cables is that the losses are minimum due to a significant reduction in the dielectric losses, offering better features for the transmission of high power over long distances [44]. In addition, the cable amount required is lower, since HVDC uses single-core wires against three-core wires of the HVAC, what reduces installation costs and complexity [39].

2.1.2 H_2

H_2 and energy have crossed paths many times throughout human history. The supply of H_2 is not new but it has exponentially increased in the last 50 years and it is now a global business with multiple applications being used mostly in refining and in ammonia (NH_3) production. The demand for H_2 in its pure form is approximately 70 million tons per year (MtH_2 / year) and it is obtained almost entirely from fossil fuels (6 % of the world's natural gas and 2 % of the world's coal are used to produce H_2) while only 2 % of it is obtained from electrolysis [12]. Therefore, H_2 production is responsible for of the emission of about 830 million tonnes of CO_2 and, in terms of energy, the total annual demand for H_2 worldwide is about 330 Million Tonnes of Oil Equivalent (Mtoe) [12]. Figure 15 shows the current different uses of H_2.

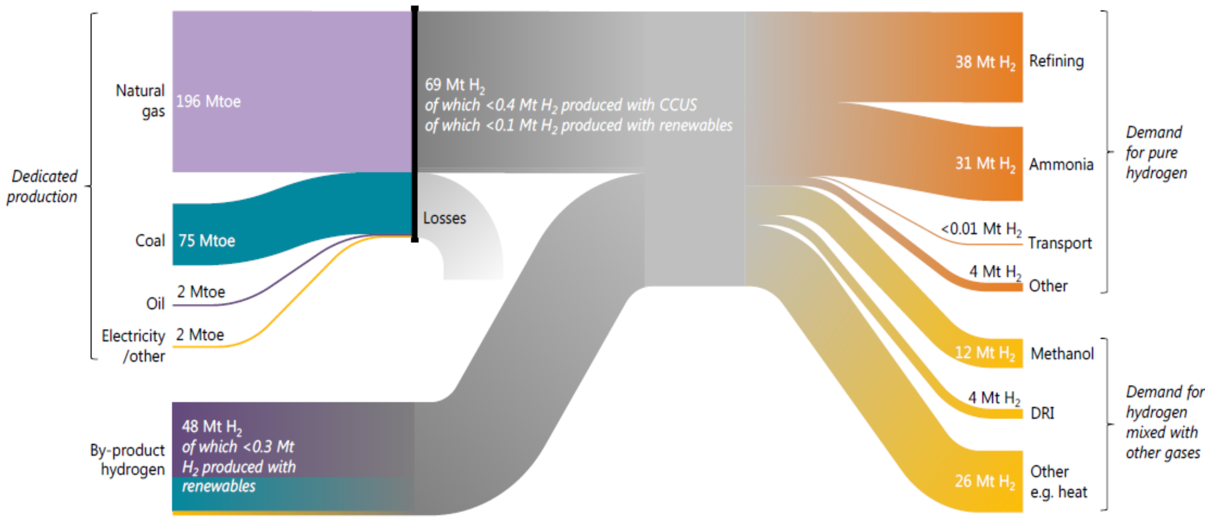


Figure 15 Sankey diagram of H_2 value chain [12]

H_2 properties

There have been peaks of inflated expectations regarding the H_2 economy in the past. The first demonstrations of water electrolysis and fuel cells took place in the 1800s [12]. Pure H_2 is found on Earth only in its molecular form (H_2), while it is generally found in compounds, mainly as water molecules (H_2O).

Due to its physical properties, H_2 is an almost permanent gas. Since gaseous H_2 has a very low density, it is usually stored under pressure, although liquefaction is also used in order to increase its energy density for optimized logistics. H_2 gas only liquefies at very low temperatures (below –253 °C), while its density is increased by a factor of 800 with an energy loss in the process of 30 % of its energetic content [12].

H_2 characteristics (both in gaseous and liquid state) such as high flammability, corrosivity and diffusivity require a careful handling of this molecule [45]. Nevertheless, it is a known process, especially at a distribution level, while it is still underdeveloped at the transmission level [12].

H_2 main benefit to the energy systems is its high versatility, which supports a deep integration of RES and the possibility of tackling emissions in several applications. Green H_2 (See Section 2.4.1) is especially interesting in the so-called hard-to-abate sectors [12], such as chemical industry, long-haul transportation and steel manufacturing, among others. Nevertheless, its role is different for each case, in the chemical reaction it is used as a feedstock, while in the high-heat production it is used as a fuel [46]. H_2 versatility particularly stands out in the transportation case, where it is expected it will be powering road vehicles and trucks in its pure form (H_2) by its application in fuel cells, or it can combine with other compounds to form synthetic fuels such as kerosene or ammonia (NH3) to be used in different air and sea transportation methods [46].

Conversely, the rollout of green H_2 at a mass scale level has two main constraints. First, the non-existence of an H_2 infrastructure, from transmission to demand, where there are very few applications that can handle 100 % pure H_2. This can be initially overcome by the introduction of small shares of H_2 in the natural gas grid, and by the use of H_2 in hubs where the production and demand are co-located, limiting the need for new infrastructure [12]. Secondly, costs of green H_2 are still very high when compared to other options such as fossil fuels or even blue H_2. For example, in Europe, green H_2 production costs are around 6 €/kgH_2 in the best cases, while H_2 produced from natural gas would cost between 1.75 – 2.3 €/kgH_2 depending on whether CCUS is used or not [12]. However, green H_2 is recognized to be the only sustainable option in the long term, while options such as the blue H_2 or fossil fuels use with CCUS are “bridge solutions” that can help decarbonize the economies but only in the medium term [2].

The possibility that H_2 offers in the decarbonization of different sectors that would not be easily addressed with direct electrification, has confirmed the key role of this molecule in the future of the energy systems, not only providing a decarbonization alternative but also more resilience and energy security for the entire system. Therefore, despite the existence of some challenges such as the above-mentioned difficulties to handle and the current high costs of its sustainable production, efforts shall be made in order to foster the adoption of H_2 in the energy systems. Figure 16 shows the global CO_2 avoided emissions in a future where Paris Agreement targets are achieved and H_2 is expected to tackle 8 % of the total CO_2 reductions in order to achieve net zero targets by 2070 [14].

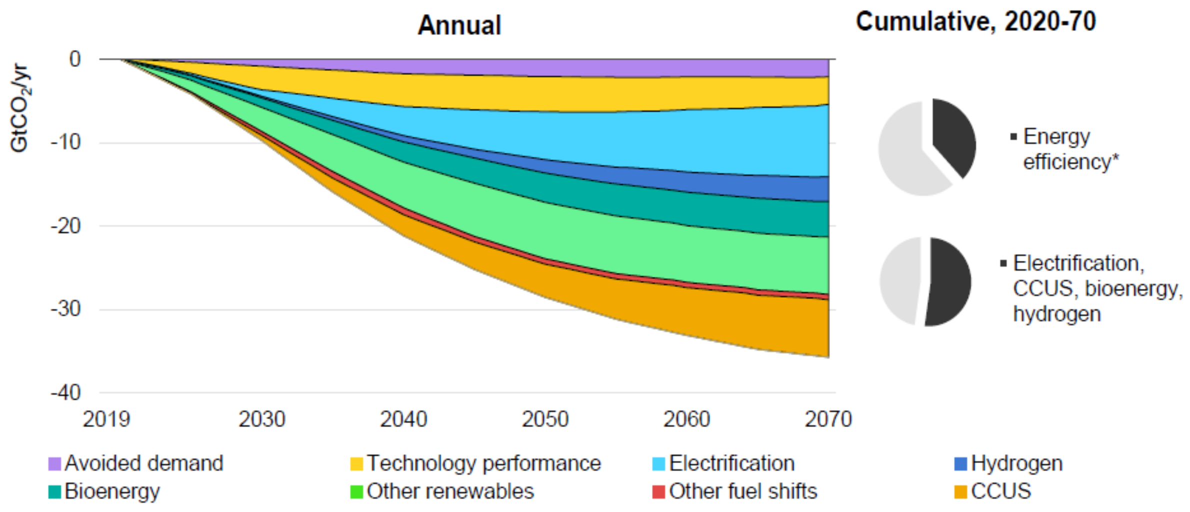


Figure 16 Cumulative global CO_2 reductions avoided by the adoption of each sustainable alternative related to the stated policies scenario forecast [14]

2.1.2.1 H_2 production

H_2 can be produced using a variety of energy sources and technologies. Global H_2 production today is dominated by the use of fossil fuels. Electrolytic H_2, that is, H_2 produced from water and renewable electricity, plays only a minor role, with 0.1 % of the dedicated H_2 production globally [12]. With the costs of renewable energies declining (in particular solar PV and wind energy), there is a growing interest in electrolysis of water for the production of green H_2 and in the scope of a greater conversion of this H_2 into fuels or H_2-based substances, such as synthetic hydrocarbons or NH_3 that could be more compatible than H_2 with the already existing infrastructure (gas pipelines etc) [12].

In order to sort the different routes from where the H_2 is produced and its carbon footprint, the following nomenclature is used [47]:

- **Green H_2:** H_2 produced from renewable energy and has no associated CO_2 emissions.
- **Blue H_2:** H_2 produced from fossil fuels with reduced CO_2 emissions due to the use of CCUS or from electricity from the grid.
- **Grey H_2:** H_2 produced from fossil fuels with no reduction of CO_2 emissions.

While grey H_2 is the main type of H_2 nowadays, green H_2 is expected to replace all this production in the future, while coping with most of the installations in the long term. Blue H_2 is also expected to have a role in the energy transition, acting as a bridge fuel for the introduction of green H_2 [2]. Nevertheless, this is policy dependent, and big H_2 consumers such as USA or China have still not expressed their position about the matter yet.

Depending on the primary energy used, H_2 production involves different conversion steps, as shown in Figure 17, being natural gas and coal the most representative in today's production, and electrolysis from renewable sources the one with highest potential. In addition, it is worth to mention that other pathways to obtain H_2 exist, but they are not expected to play an important role in the future H_2 production due to their difficulties to scale up, or the higher costs that these may represent [12].

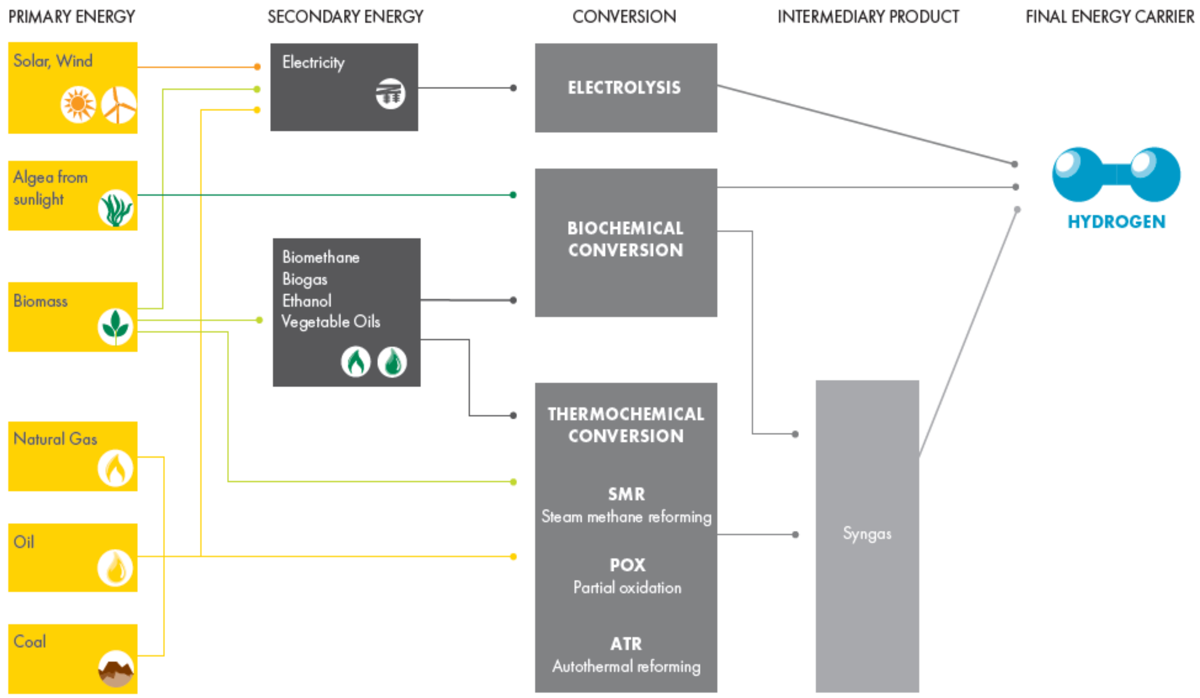


Figure 17 H_2 production pathways [48]

2.1.2.1.1 Natural gas

Most H_2 stock today is produced via steam-methane reforming of natural gas [49], which is a mature production technique, being NH_3 and refineries the main destination of it. Natural gas is the energy provider for about 75 % of the world's annual dedicated production of H_2. The description of the most common methods to produce H_2 from natural gas are described below:

- **Steam Methane Reforming (SMR):** It is used to extract H_2 mostly from natural gas and sometimes from liquefied petroleum gas (LPG) and naphtha. Natural gas in SMR is both a fuel and a feedstock (together with water). Typically, 30 to 40 % of the natural gas is combusted to fuel the process, giving rise to a "diluted" CO_2 stream, while the rest of it is split by the process into H_2 and CO_2 [12].
- **Autothermal Reforming (ATR):** ATR is an alternative technology in which the required heat is produced in the reformer itself. This means that all the CO_2 is produced inside the reactor, which

allows for higher CO_2 recovery rates than can be achieved with SMR. ATR also allows for the capture of emissions at lower cost than SMR because the emissions are more concentrated [12].

The cost of producing H_2 from natural gas is influenced by several technical and economic factors, with the price of gas and CAPEX being the two most important [12]. Moreover, in a future where the emissions will have to be captured, the easiness of this will lower the costs of the overall system. ATR is expected to compete with SMR due to lower CCUS costs thanks to the more concentrated CO_2 outflow [12]. This blue H_2 production with the use of CCUS raises the costs of the final product (See Figure 18), however, increasing costs of CO_2 emissions will make blue H_2 competitive with grey H_2 in the medium term [46].

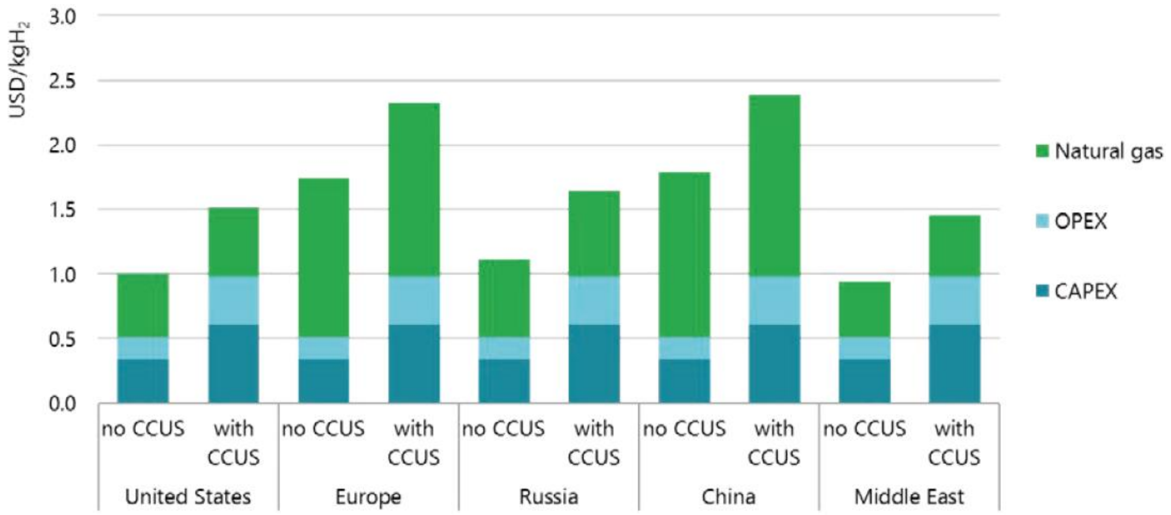


Figure 18 Cost of producing Blue and Grey H_2 depending on the region [12]

2.1.2.1.2 Coal

Coal represents the second most common source of dedicated H_2 with a 23 % of the total world's production [12]. Although the use of coal for H_2 production has become an unpopular source of energy due its CO_2 emissions, which double those of natural gas, it keeps playing a dominant role in countries such as USA and China, where more than 80 % of the current coal gasification plants in operation are located [12].

On one hand, coal is a complex and highly variable substance that can be converted into a variety of products. On the other hand, gasification is a well-established technology that can produce a synthesis gas, which is composed of a mixture consisting primarily of carbon monoxide and H_2 [50].

As it occurs with natural gas, the production of H_2 from coal also offers potential for further emission reduction when integrated with advanced technologies in coal gasification, power production, and CCUS [50].

2.1.2.1.3 Electrolysis

Electrolysis consists on the separation of the elements of a compound by applying a voltage differential. Therefore, water electrolysis is an electrochemical process that splits water (H_2O) into H_2 and Oxygen (O_2). As shown in Equation 1.

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{1}$$

If natural gas is 75 % and coal is 23 %, nowadays only around 2 % of the production of dedicated H_2 globally comes from water electrolysis (only 0.1 % from renewable electricity) [12] and the H_2 produced with this technology is used in markets where high purity H_2 is needed (See Section 2.4.1). Green H_2 produced with renewable electricity is projected to grow rapidly in the next years [51]. By replacing fossil fuels, electrolysis can help to reduce greenhouse gas emissions in the power, mobility and chemical sectors [52] and the reason is that electrolysis requires just two elements: water and electricity.

As introduced in Section 1.1, it is expected that by 2070, the global capacity of electrolysers will expand to 3,300 GW (in order to produce around 310 Mt of green H_2) by 2070 from 0.2 GW today [14]. These electrolysers would use around 13750 TWh of electricity per year [14].

Green H_2 produced from electrolysis depends greatly on the electricity input costs, which may account for 60-90 % of the LCOH [12]. Therefore, after the great renewable electricity cost reductions in the recent years, increasing interest in sustainable H_2 produced through electrolysis is taking place [17]. Several companies, especially utilities, have already announced big projects using electrolysis [53].

Approximately 9 kg of water are needed to produce 1 kg of H_2 and 8 kg of O_2 [12] (H_2 and O_2 can be used in different fields, from the health sector to many industrial purposes (See Section 2.4)). For industrial H_2 production, there is significant need of water, which can be a problem in areas that go under water stress, but the use of sea water can become an alternative in coastal areas. Direct use of sea water in electrolysis today leads to corrosive damage and chlorine production and researchers are seeking for ways to use sea water [54]. In this context, water desalination, which is a widely known technology, can be applied in order to obtain useful feedstock with relative low costs. The most common method for purifying the sea water is to use reverse osmosis demanding 3–4 kWh/m^3 and having costs around 0.63–2.25 €/m^3 of water [12]. The typical layout of an electrolyser system can be seen in Figure 19.

Figure 19 Electrolyser configuration [55]

There has been an increase in new electrolysis installations over the last decade aimed at producing H_2 from water, with PEM Alkaline Electrolysis and SOEL (Section 2.1.2.2.1) as the most popular technologies in the market.

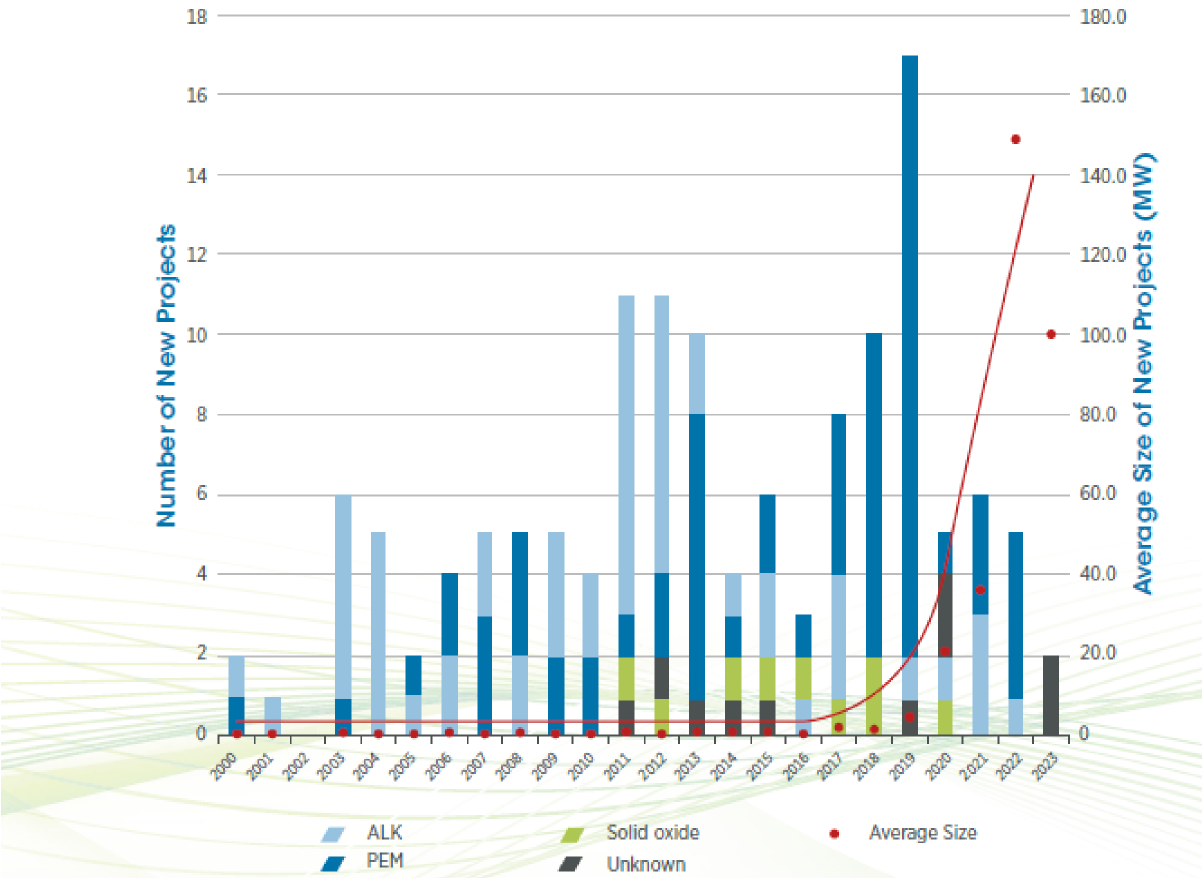


Figure 20 Timeline of power-to-H_2 projects by electrolyser technology and project scale [51]

Efforts to ramp-up green H_2 use for the energy transition are increasing in many countries, but geographically most of the projects are located in Europe (Norway, UK…), although projects have also been started or announced in Australia, China and North America [51]. The average unit size of these electrolyser additions has increased in recent years from early 2010s were most projects were below 0.5 MW, while the largest in 2017-2019 were 6 MW [12], indicating a shift from small pilot and demonstration projects to more suitable to be commercial-scale applications Figure 20. This, in many cases with government subsides should start to create economies of scale that will drive down costs and will help to scale up the supply chain of the electrolyser industry.

2.1.2.1.4 H_2 production cost and CO_2 comparison

LCOH breakdown and CO_2 intensity for different production pathways are shown in Figure 21 [12]. It can be observed how, in terms of cost, H_2 production coming from fossil fuels are the cheapest options, even though the carbon intensity is also significant. On the contrary, both green and blue H_2 offer sensible CO_2 footprint reductions while representing higher costs of production. Renewable electricity production can still offer further cost reductions as CAPEX and fuel costs are expected to halve in the next years.

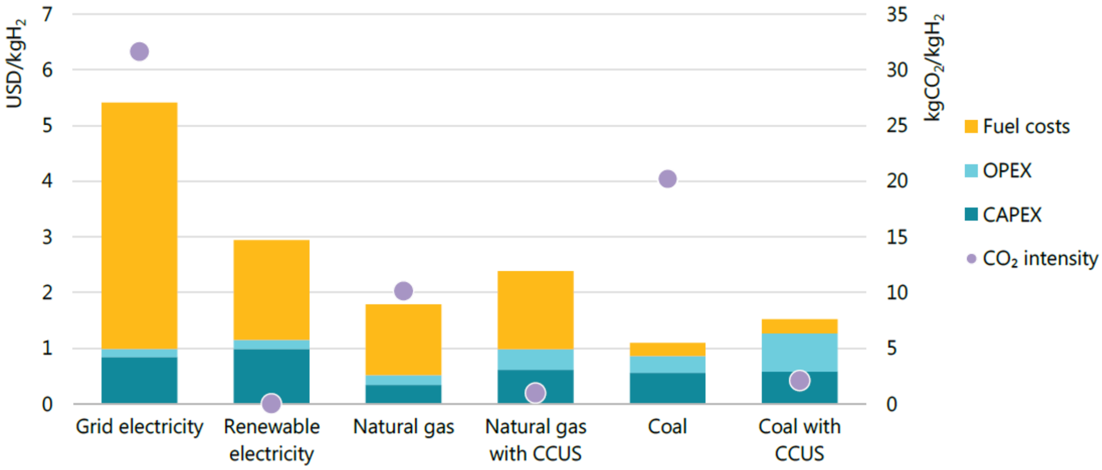


Figure 21 LCOH breakdown and CO_2 intensity for different production pathways2 [12]

For the coal case, CAPEX requirements represent about 50 % of the cost of producing H_2. In the case of including CCUS the OPEX will be doubled while the fuel cost represents a minor share of the LCOH. Therefore, the availability and cost of coal play an important role in determining the viability of coal based H_2 projects. In terms of emissions, coal is at the top with more than 20 $kgCO_2/kgH_2$, being drastically reduced with CCUS to 2.5 $kgCO_2/kgH_2$. Reducing the carbon footprint will be a critical factor for the prospects of coal-based H_2 in a low-carbon context. In China and India, with their well-established coal mining, coal based H_2 equipped with CCUS is likely to be in the medium term the cheapest option for clean H_2 production [12].

[2] CO_2 tax not included in the “fuel costs”

In the case of natural gas, fuel cost represents more than 60 % of the final share, being the CAPEX and the OPEX the lowest values within all the options. Adding CCUS doubles both CAPEX and OPEX. Blue H_2 from natural gas will probably occupy the leadership in the medium-term production of H_2 because of the established distribution networks for natural gas and the cheaper prices if compared to renewable energy. Also, the CO_2 footprint is significantly lower than for the coal case, halving its emissions for both the grey and blue H_2 cases.

For the electrolytic production of H_2, both grid and dedicated renewable energy inputs are analysed. In both options, the fuel source represents the major cost of the LCOH. The main reason is the efficiency in the electrolysers (Section 2.1.2.2.1). Particularly interesting are the significant disadvantages presented by the grid connection case, where both costs and CO_2 associated emissions rocket if compared to the other possibilities. On the other hand, electricity from renewable sources implies no direct emissions.

2.1.2.2 Considerations

H_2 production from electrolysis is a well-established industry. However, it is a novel concept in the energy sector. Its coupling to RES may bring new opportunities but also new designs and requirements. Regarding the nature of this project, some of the main considerations to consider are presented as follows.

2.1.2.2.1 Technology

Water electrolysis technologies can be classified according to the applied electrolyte, which separates the two half reactions at the anode (O_2 Evolution Reaction (OER)) and cathode (H_2 Evolution Reaction (HER)) of the electrolyser [56]. The main water electrolysis technologies are Alkaline Electrolysis (AEL), Polymer Electrolyte Membrane Electrolysis (PEMEL) and Solid Oxide Electrolysis (SOEL).

The principles, layout, reactions and relating properties of AEL, PEMEL and SOEL are hereunder discussed.

AEL is a mature, commercial and bankable technology, which has been applied for large-scale H_2 production already in the beginning of the 20th century in particular for H_2 production in the fertiliser and chlorine industries [12]. These electrolysers operate with a liquid electrolyte solution (KOH/NaOH) with 25-30 % concentration. Anode and cathode are separated by a membrane which has the dual purpose of carrying electric charge between the electrodes and separating the products formed at each electrode [57] in order to obtain H_2 or O_2 at the cathode and anode respectively [58]. This layout of the cells is also characterised by the absence of precious materials, leading to low capital costs if compared to other electrolyser technologies. The reactions occurring at each side of the cell are shown in Equation 2 and Equation 3.

$$2H_2O\ (l) + 2e^- \rightarrow H_2(g) + 2OH^-(g) \qquad \text{Cathode} \qquad (2)$$

$$2OH^-(g) \rightarrow \frac{1}{2}O_2(g) + H_2O(l) + 2e^- \qquad \text{Anode} \qquad (3)$$

The process principle of an alkaline electrolyser is shown in Figure 22. The electrolyte is stored in two separated drums for each product gas (O_2 and H_2) which serve also as gas-liquid-separator.

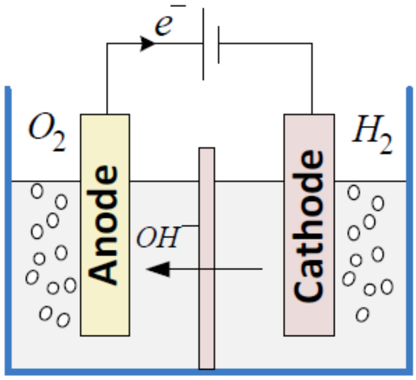


Figure 22 Alkaline electrolysis process illustration [16]

PEM electrolyser systems were first introduced in the 1960s to overcome some of the operational drawbacks of alkaline electrolysers such as the recovery and recycling of the potassium hydroxide electrolyte solution that is necessary with AEL [16]. PEM water electrolysers use a polymer electrolyte membrane, which consists of a thin, solid ion-conducting membrane. The membrane not only transfers the H+ ion (i.e., proton) from the anode to the cathode side, but also separates the H_2 and O_2 gases [56].

As in the previous case, two sides can be distinguished, anode and cathode. Both divided by the proton exchange membrane. However, in this case, precious metals are used in the system, the electrocatalysts or electrodes are deposited in both sides of the membrane, creating the membrane electrode assembly (MEA) [56]. These metals vary depending on the reaction to be activated. In the anode, iridium or ruthenium are used in order to lower the activation energy of the O_2 evolution reaction (OER), while in the cathode, platinum or palladium supported in carbon black are the electrocatalysts used for the H_2 evolution reaction (HER). The reactions occurring at both sides of the cell are shown in Equation 4 and Equation 5.

$$2H^+(g) + 2e^- \rightarrow H_2(g) \qquad \text{Cathode} \qquad (4)$$

$$H_2O(l) \rightarrow \frac{1}{2}O_2(g) + 2H^-\ (g) + 2e^- \qquad \text{Anode} \qquad (5)$$

The process working principle of a PEM electrolyser is shown in Figure 23. Water is oxidized at the anode to produce O_2 and H_2 evolves at the cathode [16]. The structural properties of the electrolyte also allow for high differential pressure between the H_2 and the O_2 side [56].

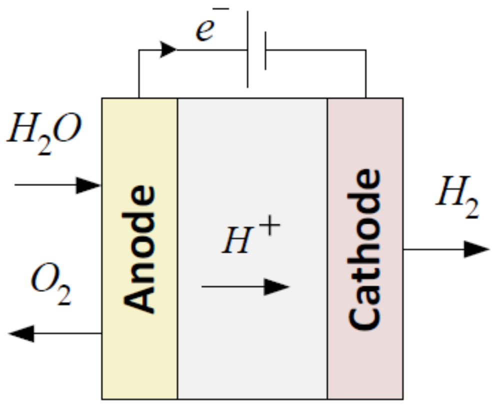


Figure 23 PEM electrolysis process illustration [16]

SOEL systems are the least developed electrolysis technology, still in a demonstration stage and has not been commercialised at a big scale yet [12]. The elements of a SOEC are a ceramic electrolyte and two porous electrodes (anode and cathode). These electrolysers work under high temperatures (650-1000ºC), which offers better electrical efficiency in the H_2 generation (90 %). SOEL is receiving increasing interest due to the possibility that it offers to take advantage of waste heat [12]. Also, these systems can operate in reverse mode, acting as a fuel cell. In addition, they can synthesise syngas if CO_2 is pumped inside the cell with the water [12]. However, limitations still need to be addressed, such as the degradation of the materials of the whole system at these high temperatures [12].

Water is fed to cathode and O_2 ions are transported to the anode side through the electrolyte, and H_2 is produced at the cathode side. The reactions at the electrode are as indicated in Equation 6 and Equation 7.

$$H_2O\ (l) + 2e^- \rightarrow H_2(g) + O^{2-}(g) \qquad \text{Cathode} \qquad (6)$$

$$O^{2-}(g) \rightarrow \frac{1}{2}O_2(g) + 2e^- \qquad \text{Anode} \qquad (7)$$

The working principles illustration of a SOEL cell is shown in Figure 24:

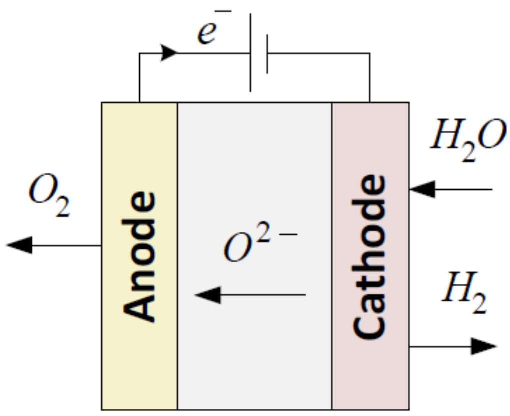


Figure 24 SOE process illustration [16]

A quantitative comparison of the different technical, performing and economic characteristics the abovementioned technologies is shown in Table 3:

Table 3 Electrolysis technologies comparison [12] [16]

	Alkaline	PEM	SOEL	Unit
Operating Pressure	2-30	15-30	<30	bar
Operating Temperature	60-90 up to 200	50-90	500-1000	h
Stack Lifetime	<90,000	<40,000	<40,000	h
System Lifetime	20-30	10-20	-	Years
Efficiency (HHV)	62-82	67-84	~90	%
Cold Startup	>15	<10	> 60	min
Maturity	Commercial	Early Commercial	R&D	-
CAPEX	450-1,260	990-1,620	2,520-5,040	€/kW$_e$
OPEX	3 %	2 %	-	Of CAPEX

Also, a qualitative comparison is presented in Table 4 in order to understand the possible contributions of the different types of electrolysers.

Table 4 Advantages and disadvantages of the different electrolysis technologies [16]

	Alkaline	PEM	SOEL
Advantages	– Well-established – Large stack size – Long-term stability – Low capital cost – Non-noble materials	– High current density – Design Simplicity – Compact system – Dynamic operation – Rapid response	– High energy efficiency – Non-noble materials – Low capital cost – Reversible operation as fuel cell – Possibility of using waste heat
Disadvantages	– Low current density – Corrosive electrolyte – Slow dynamics – Gas permeation	– High membrane cost – Noble materials – Acidic environment – Low durability	– Bulky design – Unstable electrodes – Brittle ceramics – Sealing issues

2.1.2.2.2 Location of the station

Even if today most of the projects are considering inland H_2 production, coupling H_2 with offshore wind may bring up the possibility of producing H_2 offshore too. Some projects are already considering this reality (See Section 2.2.5). Therefore, the location of the infrastructure required to produce the desired H_2 could be placed onshore or offshore (As shown in Figure 25). There are multiple factors that must be assessed in order to choose the most suitable option.

For the inland case, the H_2 production plant is located in firm ground and installation and maintenance represent low costs in comparison to the offshore case. Also, the response to unpredicted events (e.g., corrective maintenance) is more rapid than if the workers have to go to the offshore plant. Moreover, for an inland production case, water can be taken not only from the sea but also from freshwater resources depending on the availability of these, skipping the desalination step.

On the contrary, an offshore platform (Figure 25) would be much more limited, representing higher costs in terms of installation and OPEX. In addition, it would be limited in terms of what resource to use, since sea water is the only available option as the feedstock. Other considerations to take into account in the offshore environment are how the instability of the platform affects the operating conditions of the equipment and how the marine corrosivity may influence the integrity of the systems.

However, when analysed, the offshore case may bring certain benefits in terms of cost reductions, especially for a dedicated production case, where the OWF would be directly connected to the H_2 production plant. In this case, the use of electric cables to land would be avoided, saving a large amount of money from the installation of these. Moreover, the use of pipelines to export the H_2 is cheaper than the use of cables for long distances. Besides, offshore plants offer a more modular package if combined to the OFW, what eases the design and installation, apart from avoiding complexities in terms of land rights, grid connections inland or scarcity of useful land.

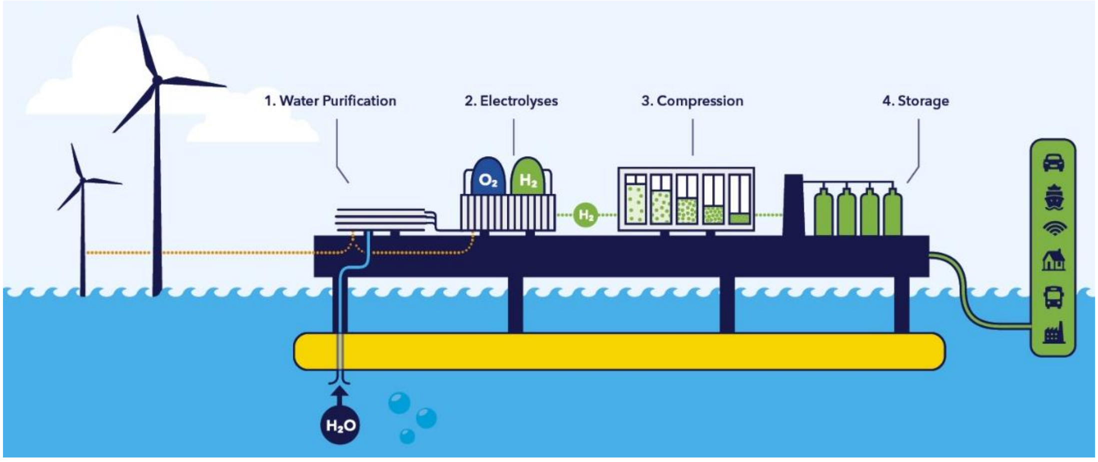


Figure 25 Offshore H_2 plant configuration [59]

Some of the upsides and downsides of these two possible options are summarized in Table 5.

Table 5 Location of the H_2 substation pros and cons [18]

	Onshore	Offshore station	Offshore wind turbines
Advantages	– No space problems – Cheap installation – Easy maintenance – Flexibility	– Flexibility – Easy maintenance	– Installed from port – Small scale already proven – Close to the wind farm
Disadvantages	– Far from the wind farm	– Need of a platform – Sea conditions	– Sea conditions – Space

2.1.2.2.3 Production method

Very related to the location of the H_2 station is the production method. Production facilities have the possibility of producing in a decentralized or a centralized way. These two possible configurations comprise either a modular electrolyser system being included on the wind turbine structure or a centralised plant, following an electric substation concept to house the electrolysis equipment (See Figure 26).

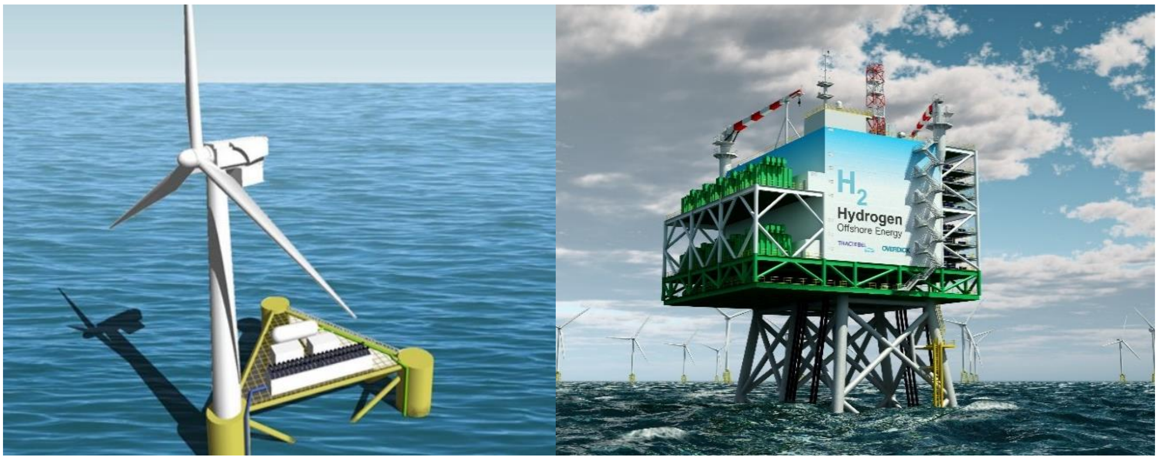


Figure 26 Decentralised production, from Dolphyn project [60] and centralised production, from Tractebel [61]

For the first case, the electrolysis system will be located on the wind turbine. The installation of this H_2 facilities would be very linked to the wind turbine design, with the benefit of being assembled at the port. Moreover, the electrolyser can benefit from direct DC transmission from the turbine, while also erasing the need for inter-array cables. The main driver for this option would be the distance from shore. [38]

In this thesis, the decentralised way will correspond to the electrolysers incorporated on the wind turbines. Small electrolyser units (<12MW) used in this option are attractive for early low-demand stages. They require less absolute capital investment, it can be stepped-wise and no transport and delivery infrastructure for the electricity produced since the H_2 will be produced in-situ. However, operation, control and maintenance of many small H_2 units require a high cost-effective process control [62]. It is also important to remark that specific costs of the electrolyser system itself will be higher (economies of scale). On the contrary, savings from a structure to host a centralized facility also occur. Therefore, it is necessary to assess which options are more attractive in the overall system analysis. Table 6 shows the advantages and disadvantages of both configurations.

Regarding the centralised production, it presents a more secure and stable supply. Centralised large facilities decrease specific costs by the implementation of economies of scale. Furthermore, it increases the efficiency of the production and storage systems. [62]

Also, the possibility of implementing permanent manned facilities, could provide a faster response time for unplanned maintenance activities. The main driver for the selection and specification of substation is the space requirement of the electrolysers. [38]

Table 6 H_2 Production methods pros and cons [18]

	Centralized	**Decentralized**
Advantages	− Easy maintenance − High efficiency	− Independency of the modules − No need of electricity cables
Disadvantages	− Need of electricity transmission − Extra area required	− Expensive maintenance − Need of link all the systems

2.2 Coupling concept

Offshore wind projects dedicated to the production of H_2 from renewable sources can offer significant cost advantages over projects that use electricity directly from the grid or other renewable sources that offer lower capacity factors. This fact is recognised by several companies and institutions such as the IEA [17]. Moreover, and as previously stated, OWFs can reach places where there are no transmission grids, or that other RES cannot reach (See Figure 6).

High initial capital costs of electrolysers mean that they need to operate as often as possible in order to offer competitive LCOH, and the high annual capacity factors (around 50 %) combined with the affordable LCOE (25 €/MWh by 2040 without transmission assets) offered by offshore wind energy would meet this need [17].

There exist different possible configurations when combining offshore wind with H_2 production, such as dedicated production, the use of curtailed electricity or a hybrid between both, these are explained more in deep in Section 2.2.2.

When coupling OWFs and H_2, some of the main considerations for the layout are presented in the following subchapter.

2.2.1 Location characteristics

2.2.1.1 Water depth

The water depth affects both the wind farm and the H_2 station (in case it is located offshore). As it has been described in Section 2.1.1.2.3, depending on the sea depth and conditions, different foundations are used for the wind turbines, going from monopiles for low depths to floating structures where the depth is 50 meters or more. On the other hand, having an offshore plant will require a floating structure or a bottom fixed platform.

In both cases, the path to follow will be similar to those of the existing electric substations. However, there is a possible synergy to consider as well, since there is the possibility of taking advantage of already existing infrastructure from the oil and gas industry for the centralised H_2 production. This would lower the costs for this method. However, compatibility of existing pipe materials with H_2 should be considered. Especially if some of the pipes are made of non stainless steel. Therefore, in some cases appropriate reconditioning of these pipes will be necessary. Something similar is being done at PosHYdon project (See 2.2.5), which is already producing H_2 in an offshore oil rig [63] [64].

For the decentralised production, water depth will only influence the design of the wind turbine/farm foundation. However, sufficient space must be left for the electrolyser systems to be installed and it must not impact the platform's stability.

2.2.1.2 Wind conditions

The wind resource is vital for the success of the coupling concept and a deep study should be performed to find the best suitable location and its characteristics so that the wind turbines are adapted to the resource. In order to carry out wind potential assessments, Weibull, Nakagami, Rician, and Rayleigh distributions are commonly used to forecast wind speed distributions [65].

Compared to onshore wind, offshore wind energy is generally more reliable and consistent [17]. As wind is highly temporally variable, detailed analysis of wind characteristics should be conducted at different timescales. For wind power, the wind data, including the wind speed and direction, should be measured for at least one year with the aim to increase the reliability of the results [65].

Figure 27 shows a wind rose of an unspecific site. It is visible as the prevailing wind direction can be determined easily, what drives the orientation of the wind turbines [65]. However, it is also observable that wind does not come from only one specific direction. Therefore, the nacelle typically offers the possibility to rotate 360 º [66].

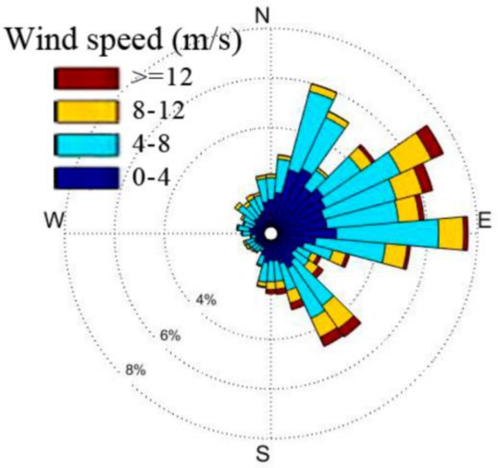


Figure 27 Example of a wind rose [67]

The Figure 27 also shows that apart from variations in wind direction, there are variations regarding the wind speed. These two factors affect the power load given from the turbine to the electrolyser. Therefore, careful attention must be paid to the selection of the electrolyser, in order to select the technology that better adapts to electricity input intermittencies, particularly for the case of the decentralised production, where every electrolyser is coupled to a wind turbine and the variability is higher besides, they suffer from Wake Effect.

2.2.1.3 Distance to shore

The distance to the coast is highly related to the transport of H_2 or electricity transmission and will affect significantly on the final cost of the installation and therefore the LCOH. Depending on the distance of the wind farm to the shore, it may be technically and economically preferable to install pipelines, cables or even the use of ships (Section 2.2.4) [38]. Moreover, this will have an impact not only on the economics but also on the complexity of the installation and the losses over the transmission.

Apart from that, there exists a subjective problem coming from the visual impact on the seascape that could entail the successful development of the energy project [68]. In this case for this type of projects, several parameters are considered such as the surface covered and the arrangement of the wind farm as well as its perception from the horizon as perceived from the shore and it may increase the perception of security and safety from local population, parameters that mainly depend on the distance of the facilities to the coast. [68]

2.2.2 Electricity source

As mentioned above, when considering a coupling project of OWF and H_2 production, there can be different configurations when it comes to the electricity input to power the electrolysers. Going from a dedicated production to a scenario in which only the curtailed electricity is used, or a combination of these two.

2.2.2.1 Dedicated H_2 production

The first possibility for the H_2 production would be having dedicated production of H_2, this means that all the energy produced from the OWF is exclusively used to power the electrolysers in order to produce H_2. [67] In this case the OWF is connected directly to the H_2 production facility, it allows a more optimised design of both systems since it could, for example, run only in DC, avoiding redundant conversion equipment, both in the turbines and in the H_2 production systems. Moreover, the electrolysers would have a more optimised capacity since the forecast of the energy use is more reliable than in a case in which only the curtailed electricity is considered. Besides, the capacity factor of the electrolysers will be higher and therefore, taking advantage of more operating hours helps to dilute the high initial investment, however, this needs to be weighed against higher costs due to electricity prices or higher OPEX due to degradation of the system, specially the stack, which has a typical lifetime of 60,000 h, what would equal 17 years if the electrolyser was running 50 % of the time, or 34 years if the capacity factor was 20 % [12].

A typical situation suitable for this scenario would be an area of high wind resources but limited grid access (long distance from coast or no transmission grids inland). Instead of being connected to electricity grid on shore by expensive submarine transmission lines, they can be substituted by specialised vessels to transport the H_2 from an offshore platform, removing the distance issue. [17]

2.2.2.2 Curtailed H_2 production

A second possibility for the electricity connection to the H_2 production plant, is to take advantage only of the curtailed electricity from the OWFs, which are typically shut down when the grid is already saturated. Curtailments face an uncertain future, smart grids, priority dispatching and better forecasting are helping to decrease the curtailment hours, yet it is emerging as a major concern for the investors and wind farm operators [69], even more as the share of renewable capacity in the grid is increasing.

In this thesis, it is considered curtailment only when energy delivery from the OWF to the electrical grid is restricted, because the transmission system is overloaded, this is when supply exceeds demand (mostly at night), and the grid operator may need to back down generation [70]. In these cases, the electricity produced has a price of 0 €/MWh. When it happens, the electricity generated would be redirected to be used in the electrolysers to produce H_2.

This scenario could require an inner software which must choose between electricity grid and H_2 production depending on the grid price [67]. It also has extra costs associated with the transmission assets, since apart from having transmission cables to land, also a H_2 transportation method is needed.

2.2.3 H_2 and other gases production

When H_2 is produced by water electrolysis process, O_2 is also produced simultaneously as a by-product of H_2 and 1 kg of H_2 implies the production of 8 kg of O_2. Although the main driver of this thesis is the H_2 production, the potential of selling O_2 is also assessed, paying special attention to its effect on the overall economics of the project [71]. Figure 28 shows the large range of applications for the products of the electrolysis process.

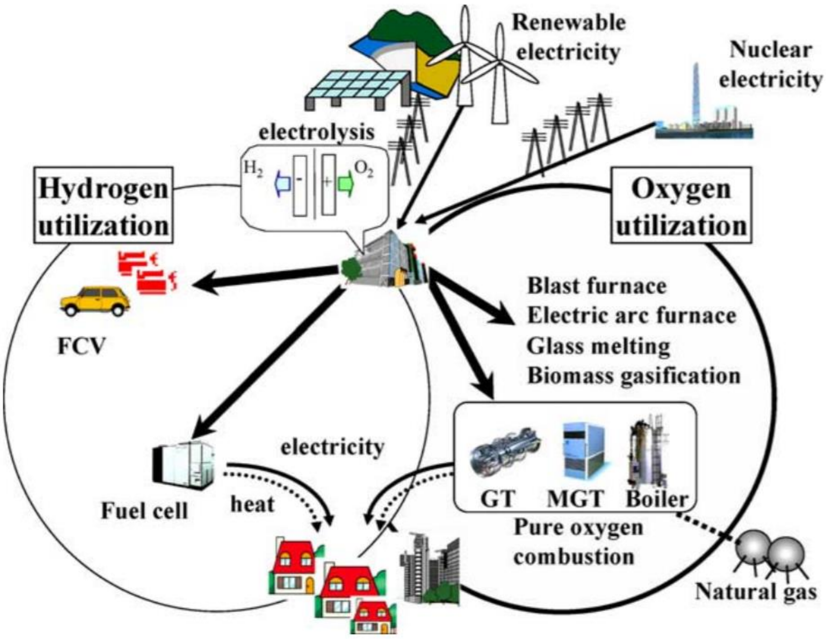


Figure 28 Diagram of utilization of H_2 and by-product O_2 [71]

In order to understand the potential of selling O_2, its industrial applications have to be evaluated. O_2 is an important industrial gas utilized in many processes (See Section 2.4.2) [71].

The commercialization of O_2 also implies that a new infrastructure has to be considered for this gas. Although it does not require a complex system, some equipment such as the O_2 compressor and its dedicated pipelines has to be included in the system configuration if sales were to be accounted.

2.2.4 Transport and storage method

Once produced, H_2 needs to be transported in order to be delivered to consumers. It can be considered a transportation at a transmission level, with larger quantities and longer distances, or at a distribution level, where the amounts of transported H_2 and the distances are smaller.

Transportation of H_2 is a trendy topic, since its new applications, especially in the energy field, are opening the discussion about exporting H_2 from country to country. There are two main options when transporting H_2, as a pure H_2 molecule, or as a larger compound, the so-called H_2 carriers. Both cases offer different performances, in terms of complexities and costs, as seen in Figure 30.

For the pure H_2 transportation, two possibilities exist:

- Gaseous H_2 transportation: It can be either done by pipelines or stored in gaseous cylinders. For the pipelines case, there are already more than 5,000 km of pipelines installed worldwide currently, although these are used at a distribution level in different industrial hubs [12]. The industrial gas providers operate their own pipeline transportation network to meet the demands of their customers, for example, Air Liquide operates an 879 km transport network line located in Belgium, the Netherlands and France. Air Products and Praxair operate transportation lines in the United States with total lengths of 175 and 275 km respectively. The existing ducts have a diameter of 25-30 cm and operate at pressures of 10-20 bar (although pressures of 100 bar are also used) [72]. In the case of cylinders, until the current date, the most used transportation methods are the metallic vessels, where H_2 is compressed up to 350 bar and stored, although generally this pressure is 200 bar [73]. However, the development of new storage vessels made from carbon fibres (Types III and IV) instead of metals (Types I and II) are expected to take these pressures up to 750 bar [73]. These vessels are then transported by trucks to the final consumers.

H_2 compression consumes different amounts of energy regarding the initial and final pressures (See Figure 29). Mechanical compressors have been the most widely methods to compress H_2 [74], however, new ionic liquid piston compressors are expected to cope with the highest share of new installations, due to their better performance with H_2 such as higher efficiencies and lower maintenance [74].

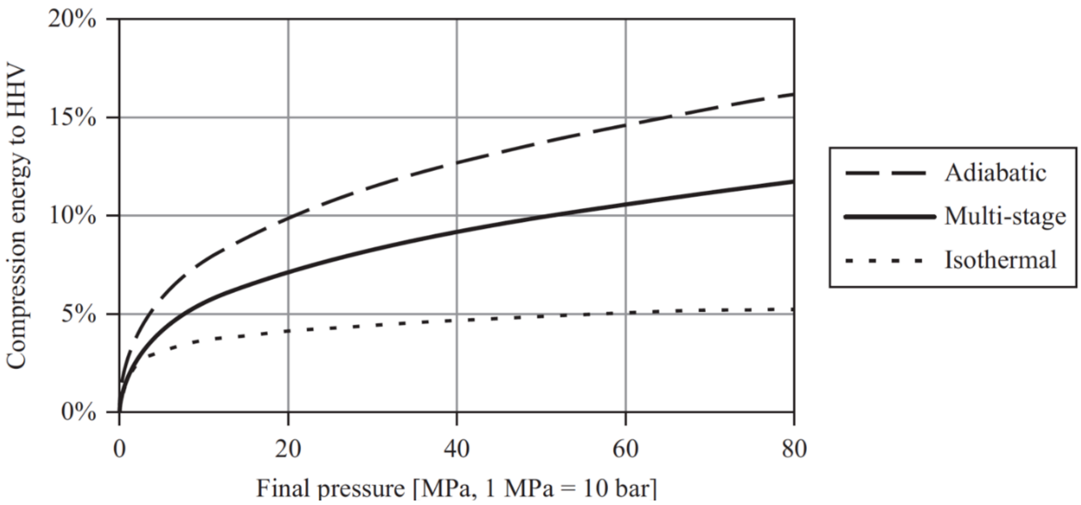


Figure 29 Energy required to compress H_2 in terms of its HHV

It is necessary to bear in mind that although these two methods are transporting gaseous H_2 they differ significantly from each other, both in logistics and in costs. In the pipelines case, high investments are required in order to set the infrastructure, however lower OPEX and losses would be expected. On the contrary, trucks distribution is not CAPEX intensive, although the annual costs and losses can add high expenses over the lifetime of the project. Moreover, the distribution by trucks becomes less competitive as the distance increases [12].

In terms of offshore operations, H_2 is not transported either by boat or pipeline in its pure form currently. However, the oil and gas industry has been installing and operating sub-sea pipelines for many years and values from this industry can be extrapolated for the development of this project.

- Liquefied H_2 (LH_2) transportation: in order to increase the energy density of H_2 for more optimized logistics, H_2 can be liquefied by lowering its temperature down to -253 ºC. This is a high energy requiring process, that consumes up to 30 % of the Lower Heating Value (LHV) contained in the H_2 (10-13 kWh/kgH_2) [75] [76] although new concepts such as the project IDEALHY are expected to lower this value down to 6 kWh/kgH_2 [77] [78].

  This cryogenic H_2 is kept in vessels with efficient insulation, covered with an external protective jacket and an inner pressure tank. H_2 evaporation, or boil-off, can be a problem for long term storage, representing a daily loss of 0.1 % of H_2 contained in a vessel loss [79]. However, this H_2 can be used to power the auxiliary systems, or to supply that hydrogen to the ship's fuel cells to move the ship in a sustainable manner with zero emissions [77].

  Transportation of liquid H_2 is typically performed by trucks with insulated tanks, although new opportunities may arise with international trading of this molecule, with the seaborne transportation of H_2 from exporting to importing countries. To date, there is only one ship dedicated to the transportation of LH_2, the "Suiso Frontier" dedicated to provide Japan with H_2 produced in Australia, this vessel can carry 1,250 m^3 of LH_2 per journey [80].

Despite the energy density increase when H_2 is liquefied or compressed, the transportation as a pure molecule implies several challenges [81]. Firstly, its energy density is still low compared to other fuels or H_2 transportation alternatives. Moreover, the development of a new infrastructure can be very costly. In addition, the transportation and handling of H_2 as a pure substance is still difficult due to its flammability, its diffusivity and its corrosivity on different materials [12]. This is the reason why H_2 carriers are being explored in order to enable a large-scale transportation of H_2. These carriers rely on the combination of H_2 with molecules in order to form larger and more stable compounds that offer better characteristics for its transportation and storage.

Among the most common H_2 carriers, NH_3, methane (CH_4), methanol (CH_3OH) and liquid organic H_2 carriers (LOHC) standout [79]. Most of these carriers are already used nowadays, however their utilization is not considered for H_2 transportation, but for end uses, such as the case of methane, with all the natural gas uses worldwide, or the NH_3, which is used to produce fertilizers. Conversely, their application as H_2 carriers is not operating yet, although new upcoming projects already rely on these molecules as the H_2 offloading methods [82] [83]. These cases can take advantage both of pipelines and vessels. Particularly interesting is the case of LOHC, which are oil alike compounds that can take advantage of all the existing infrastructure for the oil industry such as the tankers or the storage tanks [84].

However, although the importance of these offloading methods is significant in order to improve the transportation of H_2, only pipelines transportation to land by a mature and cheap option, such as compressed H_2, is considered as the transportation method. in the scope of this thesis.

Pipelines transporting compressed H_2 are a mature technology, while the know-how to install and operate sub-sea pipelines can be incorporated from the oil and gas industry.

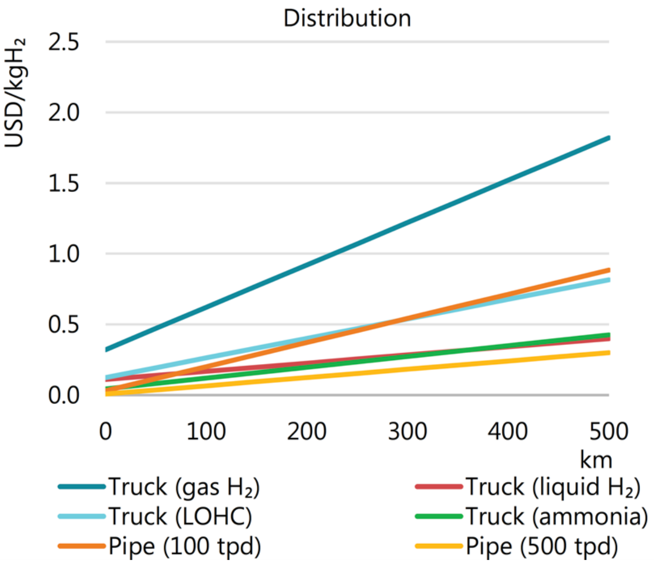


Figure 30 Distribution costs for different H_2 transportation methods [12]

2.2.5 Current concepts/projects

Several companies or institutions have identified that the aforementioned synergies between H_2 and offshore wind can provide significant benefits to the energy systems. Therefore, several projects, have been developed or are under development stages. Some which standouts are:

- **Dolphyn project**, led by the Environmental Resources Management (ERM), it consists on the development of a H_2 production unit on a floating semi-submersible platform with an integrated wind turbine (See Figure 26). The goal is to produce green H_2 in an electrolyser that is directly coupled to the turbine, avoiding extra costs such as a centralised structure, and the installation of cables. The ambition is to have an operational prototype in 2023. This project was awarded by the UK government and will test a 2 MW pilot [60].
- **PosHYdon,** by Neptune Energy consists on the installation of an electrolyser on an already existing bottom-fixed Oil&Gas platform, powered with cable from shore. A 1 MW electrolyser will be placed within a sea container and installed on Neptune's Q13a platform, located 13 km from the Dutch coast. The H_2 will be transported via an existing pipeline to an offshore structure where it will be used to generate electricity for the oil rigs operations. This project aims to obtain knowledge useful for a future coupling with the OWFs in the area [64].
- **Tractebel:** part of Engie, is developing a concept for an offshore bottom-fixed platform with large-scale H_2 (400 MW) through electrolysis from offshore wind. A wide range of applications is mentioned: Mix H_2 in natural gas grid, relief for constrained electrical grids, seasonal storage. This concept aims to give a second life to oil extraction platforms [61].

- **Deep Purple**, which is being developed by TechnipFMC and HYON plans to convert power from offshore wind to H_2 and store it on the seabed. Offshore fuel cells would then be used to provide sustainable power for offshore oil and gas platforms [85].
- **Gigastack project,** which is a consortium between ITM Power and Örsted, aims to produce low-cost and zero-carbon H_2 from offshore electricity, which will power PEM electrolysers, based inland. The project already accounts for a high electrolysis capacity, reaching up to 100 MW [86].

2.3 Other characteristics

2.3.1 Technological Readiness Level

The Technology Readiness Level (TRL) is a measure to describe the maturity of a technology [87]. The use of TRLs enables consistent discussions about the technical maturity of different types of technologies. The 9 different TRLs classification used in the thesis are defined as [87] [88]:

- **TRL 1. Basic principles observed**: In this phase the idea is developed and the transition from basic research to applied research begins, but there is still no specific activity or business application.
- **TRL 2. Formulation of the technology**: In this phase, the technology is formulated and practical applications that may become an invention are observed, which may still be speculative and there may not yet be detailed tests or analyses to confirm these assumptions.
- **TRL 3. Applied research - proof of concept**: In this phase, the validation of the idea begins, which already includes research and development activities such as analytical studies and laboratory-level tests to physically validate the predictions of the separate elements of the technology, although these are not yet integrated into a complete system.
- **TRL 4. Small-scale development in laboratory**: In this phase, the basic components or separate elements of the technology are integrated, and it is validated that they work together at the laboratory level in order to identify the potential for expansion and operational issues.
- **TRL 5. Real-scale development**: In this phase, the first prototype is developed, that is, the components are integrated in such a way that the system configuration is similar to its final application in almost all its characteristics, but its operation is still at the laboratory level.
- **TRL 6. Prototype validated in simulated environment**: In this phase, the prototype is validated under conditions similar to those expected to work, so the prototype must be capable of developing all the functions required by an operating system and the processes are expanded to demonstrate the industrial potential.
- **TRL 7. Prototype validated in a real environment**: In this phase it is demonstrated that the technology works and operates on a pre-commercial scale, it is usually where the first pilot run and real tests are carried out to identify the issues of the manufacturing and final operations.

- **TRL 8. Commercial prototype:** In this phase, it is demonstrated that the technology works on a commercial level through a large-scale application, operational and manufacturing issues have been resolved and documents for the use and maintenance of the product are prepared.
- **TRL 9. Commercial application:** In this phase, the product is fully developed and available to society, since technology is in its final form and operable in a number of operating conditions.

2.3.2 Commercial readiness index

Beyond being able to classify the maturity of the project´s technologies with the TRLs, it is also important to consider their Commercial Readiness Index (CRI). Usually, both TRL and CRI are at the same level, meaning that when a technology is fully developed you can find it easily in the market, however it is possible to have that a mismatch occurs. For example, this is happening currently for the case of the fuel cell trucks. The technology is proven, and it has been operating at a commercial stage for some years now, but the manufacturing capacity remains still very limited. This bottleneck constraints the fuel cell trucks supply, even if the TRL is already at its maximum.

Despite being a subjective concept and very difficult to determine, it can be estimated based on the manufacturer´s offers in the current market (Figure 31)

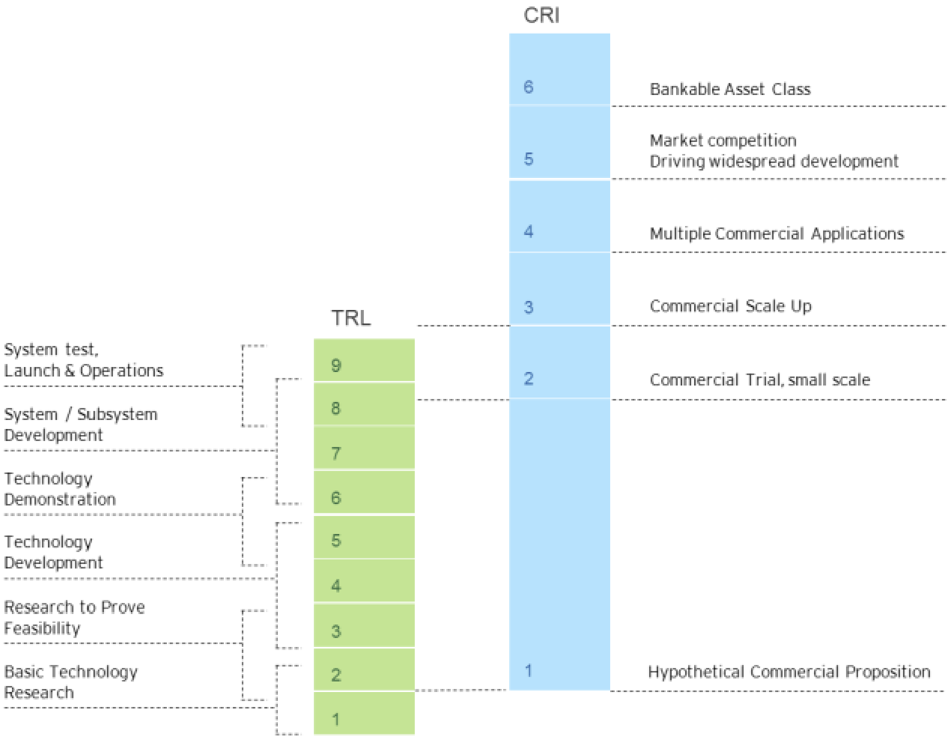


Figure 31 TRL and CRI [89]

2.3.3 Economical characteristics

When developing a project such as the one covered in this thesis, there are several economic indicators that acquire special relevance from both a feasibility and bankability point of view. These indicators may allow to see the project developers how far the project can go, and in what markets the product will be competitive. In the other side, other metrics, allow investors to decide whether the investment is attractive or not. The main financial indicators considered in this project are:

- **CAPEX:** Capital expenditures (CAPEX) are funds used by a company to acquire, upgrade, and maintain physical assets such as property, plants, buildings, technology, or equipment. CAPEX in this project considered as the initial investment since no other acquisitions are expected to be accomplished [90].
- **OPEX:** An operating expense (OPEX) is an expense a business incurs through its normal business operations. These expenses include rent, equipment, inventory costs, marketing, payroll, insurance, step costs, and funds allocated for research and development [91].
- **REVENUES:** Revenue, often referred to as sales, is the income received from normal business operations and other business activities [92].
- **LCOH:** Levelized cost of H_2 represents the average revenue per kg of H_2 produced that would be required to recover the costs of building and operating a production plant during an assumed financial life and duty cycle.
- **IRR:** It is the annual rate of growth an investment is expected to generate. It is ideal for analysing capital budgeting projects to understand and compare potential rates of annual return over time [93].

2.4 Markets for H_2/O_2

2.4.1 H_2

Nowadays, the majority of the H_2 (pure and mixed) is used in only three industrial sectors: oil refining (33 %), chemicals (NH_3 production 27 %, methanol production 11 %) and metals (iron and steel 3 %). However, the H_2 used in these sectors comes mostly from fossil fuels (Section 1.1) having a negative impact in the environment providing a potential market for H_2 coming from cleaner pathways such as blue or green H_2 coming from electrolysis [94]. Nevertheless, H_2 irruption in the future energy systems will open up new markets for this molecule, as explained below.

2.4.1.1 Current applications

Oil refinery: In last decades, refinery H_2 demand has grown substantially, and the trend is that its demand in refineries will grow by 7 %, from 38 MtH_2/y to 41 MtH_2/y by 2030. In the oil refining industry, H_2 is used in order to upgrade the oily compounds, being hydrotreatment and hydrocracking the most frequent processes. In these refineries H_2 is responsible and of around 230 MtCO_2/yr. Figure 32 shows how the H_2 demand in the oil refining industry changes under different scenarios. With the current trend the demand will continue to increase slightly year by year, on the other hand following the Paris Agreement it will be decreased, being the existing refineries, the ones taking the lead in this reduction.

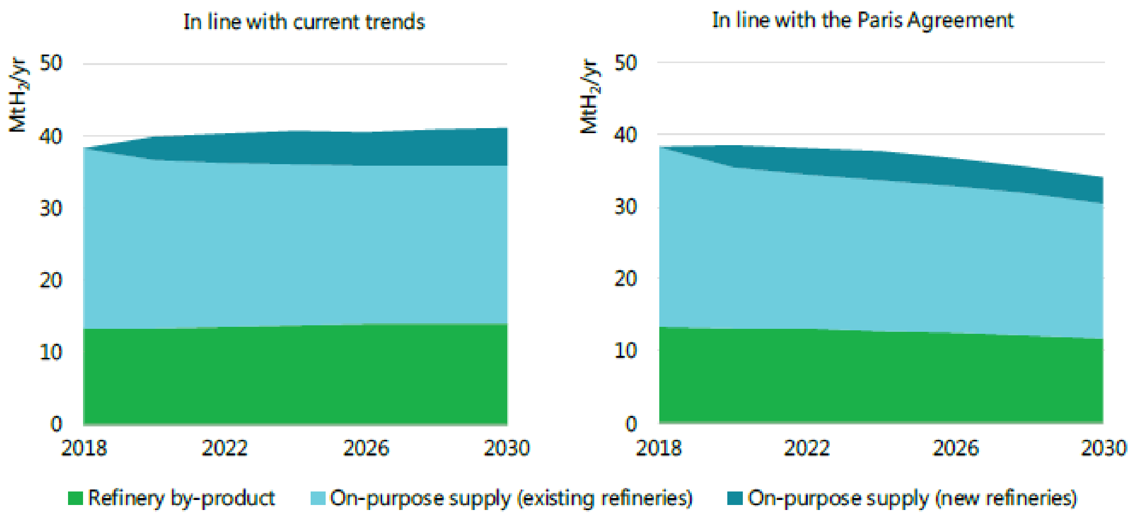


Figure 32 Future H_2 demand in oil refining under two different scenarios [12]

Chemical industry: Despite the chemical sector produces a big variety of products coming from H_2, NH_3 and methanol industries are the largest consumers with 31 Mt H_2 and 12 MtH_2 per year respectively (See Figure 33). NH_3 or methanol require large quantities of dedicated H_2 production for use as a feedstock. These compounds are expected to require 40.6 Mt of H_2 per year by 2030, increasing 52 % their current demand of H_2 [12]. NH_3 is particularly important for the manufacturing of fertilizers. Methanol is forecasted to grow significantly faster, at 3.6 % [12], spurred by the development of methanol to high-value-chemicals (HVC). Although it may seem that in the next years with the reduction of plastic consumption due to people's awareness towards climate change, recycling and new policies, demand for NH_3 and methanol could decrease it can occur the opposite. The demand could rise in the next decades Figure 33 if these chemicals become established as energy carriers for the transmission, distribution and storage of green H_2.

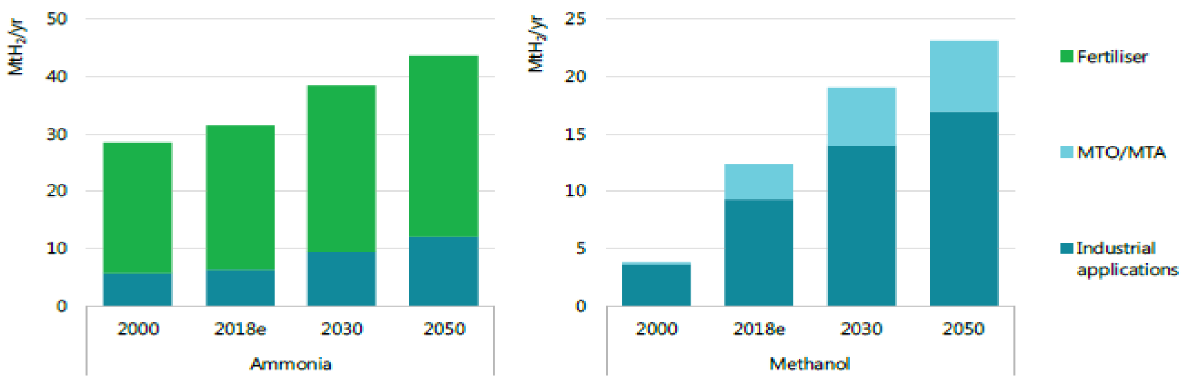


Figure 33 H_2 demand for primary chemical production for existing apps under current trends [12]

Iron and steel production: The third largest source of H_2 demand today is the production of steel from iron ore, following the Direct Reduced Iron-Electric Arc Furnace (DRI-EAF) route. Currently it represents a total demand of 4 MtH_2/yr. In a scenario where Paris Agreement goals are achieved, demand for dedicated H_2 in the steel iron industry is expected to grow and could theoretically reach 62 MtH_2/y, as shown in Figure 34, due to a complete switch to DRI-EAF route.

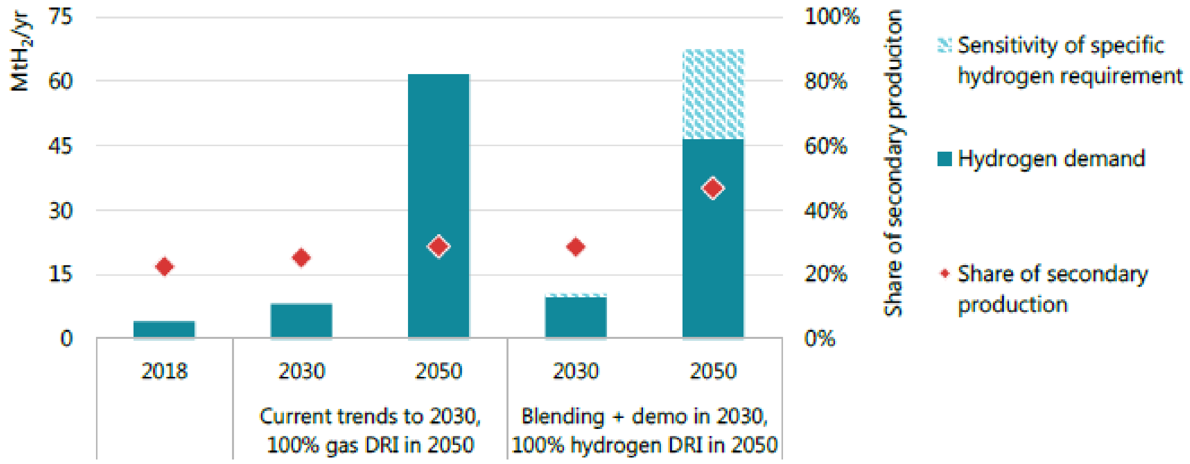


Figure 34 H_2 demand for steel production if 100 % was obtained following DRI-EAF route [12]

2.4.1.2 Potential applications

Transportation: Around 25 % of the global emissions are produced by transportation means, among these, heavy duty in roads (7.7 %), seaborne (3 %) and airborne (3 %) transportation are highlighted as hard-to-abate sectors [12], therefore, in order to turn these sectors more sustainable, H_2 is needed [95]. H_2 is expected to cope with the decarbonization of these applications, both in pure form or as part of larger compounds such as synthetic fuels [12].

The favourable road segments include transport methods such as trucks and large passenger vehicles with long ranges. Fuel Cell Electric Vehicles (FCEVs) for these applications offer better performing features than its sustainable alternative, the Battery electric vehicles (BEV) and therefore they are the most practical decarbonisation alternative in cases that require long tank range due to faster fuelling times, more payload space, which optimises the logistics and lower maintenance over the lifetime of the asset [46].

Fuel cell forklifts are also an interesting field, since they are already competitive both with BEV and Internal Combustion Engine (ICE) forklifts, due to its fast fuelling and the extra space available in the warehouses, since no charging room for the batteries is needed [46].

In the railway sector, the fuel cell train is a strong alternative for regional trains, in areas where there are no electric lines. The H_2 characteristics make the fuel cell train a good option for long and low-frequency routes, with short downtimes and limited time for battery charging. Otherwise, the investment in an electric line will be more profitable in the long term [46]. Some projects working with fuel cell trains are already operational in Germany [96].

For the airborne transportation, it is expected that it will be more difficult to decarbonize in the short/medium term. Pure H_2 use is difficult to apply, although recently Airbus has made public three different concepts of aircrafts working with liquid H_2 [97]. Nevertheless, the expected route for this sector will be the development of H_2 based synthetic fuels, which will compete with biofuels as the sustainable alternative with the current state of the art [46].

The maritime sector in another important segment when it comes to decarbonise the transportation, the use of ports as refuelling station will facilitate the incorporation of H_2 as their new fuel, moreover, the port equipment is also specially interesting for the implementation of H_2 as its powering source, as stated by the IEA, ports will have a major role for the introduction of H_2 [12]. This is already being tested at some locations, such as Valencia Port [98]

For small ships like ferries H_2 fuel cells are the most suitable option specially for the cases with short docking times [46]. For other applications and larger ships liquid NH_3 or H_2-based synfuels instead of burning fossil fuels are expected to be an interesting solution as a transition agent to a cleaner industry [46].

Heat and power: Heat and power for buildings represents over 1/3 of total global energy demand and quarter of the carbon emissions. The heating sector is a difficult segment to decarbonise, there are just a few low-carbon alternatives that can compete with fossil fuels [46]. Here, H_2 can provide a low-carbon emission alternative, specially to natural gas heating where it takes advantage of being able to use part of the infrastructure network such as pipelines or boilers making it crucial for the final cost.

For industrial heating where cheap fossil fuels (coal, natural gas) cover most of the temperature ranges and electric resistors is only used in some low-grade applications, the use of H_2 seems to be difficult unless CO_2 costs exceed USD 100 per ton (long term) [46].

In the power sector, two options may arise, using fuel cells or turbines. Fuel cells are not suitable for large scale applications, due to high capital costs and footprint. However, they can be beneficial for isolated locations or closed systems. For the turbines case, although these cannot compete with fossil fuels-based electricity [46], they are a good opportunity for cases with low-capacity factors, this means, peak power applications. Here, H_2 could outcompete biogas or natural gas combustion with CCUS, due to lower capital investments as shown in Figure 35.

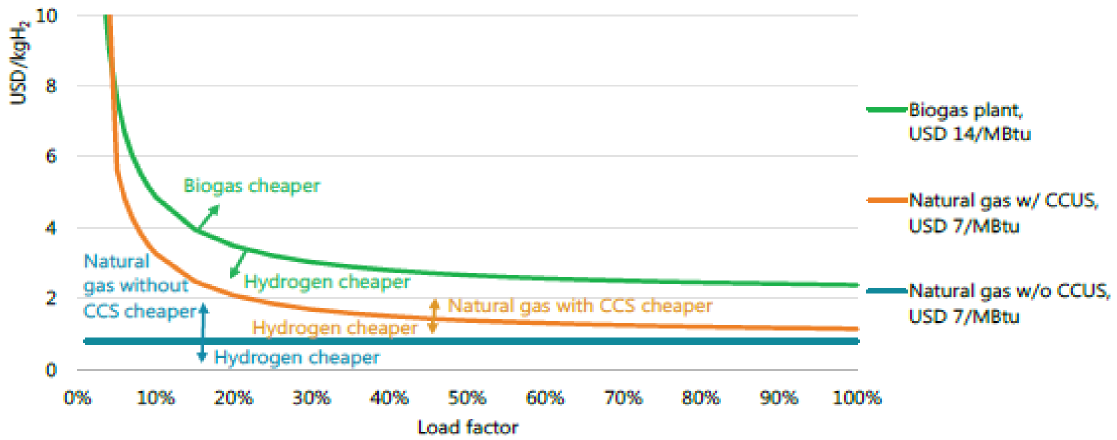


Figure 35 H_2 competitiveness with biogas or natural gas with CCUS [12]

On one hand the efficiency of producing H_2 and then converting it again to electricity is a low efficiency process. On the other hand, in the future with the proliferation of more and more renewable energies the curtailment periods would make the H_2 and storage of H_2 a back-up option for ensuring the electric supply or to balance stationary energy differences (winter and summer).

2.4.2 O_2

O_2 is a colourless and odourless gas essential for living, it accounts around 21 % of the earth's atmosphere, and is the most abundant element in the earth's crust [99]. It has the ability to optimise the performance of several industrial applications, such as combustion processes, also it can help to reduce costs and carbon footprint for many different applications [99].

One important characteristic of this project and a significant differentiation with similar studies consists on the addition of the O_2 as a value product of the process. As it was described in Section 2.2.3 8kg of O_2 are produced per 1 kg of H_2.

Although some previous works have shown that the sales of O_2 produced during electrolysis can reduce the O_2 sales prices, it is not considered that the produced volumes would saturate most markets, in fact the reality is that the O_2 has multiple applications and the demand will increase in the upcoming years [100]. Some of the applications where O_2 is used are shown in Table 7.

Table 7 O_2 demand by its purity

Low-purity O_2	− Steel industry − Metallurgical industry − Chemical industry − Cement industry − Sewage treatment − Ozone production − Food packaging in a modified atmosphere
High-purity O_2	− Microelectronics industry − Fibre optic industry − Preparation of breathable atmospheres − Analytical instrumentation
Medicinal O_2	− Hospitals − Home treatments

The cryogenic distillation of air is currently the main method available for large O_2 production rates, although other methods such as the use of membranes or solid electrolytes are also being used. Cryogenic distillation for Air Separation Units (ASUs) process has been under development for over 100 years. Current large-scale users are the chemical, steel and petroleum industries, while the plant sizes range up to 4,000 t/day [101].

Costs for O_2 markets are of difficult access, due to the secrecy in this industry. Values from different articles mention prices of around 0.01 €/kgO_2 [102].

Chapter 3.- METHODOLOGY

3.1 Introducing the system components

In order to analyse and optimize the offshore wind-to-hydrogen system, this project´s objective is to obtain H_2 from wind energy (coupling concept), based on three main systems as follows:

- System 1: Electricity generation
- System 2: H_2 production
- System 3: Transportation and storage of H_2 and electricity transmission.

This chapter presents the different options that have been assessed for each of the three systems. Afterwards, based on their characteristics, the different scenarios that will be presented in Chapter 4.- are defined with the aim of defining the best option based on a techno-economic analysis developed in Chapter 5.

Firstly, prior to the analysis of each system, its general conditions and the assumptions made are described for every scenario.

The reference date considered as the starting point of the project is year 2020. In this sense, it shall be noted that both the data and its treatment have not taken into account the Covid-19 crisis and its consequences in the short and medium term. It is not considered neither possible legal issues, delays or other external factors, being these additional factors that could be considered in further studies.

3.2 General and economic characteristics

The North Sea, off the UK coast, has been selected for the location of the project. This election has been motivated by the privileged environmental conditions that it offers, such as its good wind resource, its shallow sea depth, and the UK intention of supporting renewable projects in the next years [103].

The lifetime of the project is considered to be 25 years, according to the usual lifetime of actual OWFs [104].

Economic analysis

The same criteria for the economic analysis have been used for the different options of the systems to standardize the results. They are detailed hereunder:

Despite the fact that the project is to be developed in the UK, the currency used in the thesis is the euro (€) as a reference currency in the international outlook. All the prices and costs used have been converted into € by using as reference the exchange rate of January 1, 2020 provided by the national bank of Spain (*Banco de España*) See Table 8) [105].

Table 8 Exchange rate [105]

1 $	1.110 €
1 £	0.849 €

The discount rate used is 7 %, following the assumptions of similar international projects [106]. Regarding the income tax, which affects the NPV, it is assumed to be 20 % [107].

CAPEX: Only the initial investment is considered since no other acquisitions are expected to be accomplished (substation, electrolyser, transmission systems…).

OPEX: Only the expenses associated to normal and predicable activities are included as OPEX in the calculations, these include: rental, equipment maintenance, labour costs, electricity cost and other recurring expenses. Electricity accounts for the largest share in the OPEX costs breakdown, this is the reason why in certain explanations it is commented independently.

REVENUE: The methodology used to calculate the revenues coming from the gases sales considers fixed prices for O_2 and H_2 along the lifetime of the project.

Table 9 Considered gas prices

H_2		2.5 €/kg
O_2	Industrial	0.1 €/kg
	Medical	5 €/kg

The economic results for the different scenarios are based on the indicators stated in Section 2.3.3

NPV: As shown in Equation 8, the NPV of a project provides insights of whether the project pays off or not, taking into account the project interest rate. However, it requires to input the total costs along the lifetime of the project. This requires assumptions to be taken in certain circumstances such as this kind of innovative study, where it is challenging to forecast some factors like the degradation of the equipment and its maintenance in the long term. Therefore, it is important to understand the assumptions that are taken and draw conclusions accordingly.

$$NPV = \sum_{t=1}^{n} \frac{Net\ income_t}{(1+r)^t} - Initial\ Investment \quad (8)$$

This equation includes as variables the income tax and the depreciation rate “r”. Thus, the expenses are subtracted from the revenue (Revenue – Expenses = Cash flow → Net income) in order to obtain the net income for every period “t”.

LCOH: It is calculated for the lifetime of the project. It provides the cost of producing the H_2 for the whole lifespan of the project (Equation 9).

$$LCOH = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (9)$$

Where I_t stands for the expenditures in year t and M_t represents the OPEX. In the lower term, E_t is the total H_2 production for the period t while r and n stand for the discount rate and the lifetime of the project respectively.

PAYBACK: It is a straightforward form to evaluate a project by calculating the period of time required to recover the initial investment as it is shown in Equation 10.

$$PAYBACK = \frac{Initial\ investment}{Net\ income_t} \quad (10)$$

IRR: The Internal rate of return (IRR) is seen as the minimum rentability that an investor lending institution aims to obtain from a project, as it is the rate for which the NPV equals zero. This is the rate at which the capital invested equals the present value of net income (Equation 11).

$$0 = \sum_{t=1}^{n} \frac{Net\ income_t}{(1+IRR)^t} - Initial\ investment \quad (11)$$

3.3 Electricity generation

The **electricity** which powers the electrolysers is considered to come from a specific OWF. The calculations and analysis of the design, construction operation and maintenance and the associated costs of the power generation system are out of the scope of this thesis. Therefore, for this thesis, it is required and assumed an OWF that meets the following characteristics:

The **location** of the OWF is based on characteristics like the capacity factor, water depth, distance from shore and therefore be assumed to be 50 km off the UK coast and at a depth of 90 m. The distance to shore is selected according to the ranges for recently announced offshore wind projects [17]. With respect to water depth, it corresponds to the average depth of the North Sea [108].

Figure 36 Project location [109]

Despite the fact that the total **OWF size** is not relevant for the project, it is assumed to have 10 floating wind turbines of 10 MW each for a total capacity of 100 MW, with 1 km separation between the structures. The selection of 10 MW capacity wind turbines follows the current size of offshore wind turbines for announced offshore projects [17]. Regarding the total capacity, it is considered to be limited by the electrolyser system, where 100 MW is in the order of the greater projects announced in Europe [110]. The separation of the wind turbines will be motivated by the rotor diameter being a distance of 8 times the 96m diameter, sufficient enough to avoid perturbances [111] [112].

The **lifetime** is assumed 25 years, used in most of the calculations of OWF around the world and based on the decommissioning of one the first OWF [104].

The OWF is assumed to have a **capacity factor** of 45 %. The capacity factors for OWFs are high compared to other renewable technologies, this value has been selected according to new projects in the area [113].

Regarding the **electricity prices**, it is assumed a fixed price of 50 €/MWh. Recent auctions in Europe set the stage for a fall in costs for new projects as the industry moves to deploy higher capacity turbines. Offshore wind projects without including transmission systems as it is the cases study will bring strike prices down to almost 45 €/MWh [17].

The **curtailed wind energy** for the UK is 6 % following the literature review [114]. For the use of curtailed electricity, this is considered to have a cost of 0 €/MWh.

There are also other conditions to include as requirements in the electricity generation system. In the case of decentralised electrolysis, it should include the possibility of adding changes in the floating structure of the design in order to add greater buoyancy to the structure, the possibility of including electrolyser systems on the floating structure and the possibility of access to the platform for the operation and maintenance of the substation.

Table 10 below summarises the different characteristics of the OWF as explained in this subchapter.

Table 10 Summary of OWF characteristics

Wind farm characteristics	Units	
Total wind farm capacity	100	MW
Wind turbine capacity	10	MW
Number of wind turbines	10	
Type de wind turbine	Floating	
Distance to port	50	km
Water depth	90	m
Lifetime	25	years
Capacity factor	45	%
Electricity price	50	€/MWh

3.4 Gas production

The gas production analysed in this thesis consists of the generation of O_2 and H_2 through the electrolysis process. In this sense, this system includes electricity input from the OWF, the electrolysis process and the gases compression, making them ready for their transportation.

The current H_2 and O_2 demand is assumed to absorb all the production at a fixed cost along the lifetime of the project. Therefore, Table 11 shows the Gases selling proportion between different sector, being pure O_2 the one with purity above 95 %. The difference between industrial O_2 and medical O_2 is just the final use.

Table 11 Gases sales proportion

Gas	Share	
H_2		100 %
O_2	Industrial	90 %
	Medical	10 %

To make both gases ready for their transportation, the characteristics and requirements taken into account for the project are described in the following subchapters.

3.4.1 Substation location

The substation concept combines all the constructions and equipment where the electricity is transformed into gas. It includes the electric substation and the related housing structure.

The electrolysers can be placed following three different configurations as detailed hereunder:

Centralised offshore platform installation: The offshore platform will be a fixed-to bottom design following the ones already used in the oil and gas sector. It is supposed to be built out of the OWF at a distance of 5 km from the wind turbines at a depth of 30 m and therefore at a distance from shore of 45 km. There is also the possibility of having an offshore platform just for the electrical substation of the OWF while the electrolyser is inland.

The CAPEX includes the offshore platform and its construction, the housing structures and the electrical substation equipment needed. The OPEX covers: the substation maintenance (including the transport via boats) and onshore and offshore operation and logistics. Finally, the decommissioning covers the required expenditure when the project is done.

Decentralised wind turbine installation: The location of the required structures for the gas production is the floating wind structure itself. The electrolyser in this case is placed on the floating platform of the wind turbine. It is assumed to have a space of at least 480 m^2 to place the required structures [12]. The oscillation and sea conditions are not considered to be a limitation at this stage, although more research is needed in this regard. Installation costs are considered to be negligible, since these structures are assembled inland. Therefore, they are considered into the wind turbine installation costs.

The CAPEX includes the housing structures on the wind turbines, the electrical substation equipment needed for each wind turbine and the possible extra cost associated due to the extra-floating addition. The OPEX intention is to cover the substation maintenance (including the transport via boats to the wind turbines) and onshore and offshore operation and logistics. Finally, the decommissioning expenditure is assumed to be together with the OWF decommission and therefore not included in the calculations.

Onshore station installation: This possibility considers the state-of-the-art electrolysis plant, which is placed inland getting input from the offshore wind farm. The substation will be at the nearest port, 50 km from the wind turbines.

The CAPEX includes the offshore platform and its construction, the onshore base, the housing structures and the electrical substation equipment needed. The OPEX intention is to cover both onshore and offshore substation maintenance (including the transport via boats to the platform) and onshore and offshore operation and logistics. Finally, the decommissioning refers to the required expenditure when the project is done for the offshore platform.

Table 12 summarizes the different configurations and their costs over the lifetime of the project.

Table 12 Substation location costs [115] [116]

Substation location	Type	CAPEX €/MW	OPEX €/MWy	Decommissioning €/MW
Offshore platform	Gas production	135,410	6,122	76,536
	Just electricity	111,861	5,180	76,536
On the wind turbine	Gas production	23,550	8,477	-
Onshore substation	Gas production	64,762	1,648	-

3.4.2 Electrolyser system definition

The electrolyser will be the main component of the substation in the gas production system. As previously mentioned, the whole system is limited by the total electrolyser capacity (100 MW). However, for the curtailment case the size of 100 MW will be overrated due to the reduction in the production.

The electrolysis technology selected is PEM, which offers several advantages (See Section 2.1.2.2.1) for its coupling with offshore wind. It is also assumed that the sensitive equipment is located outside of the splash zone and it will be provided with external cladding to provide additional protection [38].

The efficiency of the electrolyser including the whole process is 60 %, as explained in Section 2.1.2.1.3. Table 13 shows the different costs for the abovementioned locations.

Table 13 Electrolyser costs [12] [115] [117]

PEM Location	Size (MW)	CAPEX (€/MW)	OPEX (€/MW/y)
Offshore platform	100	891,211	44,560
On the wind turbine	10	1,000,000	165,000
Onshore substation	100	850,000	34,000

The CAPEX includes the expenditures related to the electrolyser system. As electrolyser units are commonly delivered as a standalone package including water treatment and control system integration [38], it is considered that no further power conditioning or water filtration (desalination is needed indeed) are required. Higher CAPEX is considered for the decentralised production, since economies of scale tend to have an impact on the price of the systems. Thus, for smaller units, prices will be at the highest point of the price range provided in Table 13 whereas for the centralised cases they will be at the lowest. In this sense, the OPEX, varies at a function depending on the CAPEX, from 3 % to 5 % of the specific CAPEX/year, being the onshore centralised the cheapest system and the offshore decentralised the most expensive one.

3.4.3 Desalination process

The electrolysis module is capable of taking and purifying drinkable water for use in the electrolyser, however, in an offshore environment, the resource that is available is salty water, which must be turned into fresh water for the posterior steps. Fortunately, desalination units are a well mature technology, and, in addition, these do not add up major complexity or energy expenditures to the overall process. Hence in this thesis reverse osmosis desalination has been chosen, with a consumption between 3 - 4 kWh/m^3 included in the substation energy expenditures in the calculations [118]. Table 14 includes the selected values considered for the desalination units, both in terms of price and energy expenditure.

Table 14 Desalination cost [119] [12]

Desalination	Consumption (kWh/m^3)	CAPEX (€/m^3/day)	OPEX (€/m^3/day)
Not included in the electrolyser	4	1,126	0.9

CAPEX and OPEX accounts just for this unit. No difference among the different configurations (centralised or decentralised) is considered. Neither possible synergies with the water purification units of the electrolysers, which could be erased depending on the output quality of the desalination units.

3.4.4 Compression process

One of the characteristics of PEM electrolysis is that the output H_2 is already pressurized. The output pressure depends on the manufacturer. It is considered an exit pressure from the electrolyser of 30 bar. Therefore, the compressor systems are expected to compress both H_2 and O_2 from 30 bar to 200 bar based on the distance to shore. In the case of O_2, this pressure is already used for its transportation in trucks, whereas in the case of pipelines no information has been found. However, many cases exist for natural gas transportation, where the pipelines pressure is in this order. For the O_2 case, 200 bar is the pressure at which O_2 is generally traded when it is delivered in bottles, same consideration as with H_2 is performed at the pipelines [120]. Table 15 shows the considered costs (CAPEX and OPEX) for the required compression difference.

Table 15 Compression cost3

Compressor	Pressure difference (bar)	CAPEX (€/kg/day)	OPEX (€/kg/day)
H_2	30-200	800	5 % of CAPEX
O_2	30-200	7	5 % of CAPEX

The CAPEX considers only the compressor, since no intermediate storage is assumed at any point between compressor and pipeline, it will depend on the total production. According to conversations with experts, a compressor for 1 t/day would fit in a 20 ft container. The OPEX considers all the maintenance that is needed for the equipment and is based on the CAPEX cost.

3.4.5 Storage system

The gas storage system is out of the scope of the project; thus, the storage system would be in the import terminal where the gas is dispatched. Nevertheless, pipelines can be used as storage systems for a short period of time.

3.4.6 Balance of the plant (BoP)

Standby Power

A supply of backup/standby power must be available during periods of shutdown due to maintenance or unfavourable weather conditions [38]. It is also needed to keep all the equipment operating at minimum levels (temperature for the electrolyser stack, etc.). According to literature, this mode requires an estimated average 2 % of nominal power at the stack in the case of multi-MW electrolysers and continuous energy consumption at the BOP equipment [121]. This backup power generation is assumed to be provided by a diesel engine with a high proven reliability. Table 16 shows the cost for the considered required power.

[3] Source: hydraulic piston compressor, industry manufacturer dialogues

Table 16 Standby power system cost [122]

Type	Power (kW)	CAPEX (€/kW)	OPEX
Diesel	100	420	100 €/h
	10	420	100 €/h
Grid	100	0	60 €/MW

3.4.7 AC-DC Rectification

Wind turbine generators generate electricity with an alternating current, whilst electrolysers require a direct current input, as such AC-DC rectification is required. However, most of the electrolysers in the market are currently in use with electricity supplied from the AC transmission system, with AC-DC rectification included. It is assumed to have an AC-DC rectification in the transmission of electricity from the wind turbines to shore, the transmission system selected consist on HVDC (Section 3.5). In this case the AC-DC rectification system will be located on the offshore electrical substation. The electrical components in the offshore substation including the AC-DC rectification system are assumed to be 52,000 €/MW for the CAPEX while the OPEX is assumed to be included in the substation one [115].

3.5 Gases Transportation and electricity transmission

There are different options to transport the energy along the whole process, both as electricity or as pure H_2.

Inter-array cabling: This technology is proven and commercially available for fixed bottom OWFs, connecting loops or strings of wind turbines to the offshore substation [17]. These are needed for the cases with centralised production of H_2, either offshore or onshore.

Export cables: HVDC is considered the technology used to connect OWFs to land because of its properties of transmitting high electrical power over long distance through the sea [123]. This type of cable is currently the most used. It has been in service for more than 40 years and has proven being highly reliable [124].

Pipelines: The pipelines that are considered for the calculations account for the transport of the gases from the offshore substation to land. The pipeline is assumed to stand a pressure of 200 bar with an internal diameter based on the gas flow (6cm).

Table 17 Cables and pipelines cost [115] [125] [126] [127]

Type	CAPEX	OPEX	Losses	Decommissioning
Inter array	5,043 €/MWkm	0.5 % CAPEX	1.1 %/km	2,747 €/MW/km
Export cable	1.17 M€/km	0.1 % CAPEX	3.3 %/1,000km	2,747 €/MW/km
Pipeline	28,170 €/km	3,532 €/km	0	180,866 €//km

Chapter 4.- BUSINESS CASE PROPOSALS

4.1 CASE SCENARIO 0: Centralised and dedicated H_2 production on an offshore platform

Case 0 couples directly an OWF with H_2 production in a centralised way. This means that H_2 is produced offshore in a single location (See Figure 37). In this scenario the wind farm is ready to operate having the characteristics mentioned in Chapter 3, all the facilities and infrastructures required to produce electricity are already built. All the electricity produced is assumed to be used for the new centralised H_2 production plant, built on an offshore platform, close to the wind turbines with the produced gases being transported via pipelines to shore. The centralised substation includes not only the H_2 equipment but also the required collectors for the inter-array cables and facilities for manned labour.

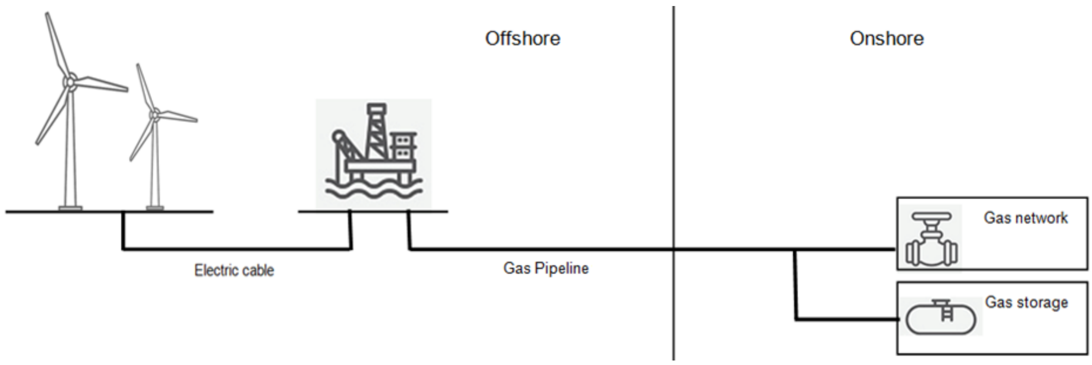


Figure 37 Case 0 diagram

Synergies occur in this system since the unification of units takes advantage of both avoiding redundancies, such as several power electronic systems or several water desalination units and also economies of scale, since larger electrolysers result into lower specific costs.

However, building and installing an offshore structure is complex and costly. In addition, electricity goes under transformation twice, first in the wind turbine where it is converted to AC to save losses in the inter-array cables and secondly when it is reconverted back to DC in order to power the electrolyser. These processes result in losses and expenditures, since power electronics for these purposes are costly. Some of the main benefits and drawbacks of this configuration are shown in Table 18.

Table 18 Advantages and disadvantages of centralised offshore H_2 production

Centralised offshore H_2 production	
Advantages	**Disadvantages**
– Advantage of scalability of the components – Rapid repair times in a single location – Economies of scale – Avoidance of redundancies – Easier to refurbish existent WF or O&G platforms	– High CAPEX and OPEX due the offshore location and installation costs – High asset risk due to all electrolysers in single location – Need of extra power electronics – High risk of complete shutdown

The specific characteristics of the case are listed below and can be associated with the numbers described in the methodology section (Chapter 3.-)

Table 19 CASE 0 Specific characteristics

Gas production	Substation	Location	Offshore platform
		Distance to OWF	5 km
		Distance to shore	45 km
		Depth	30 m
	Electrolyser	Technology	PEM
		Location	Platform
		Capacity	100 MW
	Extra desalination system	Yes	
	Compressor	Yes	
	Storage system	No	
	Stand-by power	Type	Diesel
	AC-DC	No	
Gases transportation and electricity transmission	Array cables	Distance	5 km
	Pipelines	Distance	45 km

4.2 CASE SCENARIO 1: Decentralized and dedicated H_2 production on wind turbines

In this case the electrolyser systems are directly placed at the wind turbines structures, producing H_2 in a decentralised way. All the electricity produced is supposed to be used for the new decentralised H_2 production station, built on the same floating turbines deck with the produced gases being transported via pipelines to shore, as shown in Figure 38.

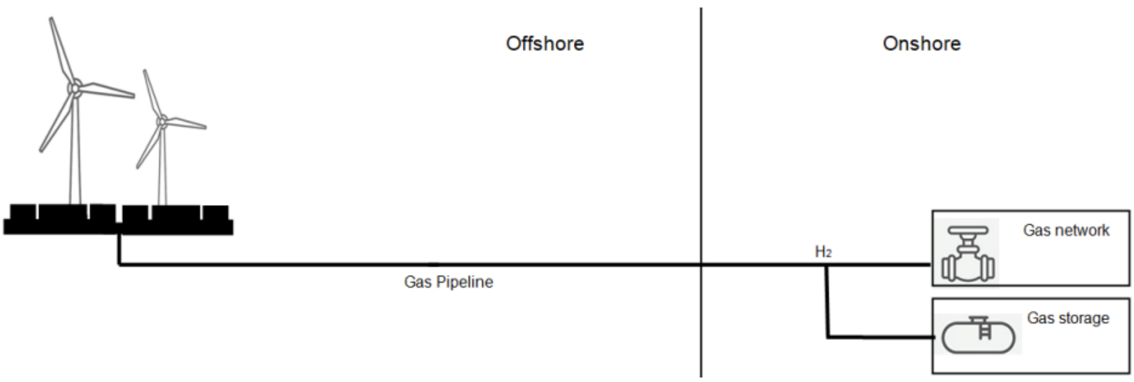


Figure 38 Case 1 diagram

This method offers several advantages, such as savings on the inter-array cables and the offshore centralised structure. Since floating wind structures have area enough for installing the electrolysers, it is assumed that no further infrastructure will be needed. In addition, electricity does not have to be converted to AC for its transportation in the inter-array cables, it can be directly coupled to the electrolyser system, avoiding costs in the power electronics.

Conversely, everything related to maintenance gets significantly costlier due to increased reparation times produced from manned labour having to move between the wind turbines.

Advantages and disadvantages of this case are summarised in Table 20.

Table 20 Advantages and disadvantages of decentralised offshore H_2 production

Decentralised offshore H_2 production	
Advantages	**Disadvantages**
– Reduced initial investment and stepwise investment possibility – Low asset risk due to the electrolysers in different locations – Easy-to-design a prototype – The electrolyser can be installed in the ports, avoiding extra costs	– Very high OPEX due the individual offshore location – Little knowledge of behaviour of the floating platform with the electrolyser system in terms of floatability motion and splash zone – Decrease in efficiency – High CAPEX and OPEX due the offshore location

The specific characteristics of the case are listed below in Table 21 and can be associated with the numbers described in the methodology section (Chapter 3.-)

Table 21 CASE 1 Specific characteristics

Gas production	Substation	Location	Offshore wind turbines platform
		Distance to shore	50 km
		Depth	90 m
	Electrolyser	Technology	PEM
		Location	Wind turbines
		Capacity	10 MW (X10)
	Extra desalination system	Yes	
	Compressor	Yes	
	Storage system	No	
	Stand-by power	Type	Diesel
	AC-DC	No	
Gases transportation and electricity transmission	Pipelines	Distance	45 km

4.3 CASE SCENARIO 2: Centralised and curtailed H_2 production on an offshore platform

This case follows the approach in Case 0, while only the curtailed electricity is taken into consideration in order to produce the H_2 (See Figure 39). In this scenario the OWF is ready to operate, meaning that all the facilities and infrastructures required to produce electricity are already built. The electricity produced in the wind turbine is supposed to be used either for the centralised H_2 production station and also input in the electricity grid, depending on the grid requirements.

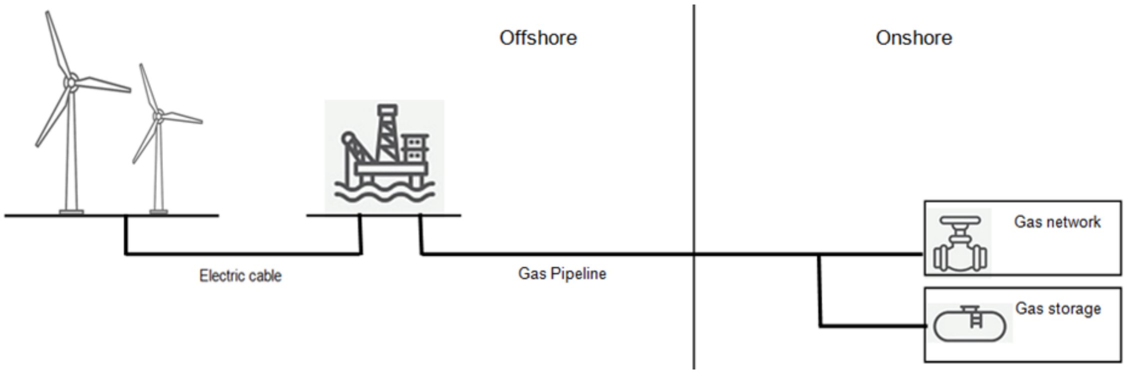


Figure 39 Case 2 diagram

Taking advantage of curtailed electricity is interesting from a point of view of maximising the wind converter assets. These can be operated at the maximum potential. However, low curtailment times have a negative effect on the LCOH, since high CAPEX costs are not diluted with high operation times. In addition, curtailed electricity is assumed to have no costs. Table 22 summarises the different advantages and disadvantages of this configuration.

Table 22 Advantages and disadvantages of curtailed H_2 production on an offshore platform

Centralised and curtailed offshore H_2 production	
Advantages	**Disadvantages**
– Flexibility of being half a way between scalability of the components and not – Rapid repair period of time in a single location – No electricity expenses	– Flexibility of being half a way between scalability of the components and not – High CAPEX and OPEX due the offshore location – High asset risk due to all electrolysers in single location

The specific characteristics of the case are listed below in Table 23 and can be associated with the numbers described in the methodology section (Chapter 3.-).

Table 23 CASE 2 Specific characteristics

Electricity generation	OWF	Price	0 €/MWh
Gas production	Substation	Location	Offshore platform
		Distance to OWF	5 km
		Distance to shore	45 km
		Depth	30 m
	Electrolyser	Technology	PEM
		Location	Platform
		Capacity	100 MW
	Extra desalination	Yes	
	Compressor	Yes	
	Storage system	No	
	Stand-by power	Type	Diesel
	AC-DC	No	
Gases transportation and electricity transmission	Array cables	Distance	5 km
	Pipelines	Distance	45 km

4.4 CASE SCENARIO 3: Centralised and dedicated H_2 production onshore

Case 3 follows the state-of-the-art for H_2 production from OWF. It consists on a typical OWF that is connected to an inland H_2 production plant. The electricity is considered to be transmitted via HVDC cables from the substation to land.

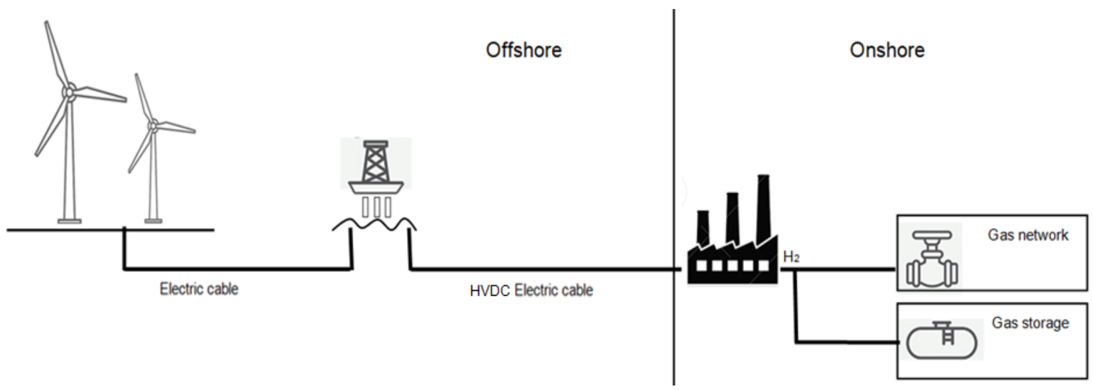


Figure 40 Case 3 diagram

This case offers the advantage of being less uncertain, since the layout is already known and has been already developed or is under study (See Section 2.2.5). Moreover, the centralised facility has all the advantages mentioned in Case 0, plus the easier maintenance and lower installation costs due to inland operations. Advantages and disadvantages are shown in Table 24

Table 24 Advantages and disadvantages of curtailed H_2 production on an offshore platform

Curtailed offshore H_2 production	
Advantages	**Disadvantages**
– Flexibility of the project – CAPEX and OPEX of the onshore substation are smaller – Standby power provided by the grid	– Requires HVDC cable connections to the coast – Requires both, offshore and onshore stations

The specific characteristics of the case are listed below in Table 23 and can be associated with the numbers described in the methodology section (Chapter 3.-).

Table 25 CASE 3 Specific characteristics

Gas production	Substation	Location (Electrical)	Onshore
		Location (Gas)	Offshore platform
		Distance to OWF	5 km
		Distance to shore	45 km
		Depth	30 m
	Electrolyser	Technology	PEM
		Location	Platform
		Capacity	100 MW
	Extra desalination	Yes	
	Compressor	Yes	
	Storage system	No	
	Stand-by power	Type	Diesel
	AC-DC	No	
Gases transportation and electricity transmission	Array cables	Distance	5 km
	Export cables	Type	HVDC
		Distance	50 km

Chapter 5.- RESULTS & DISCUSSION

After defining the different scenarios and parameters used for the calculations, the main results are shown hereunder.

5.1 CAPEX

Regarding the initial expenditures, there are two main remarks.

It can be observed in Figure 41 that the case with the highest CAPEX is Case 3 (186.3 M€) and the lowest one is Case 2 (120.9 M€) while Case 1 and Case 2 are very similar (136.4 M€ & 135.3 M€). This is principally due to the fact that in Case 3 the inclusion of export cables for electricity plus the need to maintain an electrical offshore substation anyways makes the costs soar. On the other hand, Case 2 is the cheapest due to the reduction in the size of some of the project components.

It is also worth to note that the CAPEX savings regarding the avoidance of a centralized offshore substation are outweighed by the higher CAPEX of the electrolyser systems due to smaller units. Nevertheless, possibilities of coupling the electrolyser directly to the wind converter (DC power) can help to reduce the costs and the losses, which could be assessed more in depth in further studies.

Figure 41 shows the CAPEX breakdown of the different cases.

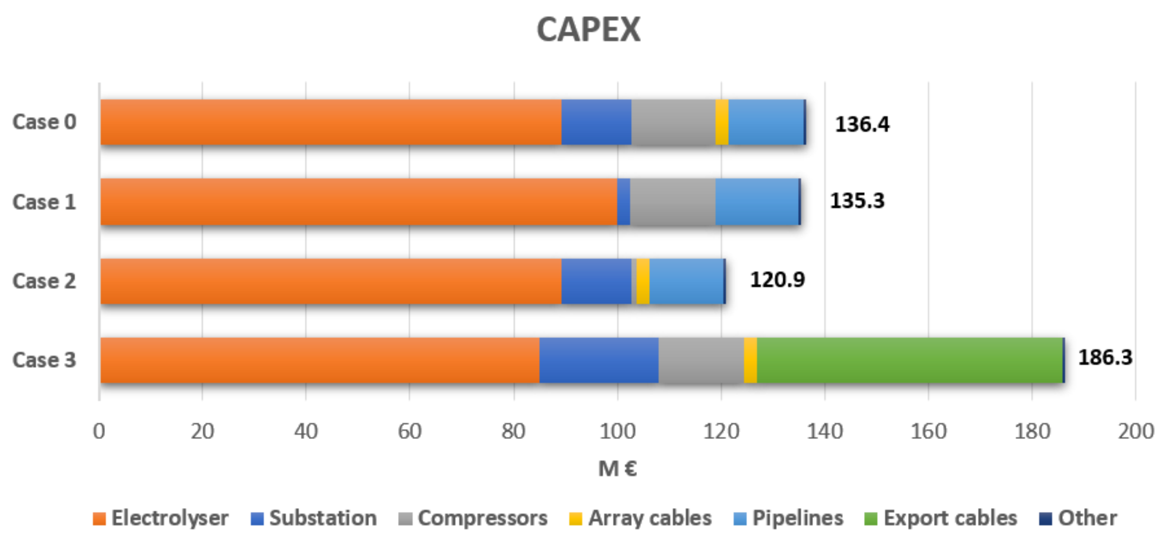


*Figure 41 CAPEX Breakdown results. *Case 0: Centralised offshore dedicated production, Case 1: Decentralised offshore dedicated production, Case 2: Centralised offshore curtailed production, Case 3: Centralised onshore dedicated production.*

Regarding the weight of each subsystem in the total CAPEX, it is noticeable the fact that the electrolyser system is the largest contributor to the initial investment in all the cases, accounting for 74 % of the total cost in Case 1. Cases 0, 2 and 3 are also strongly affected by the offshore central structure costs, which is not accounted in Case 1 as the electrolyser is directly placed in the offshore wind turbine structure.

The gas compressor, as it is proportional to the production of H_2 and O_2, is lower in Case 2, since less amounts of H_2 are produced. Pipelines account for a big share of the CAPEX as well, being particularly interesting in Case 2 being 21 % due to the high installation cost regardless the size.

Eventually, it is important to mention Case 3 situation, where the export cables account for 32 % of the total CAPEX, which is much higher if we compare it with the cost of the pipelines of the other projects and therefore, it can be easily related to the fact that Case 3 has the highest CAPEX.

5.2 OPEX

Figure 42, summarises the annual OPEX for every case. It can be observed how Case 1 has the highest annual OPEX (39.2 M€/year) while again, as it occurs with CAPEX, Case 2 offers the lowest costs (7.2 M€/year) and both Case 0 and Case 3 are similar (26.9 M€/year & 24.8 M€/year). The reason for Case 1 to have such high costs is due to the fact that most of the systems are distributed in the different wind turbines making it more expensive, while again Case 2 has lower CAPEX due to a smaller system and much lesser electricity consumption.

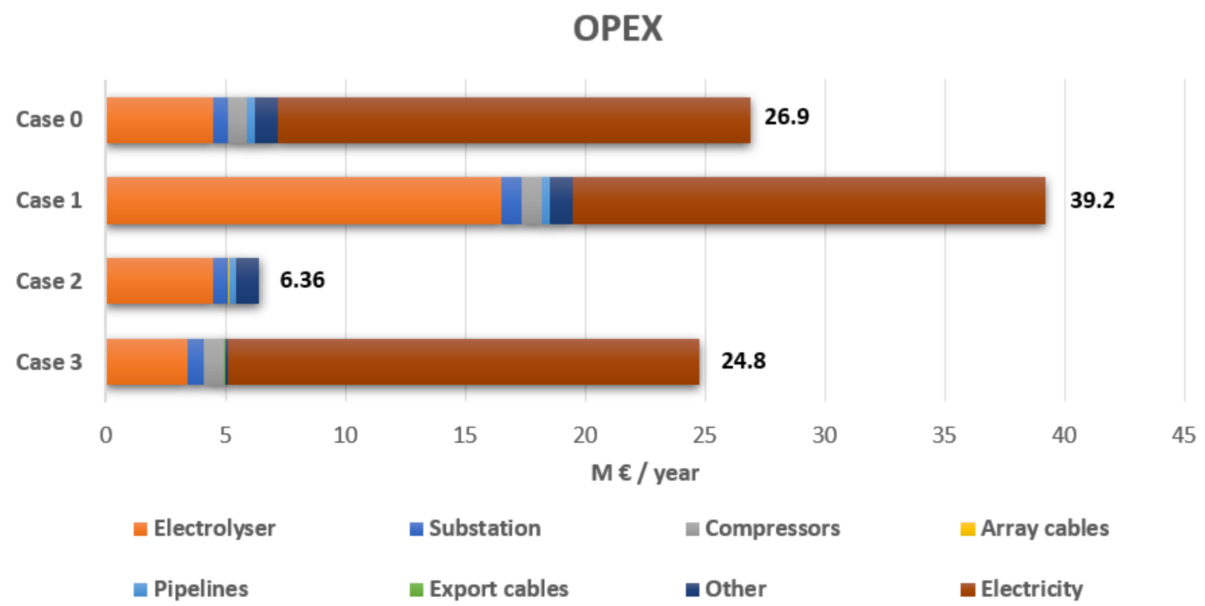


*Figure 42 OPEX Breakdown results. *Case 0: Centralised offshore dedicated production, Case 1: Decentralised offshore dedicated production, Case 2: Centralised offshore curtailed production, Case 3: Centralised onshore dedicated production.*

OPEX breakdown highlights two main factors as main contributors to operational expenses: electricity and electrolyser related expenditures. Electricity is the necessary fuel to produce H_2 and O_2 and it accounts for up to 80 % of the total annual expenditure. However, in Case 2, since it is curtailed, its price has a value of 0 €/MWh. On the other hand, the electrolyser and its maintenance depend mainly on its configuration (if it is a centralized or decentralized system), varying from 14 % in Case 3 with the electrolyser placed inland and centralised to 42 % with an offshore and decentralized electrolyser on the wind turbines.

Other components such as compressors and substation account for an important share in all cases. In addition, systems such as the back-up power or the desalination system that barely had weight in the CAPEX are larger in this case. This is especially interesting, since it points out the importance of considering the maintenance costs of this equipment rather than their CAPEX, since it can have a more substantial effect on the LCOH in the long term.

Eventually, pipelines and specifically electrical lines have minimal maintenance compared to their initial investment.

5.3 H_2 & O_2 production and sales share

Table 26 summarises the yearly production of both kind of gases (H_2 and O_2).

Table 26 H_2 & O_2 Production Results

	Gas Production (ton/year)			
	Case 0	**Case 1**	**Case 2**	**Case 3**
H_2	6,968	7,046	418	7,034
O_2	55,047	55,660	3,303	55,568

Gas production practically remains the same in all the cases, being around 7,000 tons / year of H_2 and 55,000 tons / year of O_2. Small differences are due to the electricity loss in the cables, since less electricity is input in the electrolysers. However, Case 2 is the exception with the use of only 6 % of the electricity, (since it is curtailed), the production is much lower with values of 418 ton / year of H_2 and 3,303 ton / year of O_2. However, production is not uniform and it suffers variability over the whole year. Therefore, both pipelines and compressors need to be designed for its maximum capacity.

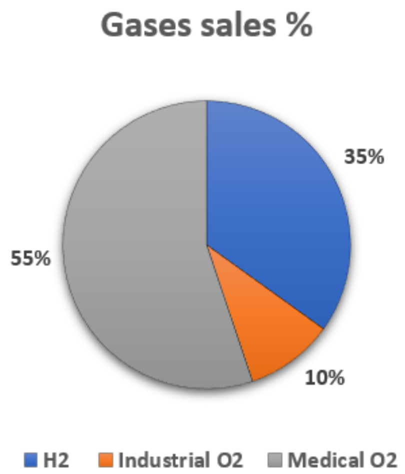


Figure 43 Gases repercussion on sales.

In Figure 43 it can be observed the effect on the sales of the different gases produced. Although, O_2 is produced 7.9 times more than H_2 it does not have the same impact on the sales. On the O_2 side, medical O_2, due to its higher price, dominates the sales, while the industrial one sold in a 9:1 ratio represent just a discrete 10 %. Finally, H_2 shows a no discrete 35 % of the total.

5.4 LCOH

Figure 44 presents the LCOH results for each of the cases.

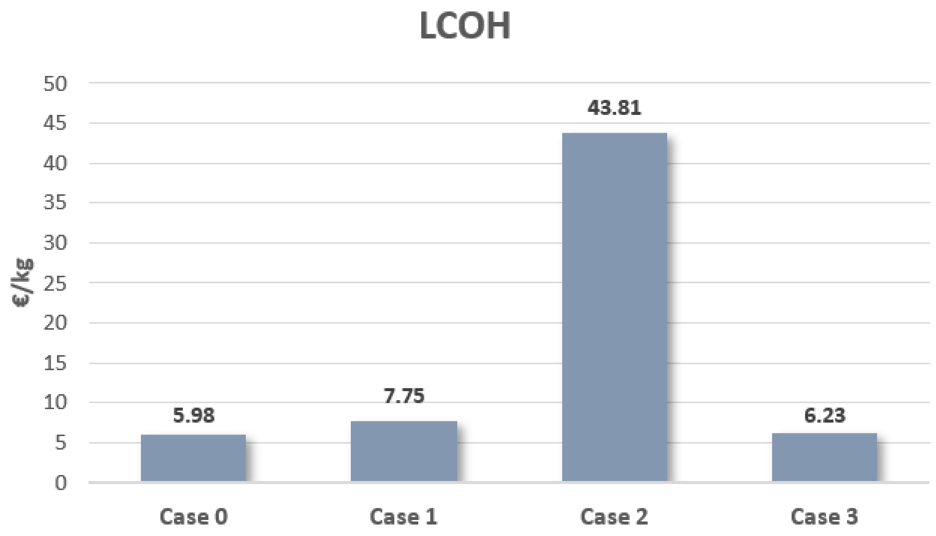


*Figure 44 LCOH results. *Case 0: Centralised offshore dedicated production, Case 1: Decentralised offshore dedicated production, Case 2: Centralised offshore curtailed production, Case 3: Centralised onshore dedicated production.*

On the one hand, Case 2 has the highest cost per kg of H_2 production, being above 43 €/kg H_2 and being up to 5 times more expensive than the rest of the cases. It is important to say that LCOH is not a fair comparison for Case 2, because it also relies on the sales of electricity. Although it is the case that has the lowest CAPEX and OPEX, it is the one with the lowest production too. Therefore, it is concluded that a project of these characteristics has certain fixed costs that are very high and just by taking advantage of free electricity the fixed costs do not dilute.

On the other hand, Case 0 has the lowest LCOH being 5.98 €/kg, less than Case 1 and Case 3 with 7.75 €/kg and 6.23 €/kg, respectively. Case 1 is particularly interesting, since OPEX affects heavily the final LCOH. However, Case 0 is even more interesting than the others in terms of LCOH, including additionally more reliability due to its centralised configuration.

5.5 NPV and IRR

Figure 45 presents the NPV results of the different cases, differentiating between the option of selling H_2 only and the option of combining it with O_2, in order to emphasize the importance that the incorporation of O_2 can have in the economic results.

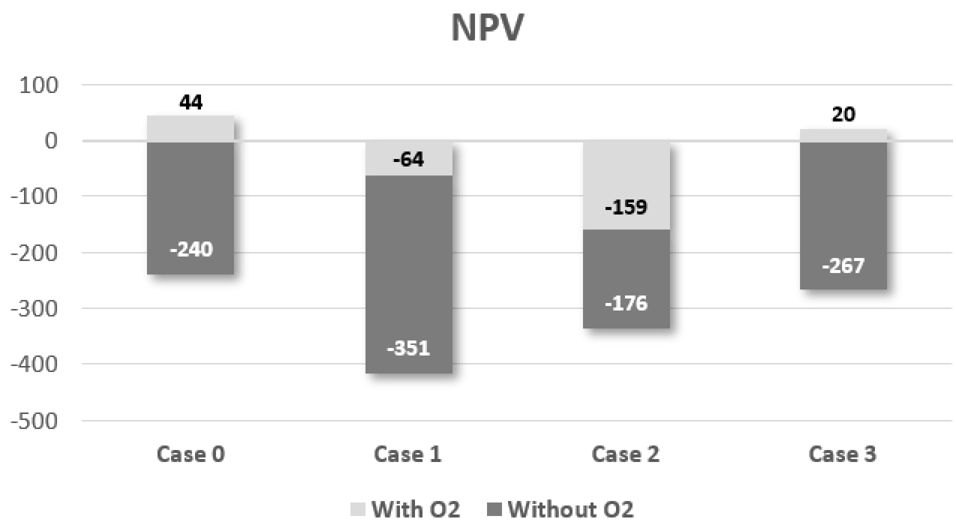


*Figure 45 NPV results. *Case 0: Centralised offshore dedicated production, Case 1: Decentralised offshore dedicated production, Case 2: Centralised offshore curtailed production, Case 3: Centralised onshore dedicated production.*

At first glance the results show that none of the cases present a positive NPV with the sales of H_2, however H_2 together with O_2 allows the NPV to become positive.

For cases 0, 1 and 3 adding the O_2 to the sales is determinant to make the NPV turn into positive and therefore making the project viable under the assumptions presented. Between these three mentioned cases, Case 0 and Case 3 are the most attractive projects. On the other hand, Case 2 does not lead to a positive NPV, not even with the addition of the O_2, making it a non-recommended investing project from a NPV point of view.

Case 0 > Case 3 > Case 1 > Case 2

As regards the IRR, Table 27 shows the estimated values for each project. The only case with a non-possible IRR value is Case 2. In this option, by definition, the IRR does not exist since the NPV does not equal zero, but it is always negative. The Table 27shows that for market interest rates below 10.62 % Case 0 would be a suitable investment as the NPV would result positive, in the same sense Case 3 would present a positive NPV when the market interest rate is below 8.2 %. Finally, Case 1 would only present positive NPV with interest rates below 0.1 %.

*Table 27 IRR results. *Case 0: Centralised offshore dedicated production, Case 1: Decentralised offshore dedicated production, Case 2: Centralised offshore curtailed production, Case 3: Centralised onshore dedicated production.*

	Gas Production (ton/year)			
	Case 0	**Case 1**	**Case 2**	**Case 3**
IRR	10.62 %	0.10 %	-	8.20 %

5.6 Payback

*Figure 46 Payback results. *Case 0: Centralised offshore dedicated production, Case 1: Decentralised offshore dedicated production, Case 2: Centralised offshore curtailed production, Case 3: Centralised onshore dedicated production.*

The payback results are shown in Figure 46. The case which requires t a shortest period for the initial capital invested in the project to recover, without taking into account inflation rate or risk as they are not included in the payback method, is Case 0 (6.9 years) with Case 3 (8.31 years) and Case 1 (16.7 years) being in a worse situation. Once again, the particularities of Case 2 make it impossible to recover the investment due to its hedge behaviour.

Chapter 6.- IMPROVEMENT OF THE BUSINESS MODEL

After the assessment of the different cases presented, some insights can be withdrawn in order to select the best possible configuration. Moreover, limitations and points of improvement have been detected along the development of this study. This chapter presents the conclusions for selecting the best case.

6.1 Selection of the best case

Once the different cases have been analysed and compared, it is concluded that **Case 0** is the most advantageous option, while Case 2 is a possibility that does not make sense from an economic perspective. This is particularly interesting since it is heard many times that H_2 could store the curtailed electricity of a system/country while the results shown in this thesis prove that this is not viable at this stage.

From an economic point of view, **Case 0** has acceptable OPEX and CAPEX as compared to the other alternatives, the production of gases is similar to the other options and lastly and most importantly, the indicators of LCOH and NPV places Case 0 as the best option among the ones presented. Its LCOH is in line with the best current indications for the cost of producing H_2 from OWFs in Europe [46].

Moreover, Case 0 offers several advantages that are welcome in new concepts with high uncertainties, such as the topic under discussion in this thesis. For instance, a centralised location may ease all the maintenance activities.

Table 28 shows the TRL and CRI for the components that belong to Case 0 (Section 2.3). It can be observed that although the Maturity of the concepts in terms of TRL is high, the market availability is lower as it occurs with many new renewable technologies.

Table 28 TRL and CRI in Case 0

<table>
<tr><th colspan="3">System</th><th>TRL</th><th>CRI</th></tr>
<tr><td rowspan="4">Substation</td><td>Location</td><td>Offshore platform</td><td rowspan="4">9</td><td rowspan="4">2</td></tr>
<tr><td>Distance to OWF</td><td>5 km</td></tr>
<tr><td>Distance to shore</td><td>45 km</td></tr>
<tr><td>Depth</td><td>30 m</td></tr>
<tr><td rowspan="3">Electrolyser</td><td>Technology</td><td>PEM</td><td rowspan="3">7</td><td rowspan="3">1</td></tr>
<tr><td>Location</td><td>Platform</td></tr>
<tr><td>Capacity</td><td>100 MW</td></tr>
<tr><td>Extra desalination system</td><td colspan="2">Yes</td><td>8</td><td>1</td></tr>
<tr><td>Compressor</td><td colspan="2">Yes</td><td>8</td><td>1</td></tr>
<tr><td>Stand-by power</td><td>Type</td><td>Diesel</td><td>9</td><td>2</td></tr>
<tr><td>Array cables</td><td>Distance</td><td>5 km</td><td>9</td><td>2</td></tr>
<tr><td>Pipelines</td><td>Distance</td><td>45 km</td><td>8</td><td>1</td></tr>
</table>

6.2 Case improvement

Once **Case 0** has been selected as the most attractive option, different alternatives are described below with the intention of improving its characteristics and making it applicable and profitable as a business idea.

An optimization of the electrolyser capacity is highly recommendable, since this thesis considers a direct relation of 1 MW of electrolyser capacity per 1 MW of wind capacity. In order to be more efficient, the ideal would be to have a lower capacity electrolyser since, in addition to the losses in electricity transmission and the electrical substation, most of the time the wind turbines are not operating at their maximum power, so a reduction of electrolyser would lead to savings without significantly affecting the production of gases.

The choice of a **more specific location** than the one chosen in Case 0 could lead to improvement and lower costs in some of the structures or their best use. A greater distance to the coast would make the pipes even more economically attractive than the cables, while selecting a shorter distance to the coast would have a completely opposite effect. In addition, placing the H_2 production plant in areas with existing oil rigs can save up costs both in pipelines and structures, by **re-using already existing infrastructures.**

B**etter integration of the systems** is needed in order to optimise the overall project. If the production is centralised, different systems that are actually accounted as independent units can offer synergies such as use of waste heat to keep the stack in stand-by mode or a centralised power conditioning unit for all the equipment. This needs further study in all the processes and to set the requirements for each unit.

Finally, it is fundamental, to take advantage of the high quality of the gases that are produced via electrolysis. These gases, with a very high purity are demanded in more specialized markets such as electronics or healthcare systems, where in exchange of purity, the prices are increased considerably, and therefore it would multiply the revenues

Chapter 7.- FUTURE SCENARIOS FOR THE H_2 ECONOMY

As commented above, H_2 has gained lots of interest in the last months due to its unique contributions to the energy systems, but also to its expected reduction in costs over the next coming years. However, future is not certain and H_2 development may vary due to different improvements or delays on the assumptions that were taken in order to define how the future would look.

For this reason, once the most attractive case has been selected, a sensitivity analysis is performed in this chapter on the most influential variables for the LCOH and NPV, assessing how the improvements on these will shape the H_2 competitiveness in the future.

7.1 Sensitivity Analysis

Case 0 has been selected as the best possible configuration. The studied variables are the electricity price, the electrolyser cost and the O_2 sales composition.

7.1.1 Electricity price

Along this thesis it has been emphasized how impactful the electricity price is on the H_2 production costs. Case 2 studies the possibility of taking advantage of the curtailed electricity with a cost of 0 €/MWh, observing that is not an interesting configuration due to the low-capacity factors. Figure 47 shows how a variation in the electricity price affects the NPV and the LCOH of the project. Varying the price at which electricity is bought to produce H_2 from 20 to 100 €/MWh implies a variation of more than twice the LCOH, from 4 €/kg to 9 €/kg. On the other hand, NPV becomes negative if the electricity price overpasses 58 €/MWh.

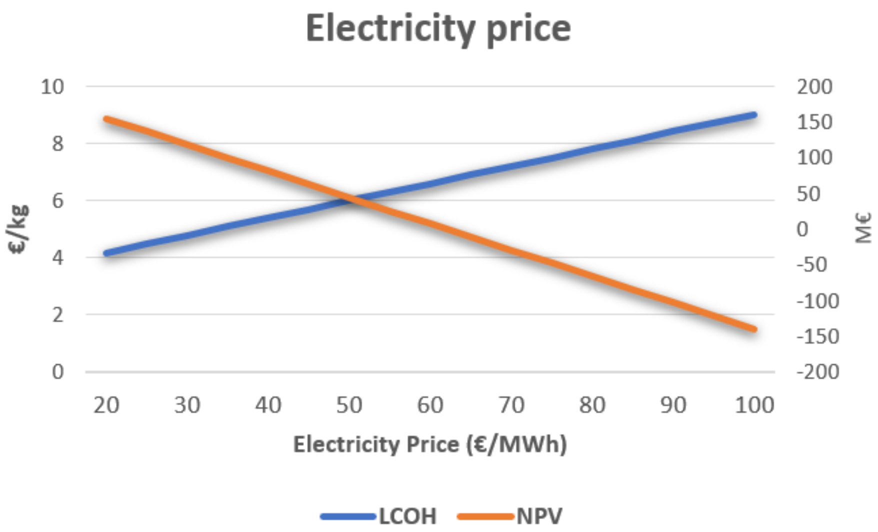


*Figure 47 Sensitivity analysis based on electricity price. LCOH and NPV results *Case 0: Centralised offshore dedicated production*

7.1.2 Electrolyser cost

The electrolyser is, regarding the CAPEX, the most influential system in the H_2 production process studied in the thesis. However, a reduction in the price of the electrolyser is envisaged to happen in the coming years. Prices of electrolysers are, according to different studies [46], set to decline up to 80 % in the next 10 years. Figure 48 shows how the reduction of the investment made only to the electrolyser part (in Case 0 it represented 65 % of CAPEX and 17 % of OPEX) affects the LCOH and the NPV. Decreasing the cost of the electrolyser by half, reduces LCOH by 1 €/kg, while the NPV would increase remarkably.

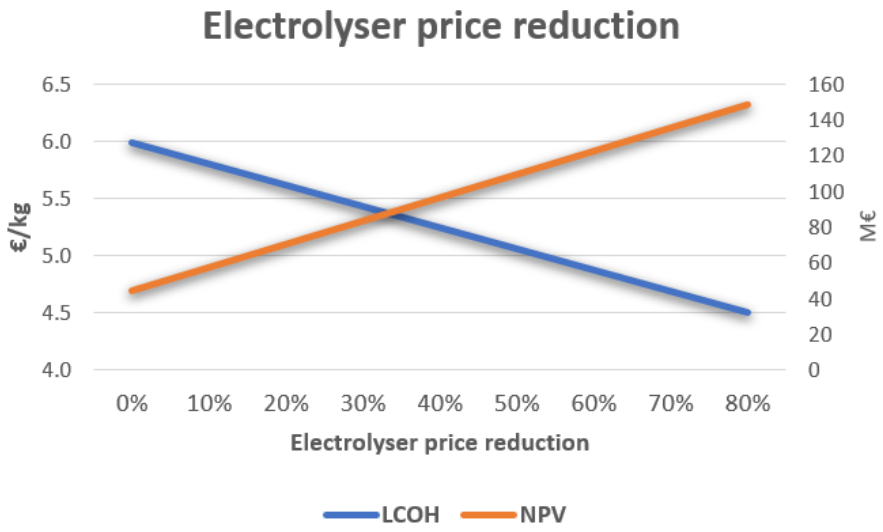


*Figure 48 Sensitivity analysis based on electrolyser price reduction. LCOH and NPV results *Case 0: Centralised offshore dedicated production*

7.1.3 O_2 sales composition

The demand for each type of gas is a factor to take into account when analysing the results as it directly affects the project revenues. The production of O_2 by electrolysis has the advantage of producing a gas with a very high purity which can be used for both industrial processes and the healthcare system. Figure 49 shows how the Payback and NPV of the project varies if the gases produced are sold according to the end-use and thus with different prices (medical = 5 €/kg, industrial = 0.1 €/kg). This final application for the O_2 will depend mostly on the possibility of selling as much O_2 as possible to the health sector, since margins are much higher for the same product.

In a scenario with half the O_2 produced for each sector, the project payback would be very low (around 1-2 years), while the NPV would increase considerably. On the other hand, if the O_2 demand is only industrial, with no space for the medical one, the investment would not be recovered having a negative NPV.

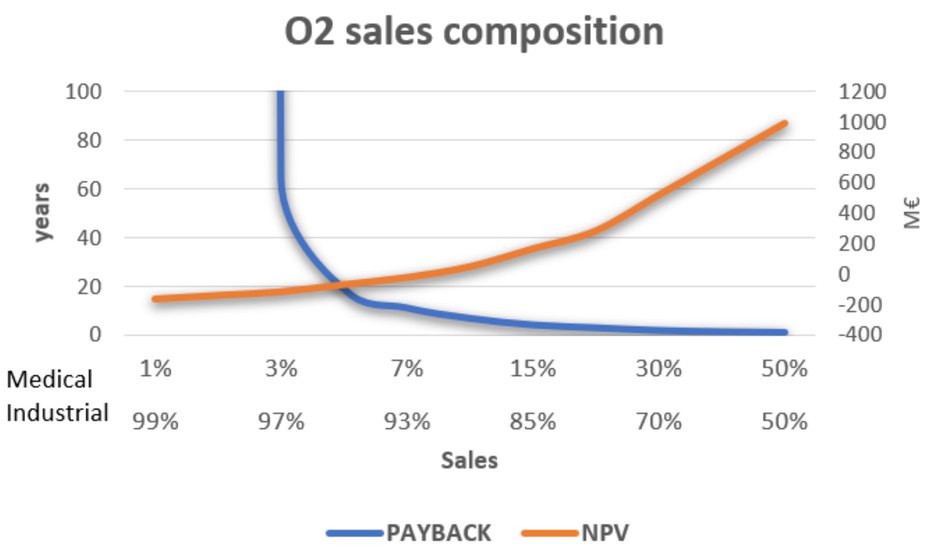


*Figure 49 Sensitivity analysis based on O_2 sales composition. Payback and NPV results *Case 0: Centralised offshore dedicated production*

7.2 Alternative scenario (Case Z)

The following is intended to show the results of a possible scenario that takes into account some factors that are expected to change in the coming years and that would require a new study with the new variables. Meanwhile, the intention with an invented scenario (Case Z) is to predict what could be the context of a project with the same characteristics. In Case Z, the cost of electricity from the OWF 35 €/MWh, it is assumed that a reduction in the price of the electrolyser of 40 % occurs, the price of all gases is reduced by 50 % and the sales of O_2 are divided equally between medicinal use and industrial use. Table 29 shows the comparison between the new scenario and Case 0, previously analysed in this thesis.

Table 29 Alternative scenario results. Case0 Vs Case Z

	Case 0	Case Z	Units
LCOH	5.98	4.33	€/kg
NPV	44	405	
Payback	6.90	1.85	years
CAPEX	136.39	100.74	M€
OPEX	26.88	19.19	M€/year

It is observed from the results how the combination of cost reductions and optimization of the sales can boost the profitability of these projects, with special focus on the O_2 sales as a main contributor to this new competitiveness.

Chapter 8.- CONCLUSIONS

OWFs and H_2 production constitute an area within the energy sector which is extremely worthy to be studied. Taking advantage of the vast offshore wind resource for H_2 production can provide economies with abundant and price-competitive resources, and the potential contributions the two sectors may offer to the energy systems go far beyond the constraints and challenges that they present in the short term.

Special consideration must be given to the synergies of these two technologies. For instance, the possibility of linking both factors in DC current would lower the costs for both applications. Moreover, technologies such as PEM are well suited for electricity input variations such as the ones experienced from wind supply. There are concepts such as the decentralised production that are very prone to experience further cost reductions as Original Equipment Manufacturers (OEMs) of both technologies develop joint projects. Both from erasing redundant systems and by proving that the equipment works properly in an offshore environment.

Additionally, another interesting insight is how important O_2 is for the H_2 projects to be feasible. O_2 is a valuable gas both for industry and health, which are markets that currently belong to few operators who are reticent to share the selling costs of this gas due to the high margins they obtain. However, O_2 production from electrolysis offers high qualities at “low” production costs, being therefore O_2 highlighted as one key enabler for the rollout of H_2 projects.

In this project, as conclusions drawn, centralised production arises as the most promising technology for the current state-of-the-art, since it allows for cheaper maintenance, enables development of economies of scale and has a higher efficiency. Decentralised production incurs into higher OPEX due to manned labour hours but nonetheless, it is argued that remote control of the equipment and predictive maintenance shall play a key role in these activities, rising the competitiveness of this method.

Conversely, curtailed production from OWFs is shown as a not a feasible option. Moreover, the increasing presence of smart grids is expected to reduce the hours of free electricity. H_2 is not an option for excess electricity at small scale.

While production in land is competitive in the current context, as time goes by, OWFs LCOE is expected to be greatly reduced, overall by the fact that WACCs are expected to shrink and the technologies are believed to be improved and produced more cheaply. Transmission assets, by contrast, are not prone to experience these cost reductions. Therefore, by 2040, almost half of the LCOE from an OWF will be related to the transmission assets. This will incur into a loss of competitiveness from this method.

As additional remarks and next steps, it must be noted that data used in the thesis are requested for the calculations and refer to the minimum requirements for the project, this is, that assuming better resources would lead to better results. For this thesis, the following hypothesis have been considered: commissioning and decommissioning periods have not been taken into account, no faults or delays throughout the project lifetime are considered, the gases produced are totally sold and the market value stable throughout the project lifetime and no other alternative incomes or debt effects are considered. Hence, to carry out a more detailed analysis of this baseline project as a next step or of any of the scenarios and systems that are presented, it is necessary to update the data used and understand its meaning and assumptions, since the project is developed in a conditioned environment, due to the continuous change of technologies and their rapid evolution as well as to the influence external factors such as political and social reasons.

Chapter 9.- References

[1] V. Dezem, “Hydrogen Breaks Through as the Hottest Thing in Green Energy,” Bloomberg, 09 24 2020. [Online]. Available: https://www.bloomberg.com/news/articles/2020-09-24/how-hydrogen-became-the-hottest-thing-in-green-energy-quicktake. [Accessed 01 10 2020].

[2] European Commission, “A hydrogen strategy for a climate-neutral Europe,” Brussels, 2020.

[3] L. Morais, “Portuguese govt approves national hydrogen policy,” 22 05 2020. [Online]. Available: https://renewablesnow.com/news/portuguese-govt-approves-national-hydrogen-policy-699832/. [Accessed 14 07 2020].

[4] “Germany's National Hydrogen Strategy,” 17 06 2020. [Online]. Available: https://www.cleanenergywire.org/factsheets/germanys-national-hydrogen-strategy. [Accessed 14 07 2020].

[5] MITECO, “El MITECO abre el periodo de información pública de la “Hoja de Ruta del Hidrógeno: una apuesta por el hidrógeno renovable”icono barra herramientas,” 29 07 2020. [Online]. Available: https://www.miteco.gob.es/es/prensa/ultimas-noticias/. [Accessed 29 09 2020].

[6] P. N. Wakim, “L’hydrogène, nouvel eldorado de la politique énergétique française,” Le Monde, 27 09 2020. [Online]. Available: https://www.lemonde.fr/economie/article/2020/09/27/l-hydrogene-nouvel-eldorado_6053802_3234.html. [Accessed 29 09 2020].

[7] Hydronews, “L’Italia investirà almeno 3 miliardi di euro sull’idrogeno: target produttivi allineati a quelli degli altri Paesi UE,” 28 09 2020. [Online]. Available: https://hydronews.it/litalia-investira-almeno-3-miliardi-di-euro-sullidrogeno-target-produttivi-allineati-a-quelli-degli-altri-paesi-ue/. [Accessed 29 09 2020].

[8] Australian Government, “Australia’s National Hydrogen Strategy,” 11 2019. [Online]. Available: https://www.industry.gov.au/data-and-publications/australias-national-hydrogen-strategy. [Accessed 14 07 2020].

[9] Hydrogen Council, “The Hydrogen Council announces 11 new members,” 07 09 2020. [Online]. Available: https://hydrogencouncil.com/en/membership-growth/. [Accessed 29 09 2020].

[10] D. Robinson, “What role could hydrogen and carbon capture tech play in the future of energy?,” *NS energybusiness,* 2020.

[11] J. Parnell, “Who Will Own the Hydrogen Future: Oil Companies or Utilities?,” GTM, 03 08 2020. [Online]. Available: https://www.greentechmedia.com/articles/read/utilities-on-both-sides-of-atlantic-follow-oil-majors-hydrogen-lead. [Accessed 30 09 2020].

[12] IEA, “The Future of Hydrogen,” Paris, 2019.

[13] HyBalance, “HyBalance,” [Online]. Available: http://hybalance.eu/. [Accessed 14 12 2020].

[14] IEA, “Energy Technology Perspectives 2020,” Paris, 2020.

[15] IPCC, “Global warming of 1.5°C,” WMO, Geneva, 2018.

[16] R. S. El-Emam and H. Ozcan, “Comprehensive review on the techno-economics of sustainable large-scale clean hydrogen productions,” *Journal of Cleaner Production,* vol. 220, pp. 593-609, 2019.

[17] IEA, “Offshore Wind Outlook 2019,” IEA, Paris, 2019.

[18] S. P.Neil and M. Hashemi, “Offshore Wind,” in *Fundamentals of Ocean Renewable Energy*, Academic Press, 2018, pp. 83-106.

[19] B. Bailey, “Wind resources for offshore wind farms: Characteristics and assessment,” in *Offshore Wind Farms: Technologies Design and Operation*, Woodhead Publishing, 2016, pp. 29-58.

[20] International Renewable Energy Agency, “Renewable Power Generation Costs in 2018,” IRENA, Abu Dhabi, 2019.

[21] Statista, “Global cumulative installed wind power capacity from 2001 to 2019,” Statista, 28 04 2020. [Online]. Available: https://www.statista.com/statistics/268363/installed-wind-power-capacity-worldwide/. [Accessed 30 09 2020].

[22] H. Díaz and C. Guedes Soares, “Review of the current status, technology and future trends of offshore,” *Ocean Engineering,* vol. 289, p. 107381, 2020.

[23] M. M. Levy, “Percentage of total population living in coastal areas,” NY, 2008.

[24] P. Morthorst and L. Kitzing, “Economics of building and operating offshore wind farms,” in *Offshore wind farms: Technologies Design and Operation*, Woodhead Publishing, 2016.

[25] P. Hevia-Koch and H. Klinge Jacobsen, “Comparing offshore and onshore wind development considering acceptance costs,” *Energy Policy,* vol. 125, pp. 9-19, 02 2919.

[26] EDP, “Offshore Wind,” [Online]. Available: https://www.edp.com/en/offshore-wind. [Accessed 20 07 2020].

[27] N. Sönnichsen, “Worldwide capacity of offshore wind power 2009-2019,” Statista, 7 04 2020. [Online]. Available: https://www.statista.com/statistics/476327/global-capacity-of-offshore-wind-energy/. [Accessed 2 10 2020].

[28] Wind Europe, “European Offshore Wind Farms Map,” 1 10 2020. [Online]. Available: https://windeurope.org/about-wind/interactive-offshore-maps/. [Accessed 1 10 2020].

[29] A. Stepek, “Review of existing wind atlases for the North Sea and the Netherlands,” *ResearchGate,* 05 2015.

[30] European Commission, “European Atlas of the Seas,” 01 10 2020. [Online]. Available: https://ec.europa.eu/maritimeaffairs/atlas/maritime_atlas. [Accessed 01 10 2020].

[31] General Electric, “Haliade-X 12 MW offshore wind turbine platform,” 04 04 2019. [Online]. Available: https://www.ge.com/renewableenergy/wind-energy/offshore-wind/haliade-x-offshore-turbine. [Accessed 2 10 2020].

[32] WInd Europe, “Wind energy in Europe in 2019,” Wind Europe.

[33] Nizar, “Renewable Solar Energy,” 2011. [Online]. Available: http://renewable-solar-energy.blogspot.com/2011/07/wind-turbine-swept-area.html. [Accessed 14 12 2020].

[34] K.-Y. Oh, W. Nam and M. Sung Ryu, “A review of foundations of offshore wind energy convertors: Current status,” *Renewable and Sustainable Energy Reviews,* vol. 88, pp. 16-36, 2018.

[35] E. P.P. Soares-Ramos, L. de Oliveira-Assis, R. Sarrias-Mena and L. M. Fernández-Ramírez, “Current status and future trends of offshore wind power in Europe,” *Energy,* vol. 202, p. 117787, 2020.

[36] R. Capata, A. Calabria, M. Di Veroli and S. Sangiorgio, “Preliminary feasibility study of a floating offshore wind plant along Italian coastal area,” in *ECOS 2015 - THE 28TH INTERNATIONAL CONFERENCE ON EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS*, Rome, 2015.

[37] C. C. A. A. A. W. Dominique Roddier, “WindFloat: A floating foundation for offshore wind turbines,” *AIP Journal of Renewable and Sustainable Energy,* 2010.

[38] M. I. K. K. W. W. L. B. David Caine, “Dolphyn Hydrogen,” 2019.

[39] C. Maienza, A. Avossa, R. F and D. Coiro, “A life cycle cost model for floating offshore wind farms,” *Applied Energy,* vol. 266, 2020.

[40] A. G. Gonzalez-Rodriguez, “Review of offshore wind farm cost components,” *Energy for Sustainable Development,* vol. 37, pp. 10-19, 03 12 2017.

[41] Renewables Now, “Prysmian wins EUR-140m DolWin5 grid connection contract,” 18 06 2019. [Online]. Available: https://renewablesnow.com/news/prysmian-wins-eur-140m-dolwin5-grid-connection-contract-658521/. [Accessed 24 04 2020].

[42] O. Anaya-Lara, “Offshore wind farm arrays,” in *Offshore Wind Farms: Technologies, Design and Operation*, Glasgow, ElSevier, 2016, pp. 389-417.

[43] O. Adeuyi and J. Liang, “Integration of power from offshore wind turbines into onshore grids,” in *Offshore Wind Farms: Technologies, Design and Operation*, Cardiff, Elsevier, 2016, pp. 441-457.

[44] N. Srinil, “Cabling to connect offshore wind turbines to onshore facilities,” in *Offshore Wind Farms: Technologies, Design and Operation*, Newcastle, Elsevier, 2016, pp. 419-440.

[45] WUPPERTAL INSTITUT; SHELL, “SHELL HYDROGEN STUDY, ENERGY OF THE FUTURE?,” Hamburg, 2017.

[46] HydrogenCouncil, “Path to hydrogen competitiveness: A cost perspective,” Brussels, 2020.

[47] EDF Energy R&D UK Centre Limited, “H2H Feasibility Report,” 2019.

[48] Hydrogen Europe, “Hydrogen Production,” Hydrogen Europe, 10 10 2020. [Online]. Available: https://hydrogeneurope.eu/hydrogen-production-0. [Accessed 10 10 2020].

[49] “ENERGY.GOV,” Office of energy efficiency & renewable energy, 2020. [Online]. Available: https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming. [Accessed 10 10 2020].

[50] “ENERGY.GOV Hydrogen Production: Coal Gasification,” Office of energy efficiency & renewable energy, 2020. [Online]. Available: https://www.energy.gov/eere/fuelcells/hydrogen-production-coal-gasification. [Accessed 10 10 2020].

[51] IRENA, D. Gielen, E. Taibi and R. Miranda, “HYDROGEN: A RENEWABLE ENERGY PERSPECTIVE,” Tokyo, 2019.

[52] A. Buttler and H. Spliethoff, “Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review,” *Renewable and Sustainable Energy Reviews,* vol. 82, no. 3, pp. 2440-2454, 2018.

[53] Iberdrola, “Iberdrola will construct the largest green hydrogen plant for industrial use in Europe,” 02 09 2020. [Online]. Available: https://www.iberdrola.com/about-us/lines-business/flagship-projects/puertollano-green-hydrogen-plant. [Accessed 28 10 2020].

[54] FuelCellWorks, “Electrolysis of sea water could provide a new boost for hydrogen as an energy source,” 22 May 2020.

[55] D. Thomas, “Large scale PEM electrolysis: technology status and upscaling strategies,” 08 10 2019. [Online]. Available: http://hybalance.eu/wp-content/uploads/2019/10/Large-scale-PEM-electrolysis.pdf. [Accessed 10 10 2020].

[56] D. Bessarabov, H. Wang and H. Li, PEM Electrolysis for Hydrogen Production, I ed., Boca Raton: Taylor & Francis Group, 2016, p. 392.

[57] P. Millet, “Membrane electrolysers for hydrogen (H2) production,” in *Advanced Membrane Science and Technology for Sustainable Energy and Environmental Applications*, Elsevier, Ed., Paris, Woodhead Publishing, 2011, pp. 568-609.

[58] A. Keçebaş, M. Bayatc and M. Kayfeci, “Electrochemical hydrogen generation,” in *Solar Hydrogen Production*, Elsevier, Ed., Karabük, 2019, pp. 299-317.

[59] J. Smalley, “windpowerengineering,” DNV GL, 2015. [Online]. Available: https://www.windpowerengineering.com/a-new-era-for-hydrogen-energy-unveiled-by-students-at-dnv-gl/. [Accessed 12 10 2020].

[60] A. Durakovic, “BEIS Backs Floating Wind to Hydrogen Project,” 18 02 2020. [Online]. Available: https://www.offshorewind.biz/2020/02/18/beis-backs-floating-wind-to-hydrogen-project/. [Accessed 13 04 2020].

[61] Tractebel, “Hydrogen production takes system to new levels,” [Online]. Available: https://tractebel-engie.com/en/news/2019/400-mw-offshore-hydrogen-production-takes-system-to-new-levels. [Accessed 13 04 2020].

[62] hysafe, “Large Scale Vs Small Scale And Centralized Vs Decentralized Production,” 2008. [Online]. Available: http://www.hysafe.net/wiki/BRHS/LargeScaleVsSmallScaleAndCentralizedVsDecentralizedProduction. [Accessed 17 10 2020].

[63] The Week Staff, “Oil rigs: Cities at sea,” 14 05 2010. [Online]. Available: https://theweek.com/articles/494480/oil-rigs-cities-sea. [Accessed 01 06 2020].

[64] A. Durakovic, “PosHYdon: First Green Offshore Hydrogen Pilot Explained – Video,” 23 10 2019. [Online]. Available: https://www.offshorewind.biz/2019/10/23/poshydon-first-green-offshore-hydrogen-pilot-explained-video/. [Accessed 13 04 2020].

[65] Y. F. Y. Y. ,. S. W. ,. Y. W. ,. M. Y. S. G. M. L. Jianxing Yu, “Assessment of Offshore Wind Characteristics and Wind Energy Potential in Bohai Bay, China,” MDPI, 2019.

[66] Z. Wu and H. Wang, “Research on Active Yaw Mechanism of Small Wind Turbines,” *Energy Procedia,* vol. 16, pp. 53-57, 2012.

[67] S. McDonaght, S. Ahmed, C. Desmond and J. D Murphy, “Hydrogen from offshore wind: Investor perspective on the profitability of a hybrid system including for curtailment,” *Applied Energy,* vol. 265, no. 114732, 01 05 2020.

[68] C. C. T. W. T. T. Nicolas Maslova, “Evaluating the Visual Impact of an Offshore Wind Farm,” 2016.

[69] M. Bilal Siddique and J. Thakur, “Assessment of curtailed wind energy potential for off-gridapplications through mobile battery storage,” *Energy,* vol. 201, 2020.

[70] leveltenenergy, “How to Manage Curtailment in a Virtual Power Purchase Agreement (VPPA),” 13 2 2019. [Online]. Available: https://leveltenenergy.com/blog/ppa-risk-management/renewable-energy-curtailment/. [Accessed 23 10 2020].

[71] M. K. N. K. Y. S. Takeyoshi Kato, “Effective Utilization of By-product Oxygen of Electrolysis Hydrogen Production,” Furo-cho Chikusa-ku Nagoya, 2005.

[72] A. G. García-Conde, “Producción, almacenamiento y distribución de hidrógeno,” 2010. [Online]. Available: http://www2.udg.edu/Portals/88/proc_industrials/5%20-%20Otros%20Combustibles-Hidrogeno.pdf. [Accessed 10 09 2020].

[73] N. Stetson, S. McWorther and C. Ahn, “Introduction to hydrogen storage,” in *Compendium of Hydrogen Energy*, Vols. Volume 2:hydrogen Storage, Transportation and Infrastructure, 1-Woodhead Publishing Series in Energy, 2016.

[74] G. Sdanghi, G. Maranzana, A. Celzard and V. Fierro, “Review of the current technologies and performances of hydrogen compression for stationary and automotive applications,” vol. 102, pp. 150-170, 2019.

[75] N. M. CleanTech, “Norwegian future value chains for liquid hydrogen,” Maritime CleanTech, Heiane, 2016.

[76] E. Connelly, M. Penev, A. Elgowainy and C. Hunter, “Current Status of Hydrogen Liquefaction Costs,” USA, 2019.

[77] IEA, “IEA G20 Hydrogen report: Assumptions,” IEA, Paris, 2019.

[78] U. Cardella, L. Decker, J. Sundberg and H. Klein, “Process optimization for large-scale hydrogen,” *International Journal Of Hydrogen Energy,* vol. 47, no. 17, 2017.

[79] J. Andersson and S. Grönkvist, “Large-scale storage of hydrogen,” *International Journal of Hydrogen Energy,* vol. 44, no. 23, pp. 11901-11919, 03 05 2019.

[80] R. Harding, “Japan launches first liquid hydrogen carrier ship,” 11 12 2019. [Online]. Available: https://www.ft.com/content/8ae16d5e-1bd4-11ea-97df-cc63de1d73f4. [Accessed 14 03 2020].

[81] A. Hammad and I. Dincer, “Analysis and assessment of an advanced hydrogen liquefaction system,” *International Journal Of Hydrogen Energy,* vol. 43, no. 2, pp. 1139-1151, 2018.

[82] J. Parnell, “World’s Largest Green Hydrogen Project Unveiled in Saudi Arabia,” 07 07 2020. [Online]. Available: https://www.greentechmedia.com/articles/read/us-firm-unveils-worlds-largest-green-hydrogen-project. [Accessed 11 07 2020].

[83] T. Kumagai, “AHEAD launches Brunei-Japan hydrogen supply chain for power generation in Tokyo Bay,” 25 06 2020. [Online]. Available: https://www.spglobal.com/platts/en/market-

insights/latest-news/natural-gas/062520-ahead-launches-brunei-japan-hydrogen-supply-chain-for-power-generation-in-tokyo-bay. [Accessed 10 07 2020].

[84] T. A.-S. Päivi, C. Cook, J. Kiviaho and T. Repo, “Liquid organic hydrogen carriers for transportation and storing of renewable energy – Review and discussion,” *Journal of Power Sources,* vol. 396, pp. 803-823, 2018.

[85] A. Lee, “'Deep Purple' seabed hydrogen storage for offshore wind plan,” 07 06 2019. [Online]. Available: https://www.rechargenews.com/wind/deep-purple-seabed-hydrogen-storage-for-offshore-wind-plan/2-1-617947. [Accessed 14 04 2020].

[86] World Energy Trade, “Producir hidrógeno a granel a través de turbinas eólicas marinas,” 10 04 2020. [Online]. Available: https://www.worldenergytrade.com/index.php/m-news-alternative-energy/95-news-gas/6989-producir-hidrogeno-a-granel-a-traves-de-turbinas-eolicas-marinas. [Accessed 13 04 2020].

[87] Rohkus Team, “Niveles de madurez de la Tecnología TRLs,” ROHKUS, [Online]. Available: https://www.gestionfondosmexico.mx/single-post/2016/07/22/Niveles-de-madurez-de-la-Tecnolog%C3%ADa-TRLs. [Accessed 17 10 2020].

[88] European Commission, “G. Technology readiness levels (TRL),” 2014. [Online]. Available: https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf. [Accessed 5 10 2020].

[89] Commonwealth of Australia (Australian Renewable Energy Agency), “Commercial Readiness Index,” 2014.

[90] W. Kenton, “Capital Expenditure (CapEx),” Investopedia, 04 08 2020. [Online]. Available: https://www.investopedia.com/terms/c/capitalexpenditure.asp. [Accessed 10 10 2020].

[91] W. Kenton, “Operating Expense,” Investopedia, 19 10 2020. [Online]. Available: https://www.investopedia.com/terms/o/operating_expense.asp. [Accessed 20 10 2020].

[92] W. Kenton, “Revenue,” 01 10 2020. [Online]. Available: https://www.investopedia.com/terms/r/revenue.asp. [Accessed 10 10 2020].

[93] A. Hayes, “Internal Rate of Return (IRR),” Investopedia, 02 09 2020. [Online]. Available: https://www.investopedia.com/terms/i/irr.asp. [Accessed 15 10 2020].

[94] Gas Renovable, “¿Qué es el Hidrógeno Renovable?,” 08 08 2020. [Online]. Available: https://www.gasrenovable.org/tipos-gas-renovable/hidrogeno-renovable/. [Accessed 08 08 2020].

[95] IEA, “Tracking Transport,” 25 05 2020. [Online]. Available: https://www.iea.org/reports/tracking-transport-2019. [Accessed 25 02 2020].

[96] Agence France-Presse, “Germany launches world's first hydrogen-powered train,” The Guardian, 17 09 2018. [Online]. Available: https://www.theguardian.com/environment/2018/sep/17/germany-launches-worlds-first-hydrogen-powered-train. [Accessed 27 10 2020].

[97] Airbus, “Airbus reveals new zero-emission concept aircraft,” 21 09 2020. [Online]. Available: https://www.airbus.com/newsroom/press-releases/en/2020/09/airbus-reveals-new-zeroemission-concept-aircraft.html. [Accessed 28 10 2020].

[98] FCHJU, “H2Ports,” [Online]. Available: https://h2ports.eu/. [Accessed 28 10 2020].

[99] Air Products, “Oxygen (O_2),” 2020. [Online]. Available: https://www.airproducts.com/gases/oxygen. [Accessed 01 09 2020].

[100] MarketWatch, “Industrial Oxygen Market Size In 2020,” 08 10 2020. [Online]. Available: https://www.marketwatch.com/press-release/industrial-oxygen-market-size-in-2020-new-report-data-is-available-for-global-separately-with-impact-of-domestic-and-global-market-top-players-manufacturers-data-opportunity-import-export-scenario-regions-and-futu. [Accessed 20 10 2020].

[101] R. J. Allam, “Improved oxygen production technologies,” *Energy Procedia,* vol. 1, pp. 461-470, 2009.

[102] L. Bonfim-Rocha, M. Luiz Gimenes, S. Henrique Bernardo de Faria, R. Orgeda Silva and L. Jimenez Esteller, “Multi-objective design of a new sustainable scenario for bio-methanol production in Brazil,” *Journal of Cleaner Production,* vol. 187, p. 1043e1056, 2018.

[103] J. Sillars, “UK targets a third of power from offshore wind by 2030,” *Sky News,* 2019.

[104] D. Wenston, “Dong announces Vindeby decommissioning,” Wind Power Monthly, 10 02 2016. [Online]. Available: https://www.windpowermonthly.com/article/1382887/dong-announces-vindeby-decommissioning. [Accessed 20 05 2020].

[105] Banco de España, *TIPOS DE CAMBIO E ÍNDICES DE COMPETITIVIDAD,* Madrid, 2020.

[106] grantthornton, “Renewable energy discount rate survey 2018,” 13 2 2019. [Online]. Available: https://www.grantthornton.co.uk/insights/renewable-energy-discount-rate-survey-2018/. [Accessed 2020].

[107] gov.uk, *Income Tax rates and Personal Allowances,* 2020.

[108] msp-platform.eu, “General Introduction to the North Sea,” 4 2020. [Online]. Available: https://www.msp-platform.eu/sea-basins/north-sea-0. [Accessed 15 11 2020].

[109] Encyclopædia Britannica, Inc., “North Sea,” [Online]. Available: https://kids.britannica.com/kids/article/North-Sea/353544. [Accessed 2020].

[110] ec.europa.eu, “Develop and demonstrate a 100 MW electrolyser upscaling the link between renewables and industrial applications,” 2018. [Online]. Available: https://ec.europa.eu/info/sites/info/files/research_and_innovation/green_deal/gdc_stakeholder_engagement_topic_02-2_electrolyser.pdf. [Accessed 15 11 2020].

[111] siemensgamesa, “Siemens Gamesa launches 10 MW offshore wind turbine; annual energy production (AEP) increase of 30% vs. predecessor,” 16 1 2019. [Online]. Available: https://www.siemensgamesa.com/en-int/newsroom/2019/01/new-siemens-gamesa-10-mw-offshore-wind-turbine-sg-10-0-193-dd. [Accessed 15 11 2020].

[112] P. A. &. S. J. Watsona, “Offshore Turbine Wake Power Losses: Is Turbine Separation Significant?,” Energy Procedia, Trondheim, 2017.

[113] IRENA, “Offshore innovation widens renewable energy options,” Abu Dhabi, 2018.

[114] E. Mearns, “UK Wind Constraint Payments,” 5 9 2016. [Online]. Available: http://euanmearns.com/uk-wind-constraint-payments/. [Accessed 2020].

[115] BVG Associates, “Catapult Offshore Renewable Energy,” 2019. [Online]. Available: https://guidetoanoffshorewindfarm.com/wind-farm-costs. [Accessed 15 11 2020].

[116] GL Garrad Hassan, “A Guide to UK Offshore Wind Operations and Maintenance,” Scottish Enterprise and The Crown State, 2013.

[117] R. O. D. M. W. J. D. J. D. M. Shane McDonagha, “Modelling of a power-to-gas system to predict the levelised cost of energy of an advanced renewable gaseous transport fuel,” Elsevier, 2018.

[118] J. Eke, A. Yusuf, A. Giwa and A. Sodiq, “The global status of desalination: An assessment of current desalinationtechnologies, plants and capacity,” *Desalination,* vol. 495, p. 114633, 2020.

[119] ,. A. Y. ,. A. G. A. S. Joyner Eke, “The global status of desalination: An assessment of current desalination technologies, plants and capacity,” Elsevier B.V, 2020.

[120] Gazprom, “Gazprom,” Gazprom, 2019. [Online]. Available: https://www.gazprom.com/projects/nord-stream/. [Accessed 14 03 2020].

[121] G. Matute, J. Yusta and L. Correas, “Techno-economic modelling of water electrolysersin the range of several MW to provide grid serviceswhile generating hydrogen for differentapplications: A case study in Spain applied tomobility with FCEVs,” *International Journal of Hydrogen Energy,* vol. 44, pp. 17431-17442, 2019.

[122] P. C. C. B. A. C. Lorién Gracia, “Use of Hydrogen in Off-Grid Locations, a Techno-Economic Assessment,” energies.

[123] Europacable, “HV DC CABLES,” Europacable, [Online]. Available: https://www.europacable.eu/energy/hvdc-cables. [Accessed 20 08 2020].

[124] A. Alassia, S. Bañalesa, O. Ellabbana, G. Adamb and C. MacIverb, “HVDC Transmission: Technology Review, Market Trends and Future Outlook,” *Renewable and Sustainable Energy Reviews,* vol. 112, pp. 530-54, 2019.

[125] C. M. S. G. G. A. O. A.-L. K. B. K. Nieradzinska, “Optioneering analysis for connecting Dogger Bank offshore windfarms to the GB electricity network,” Elsevier , 2015.

[126] Oil and Gas Authority, *UKCS Operating Costs in 2017,* London, 2018.

[127] B. Van Eeckhout, D. Van Hertem, M. Reza and K. Srivastava, “Economic comparison of VSC HVDC and HVAC as transmission system for a 300 MW offshore wind farm,” *European Transactions on Electrical Power,* vol. 20, no. 5, pp. 661 - 671, 2009.