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Offshore wind power: a reliable and renewable energy source for all?

Master's thesis

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Climate change is a major challenge of the 21st century with potential severe consequences of global warming on all biological systems. The main reason is the CO_2 emissions caused by human activities. In this context, renewable energies are one of the most promising solutions to strive against this issue. This master's thesis aims to a better understanding of the offshore wind power, by studying the advantages, drawbacks and potential of this technology.

Wind offers a large and clean resource of power, available all over the world. Wind power plants have first been developed onshore in 1980 as it is an easy and cheap technology. However, onshore wind is limited in terms of capacity suffering from volatile wind conditions and limited acceptance from the population.

Conversely, offshore wind power allows very large-scale development, featuring larger turbines in areas where a stronger and more consistent wind blows. This allows to generate more power and to have better capacity factors, explaining why offshore wind power has recently emerged as an excellent asset to develop renewable energies at large-scale.

Yet, offshore wind power currently suffers from one major drawback: the shallow-water requirement. Wind turbines are currently placed on fixed foundation that can reach a maximum water depth of 60 meters. This drastically limits the possible development areas and has led to large development inequalities across the world.

Floating wind turbines are being developed to remove this restriction. Several approaches are under testing to tackle stability issues, all successful so far. This would be a game changing technology because it would unlock countless areas to implement offshore wind farms particularly for countries that do not have offshore shallow waters.

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Introduction

Global warming has become more urgent than any time before with already dramatic consequences on the environment. The worst is yet to come, with the temperature expected to increase by 3.5°C in 2100, pessimistic estimations even considering a 7°C raise [1]. Reducing the CO_2 emissions has become a major objective for political agenda in most countries and companies while trying to maintain growth. However, most of the solutions preventing the emission of CO_2 are based on electricity, such as electric cars. This only shifts the problem as electricity generation emits great quantity of CO_2 in the atmosphere, particularly in countries using fossil fuel power plants. Conversely, renewable energy harness naturally replenished resources while having very low life-cycle CO_2 emission. This is why they have become the crux of the matter.

A massive effort in research has been conducted since the end of the 20th century to improve properties and lower cost of renewable energy technologies. The work paid off as renewable energies are now on average cheaper than fossil fuel-based power generation. However, several drawbacks remain potentially preventing renewable technologies from a large-scale development, especially their reliability. Indeed, while electrical consumption is very stable and predictable, meteorological conditions are volatile making power generation from renewable energies not entirely reliable.

Onshore wind was a technology already known in the 19th century. Research greatly improved the reliability of the technology but research cannot change the most crucial parameter: wind conditions. Offshore wind is more powerful and more consistent than the onshore one. This is why offshore wind farms have recently emerged as one of the most promising renewable technologies. Besides, offshore turbines imply limited visual and noise pollution unlike its cousin onshore wind, which allows turbines to be higher and wider in order to harness more powerful wind.

However, this technology has its own flaws. Every steps of the wind farm from conception to decommissioning are today expensive. Fixed foundations rooted in the seabed are needed to support the wind turbine. This expensive and technical process requires specific seabed conditions to ensure the stability of the structure. Furthermore, there are still uncertainties regarding the impact on biodiversity, in particular birds. There are challenging technology issues of wind farm development, some of them being similar to other renewable energies, other more specific to offshore wind power which explains why the use of offshore wind is still limited.

The goal of this master’s thesis is to explain what is an offshore wind farm, what are its current advantages and what is yet to improve to become a reliable and renewable source of energy for all countries. It will review the current available data from literature to make a clear report on this technology, accessible for people interested in this topic that do not necessarily have a scientific background. The thesis also aims at explaining the advantages and drawbacks of different renewable energy sources.

This thesis starts with a review of the basics of this technology, describing its main parameters, to enable the reader to understand how a wind farm works.

The second part will explain why certain regions of the world have developed offshore wind power technology more than the others. Maps will illustrate the offshore wind potential of different parts of the world followed by an analysis of the decisions made by countries.

The third will compare offshore wind power to other power generation technologies, in particular to other renewable energy sources. This will highlight the pros and cons of each technology on essential criteria such as costs, capacity factor and environmental footprint.

The last part will review and analyse floating foundations, a new technology that can overcome many major concerns of offshore built wind farms. Floating wind farms are expected to be game changing by making offshore wind power suitable in countries that currently cannot use this technology.

I. How an offshore wind turbine works?

Basic understanding of the offshore wind power technology is essential to support the discussion in this thesis. Onshore and offshore wind farms are based on a similar principle. Both are constituted of several wind turbines, spaced by a security margin, that generates power. Although offshore turbines are usually larger, onshore and offshore turbines are the same and can be used in both environments. Furthermore, power generation is also identical, relying on the rotation of the rotor around the stator.

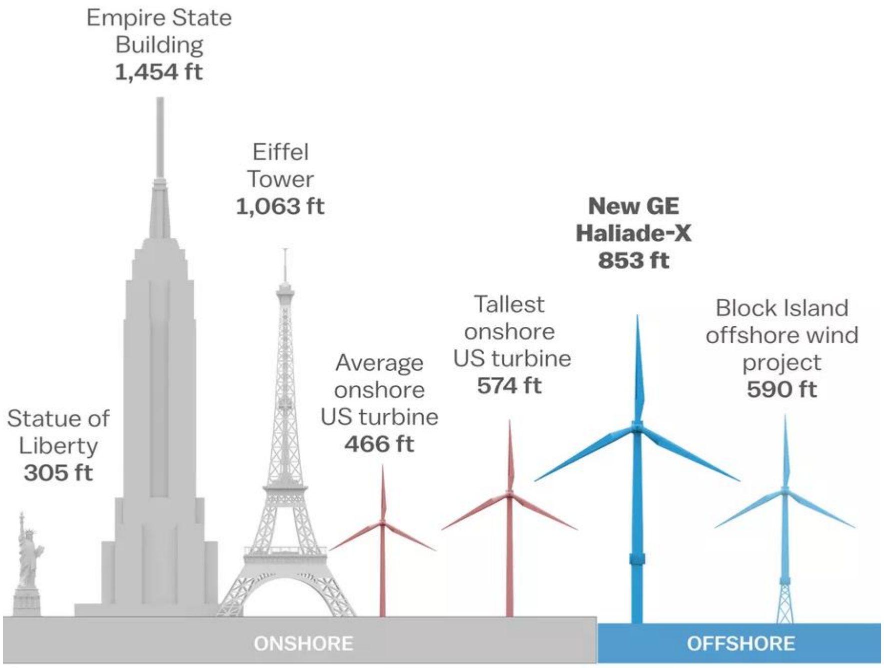


Figure 1: Comparison of the new Haliade-X size with high buildings [2]

The main difference between onshore and offshore wind farm is the foundations. The real challenge for offshore wind farm is to make the turbines stand, while facing powerful winds. Therefore, turbines need to be fixed to the seabed through the foundations. There are several types of foundations that will be described, as they are crucial. Then, a transition piece is needed to link the foundation to the turbine. Finally, subsea cables are used to transport electricity to the land. An offshore wind turbine is thus composed of four main parts:

- The foundation that roots the structure into the seabed.
- The transition piece that links the foundation to the turbine.
- The turbine that generates power
- Cables that carry electricity to the land

These four parts are essential and define an offshore wind farm. However, cables and transition piece do not really vary by wind farms, their environmental and economic impact is negligible; they will not be detailed. Foundations and turbines are truly unique elements that focus all the attention of developers. It is crucial to understand them well in order to analyse what could be improved.

A. The foundations

Foundations are the crux of the matter in offshore wind farms. It is the pillar of the whole structure. Different types of foundations exist and are yet to be created. For now, there are five main different types of foundations:

- Gravity-based
- Tripod
- Jacket
- Monopile
- Floating (The most recent technology that will be further developed in the final part)

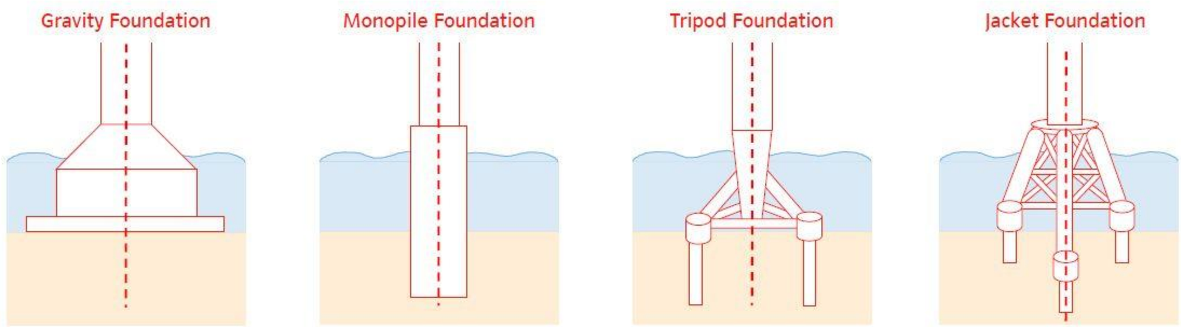


Figure 2: Main types of fixed foundations [3]

Each foundation carries advantages and drawbacks. Wind farm developer make the most adequate choice according to site of implementation, mainly the depth and the seabed properties. However, these are not the only two parameters considered, a more detailed description of each foundation type is needed to better understand the developer's possibilities and choices.

1) Monopiles

Monopiles are by far the most frequently set up foundation, representing over 80% of the total foundations in Europe [4]. They are based on a large steel cylinder rooted in the seabed. The three main characteristics are the embedment length, the diameter and the wall thickness. The larger the turbines the stronger the monopiles need to be, with some monopiles weighting over 1300 tons. [5]

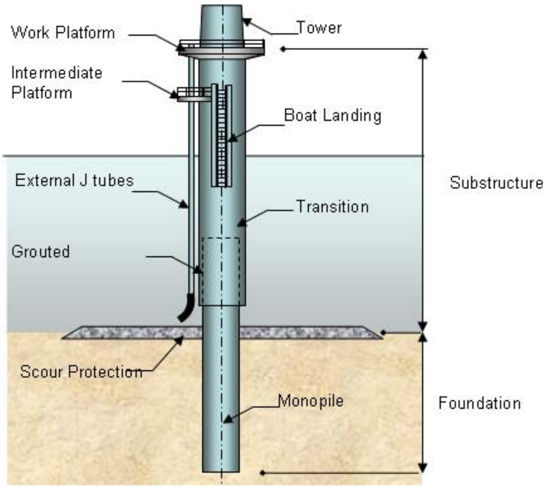


Figure 3: Scheme of a monopile foundation [6]

Monopiles offer several advantages, as they are dominant in the foundation market. First of all, it is a cheap, simple and reliable technology. Its design is simple and has proved its high reliability with over 4000 monopiles existing in Europe [4]. Besides, the technology is perfectly suited for shallow waters (<40m) [7]. As the offshore wind power technology is relatively new, developers first picked shallow-water and nearshore area where installation is cheaper and easier, making the monopile the best option.

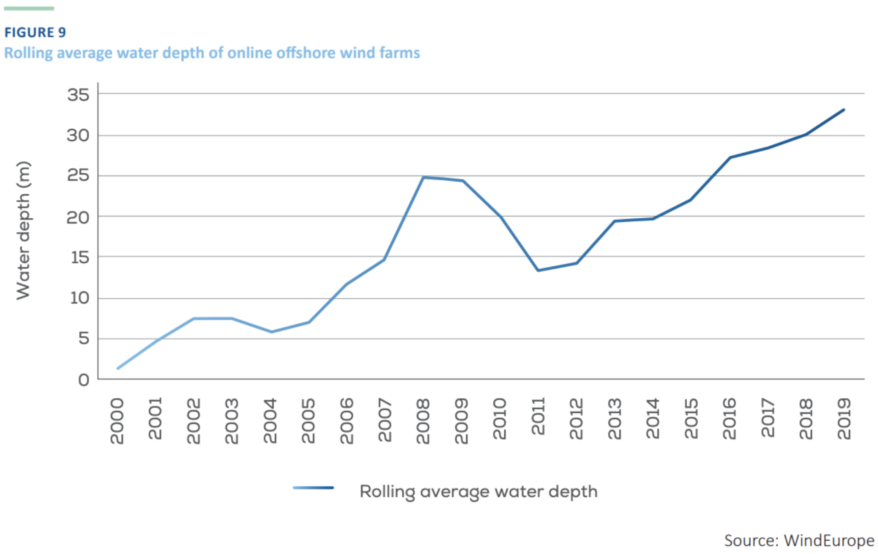


Figure 4: Average water depth of wind farms in Europe [4]

However, shallow-water areas are getting scarcer. Furthermore, developers want to harness stronger wind as more powerful turbines are available. This usually results in wind farm further away from the shore, in higher water depth, as highlighted in the figure 4. Monopiles have limited fatigue and stiffness resistance which prevent them from being installed in deeper waters [7]. Besides, a piling vessel is needed to pile the foundation into the seabed which is a relatively risky step.

Hence, monopiles is a cheap and reliable option making it the best option in shallow water. However, market is growing and aiming at more powerful turbines in deeper waters. Monopiles are going to be challenged soon enough and will have to adapt to remain competitive.

2) Jacket

Jacket foundations are the second most used foundations but far behind monopiles with only 9% of the total installations in Europe [4]. Their structure is based on tubular legs, usually four, made out of steel, with smaller cross stiffening tubulars welded in place between the main legs. At the bottom of each leg, a pile is rooted into the seabed to strengthen the structure. The first wind farm with jacket foundation was Alpha Ventus, commissioned in 2009. It is a relatively new foundation that keeps enhancing its performances thanks to research.

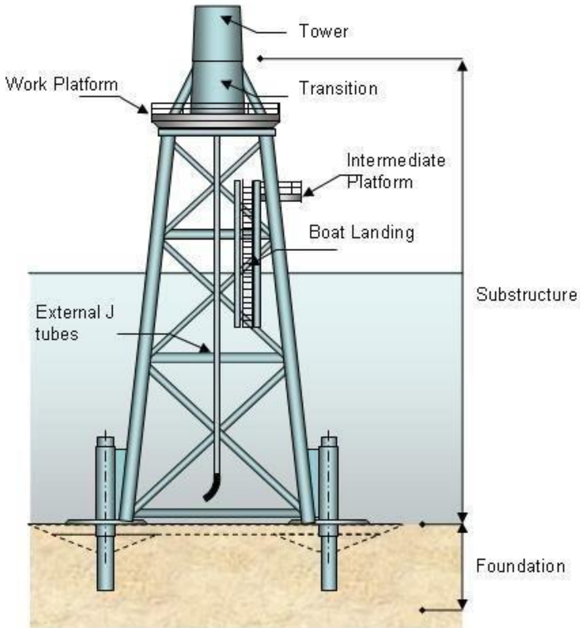


Figure 5: Scheme of a jacket foundation [6]

Their main advantage of jacket foundations is their ability to be installed in deeper waters. Indeed, they are suitable in "high water depths", up to 50 meters such as in the Wikinger wind farm, while monopiles can hardly go deeper 30 meters [7]. This represents a great asset, especially nowadays when developers aim towards more powerful wind farms further from the shore and thus in higher water depths. Besides, there are less requirements on the seabed properties than monopiles, as the pile sleeves only go few meters down into the seabed.

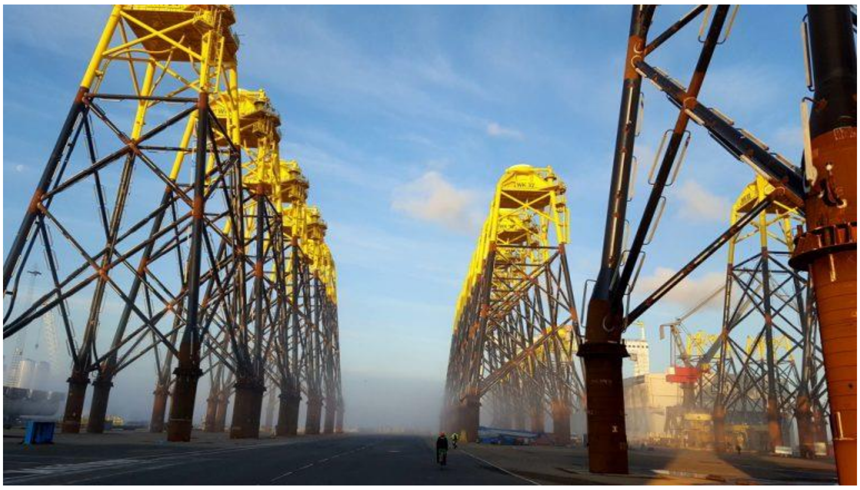


Figure 6: Jacket foundations for the Wikinger wind farm [8]

However, jackets still present some drawbacks that often make other foundation types a better option. Firstly, the jacket structure is complex and needs more studies before being installed [9]. Then, the structure is also more exposed to corrosion issues with more surface in contact with the sea. Finally, a new type of foundation appeared in recent years and will threaten jackets: floating foundations. They have proven to be a reliable and very promising option during the last decade. This new type of foundation is expected to revolutionize the offshore wind market. It will be thus largely studied in a part below. Hence, jackets seem to be stuck between the cost effective monopiles and the very promising floating structures. However, the latter has yet to prove its reliability, allowing the jacket foundations to become one of the best options for developers in the next decade.

3) Gravity-based

Gravity-based structures (GBS) are the third most used foundation type with 6% of the total installations in Europe [4]. It is a support structure that anchors and maintain the turbine stability thanks to its gigantic mass. The caisson which constitutes the main body of the base is usually filled in situ with ballast stones, concrete or other high-density aggregates.

GBS foundations do not have real advantages but rather display several disadvantages. As the key of this foundation is the weight, the seafloor requirements are high to carry such a heavy structure. Besides, the seafloor needs to be flat and not slippery [10]. The installation is long and requires large vessels and ports. The larger the turbine, the bigger the GBS needs to be. This means the largest turbines cannot stand on GBS foundation without damaging the seafloor.

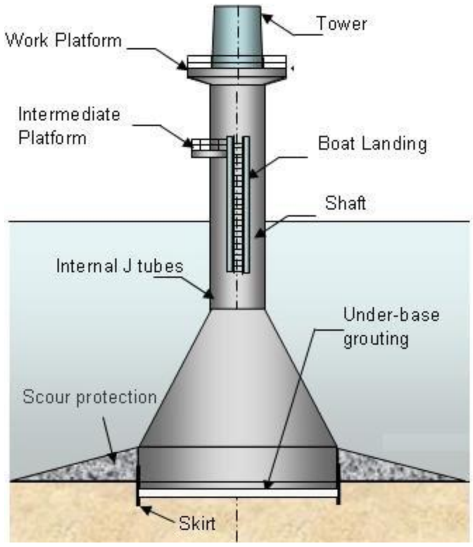


Figure 7: Scheme of a gravity-based foundation [6]

The flowing table listing all the European wind farms based on this foundation highlights the drawbacks [11]. First of all, these wind farms are relatively old as 85% of them were built before 2013. It means that GBS are not suitable for the market of today. One explanation is the water depth: except for the Blyth wind farm in UK, all water depths are below 20 meters. GBS seems not suitable for deep waters while being a worse option than monopiles in shallow waters. Hence, GBS were the first foundations used and presented great advantages back then in ultra-shallow water, but the market has changed and better foundations have been developed since.

Table 1: List of European wind farms with GBS foundations [11]

Wind Farm	Country	Year built	Total Power	Turbine power	Depth
Blyth	UK	2017	40	5 MW	30-40
Tahkoluoto	Finland	2017	42	4.2 MW	2
Kårehamn	Sweden	2013	48	3 MW	6–20
Vindpark Vänern	Sweden	2012	30	3 MW	-
Avedϕre Holme	Denmark	2011	10.8	3.6 MW	2
Nysted II	Denmark	2010	207	2.3 MW	6–12
Sprogϕ	Denmark	2009	21	3 MW	10–16
Thorntonbank Phase 1	Belgium	2009	30	5 MW	13–20
Lillgrund	Sweden	2007	110	2.3 MW	4–13
Breitling	Germany	2006	2.5	2.5 MW	0.5
Nysted I	Denmark	2003	166	2.3 MW	6–10

Middelgrunden	Denmark	2001	40	2 MW	3–6
Tunф Knob	Denmark	1995	5	500 kW	4–7
Vindeby (dismantled)	Denmark	1991	4,95	450 kW	2–4

4) Tripod

Tripod foundation are the fourth most common type of foundation but they only represent 2.4% of all European wind foundations [4]. Tripods are based on a large central column that holds thanks to three diagonal braces linked to pile sleeves rooted into the sea bed.

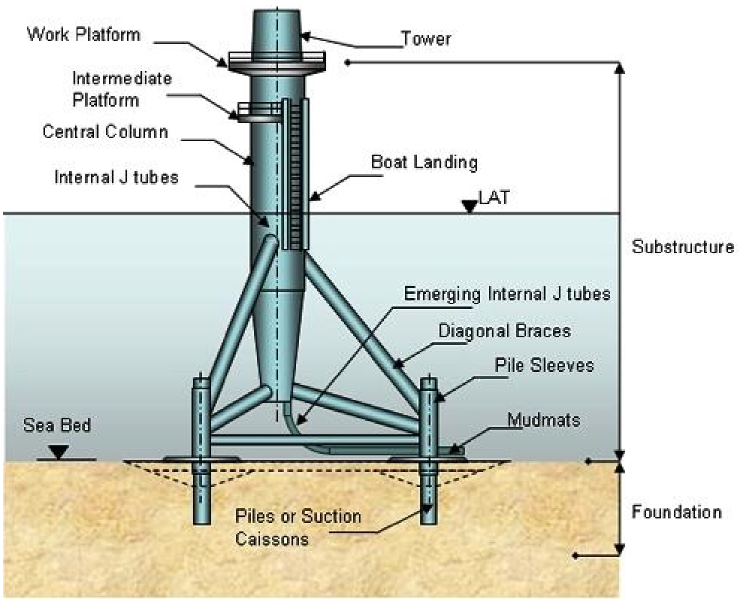


Figure 8: Scheme of a tripod foundation [6]

This foundation, designed in 2006 by OWT, present several advantages very interesting in certain cases. They can be suitable in water depth up to 50 meters [7] and can carry large turbines, which is excellent according to the market trends. Furthermore, their durability is said to be better than other foundation types thanks to a better design. [12]

However, this foundation is much more expensive [13]. They can't compete against the monopiles in the shallow water market, and they have yet to prove to be a better choice than jackets. They have been selected for only two wind farms so far (excluding demonstrations): Global Tech I and Trianel Windpark Borkum. Hence, tripods could be a promising option, but a lot of research is needed to lower the cost of this technology.

A fifth type of foundation exists, tripile, but they have only been used for a single wind farm which faced many problems, including a 3-year delay on the schedule. It is a technology worth mentioning but too little has been done on it to describe it. As explained, a sixth type was recently developed: floating foundations. They are extremely promising and will consequently be focused in the final part of this master's thesis.

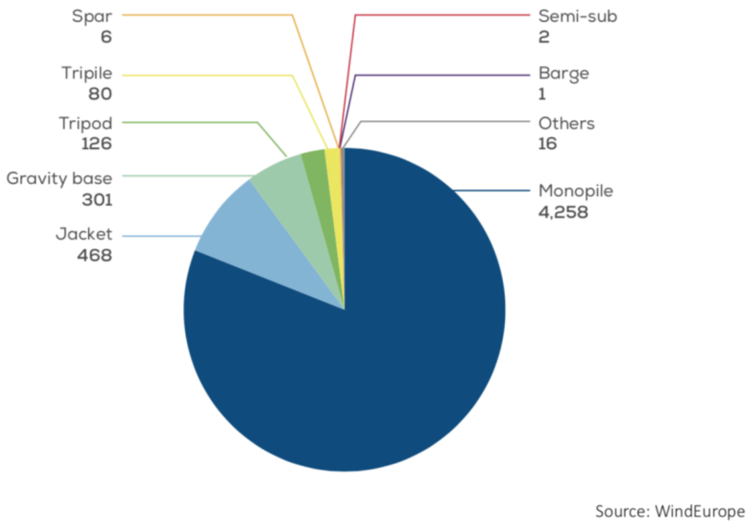


Figure 9: Numbers of foundations installed by type [4]

As highlighted by the figure 9, monopiles are overwhelming because it is the most cost-effective option until high water depths. Besides, research keeps improving monopiles suitability in high water depths, up to 40 meters. Jacket structures only represents 8.9% of the total foundations but it is growing fast [4]. It has proved to be the most reliable option while being cost-effective for the high-water depth market. Besides, its design is under study to enhance its performances, while monopiles cannot improved their design. Gravity-based, tripod and tripile foundations are marginal and have a lot to overcome to become a serious option. Last but not least, floating foundations are on the limelight as some very promising tests have been conducted. This technology could revolutionize offshore wind farms and will be thus discussed in more detail in the end of the thesis. The following table summarizes the advantages and drawbacks explained in this part.

Table 2: Summary of foundations' advantages and drawbacks

	Monopiles	Jackets	Gravity based	Tripod
Water depth	Medium WD Up to 40m	High WD Up to 50m	Shallow water Up to 30m	High WD Up to 50m
Reliability	High	High	Medium	High
Facility of installation	Medium	Medium	Complex	Medium
Seabed requirements	Medium	Low	High	Low
Weight	Low	Medium	High	Medium

B. Turbines

Turbines are a key part of an offshore wind turbine as it generates power. Even though their design barely evolved over time, major advancements have been made in order to build increasingly more powerful wind turbines.

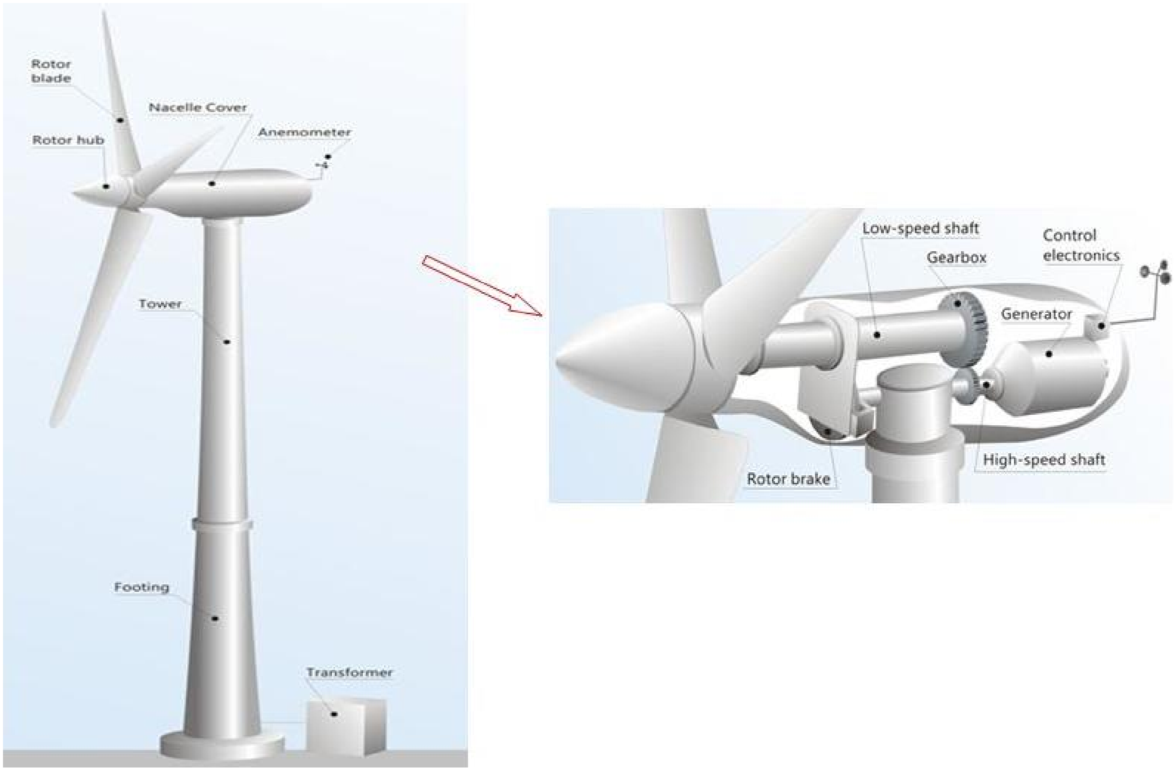


Figure 10: Scheme of a wind turbine [15]

A wind turbine is composed of three main parts:

- A tower that constitute the body
- A nacelle that gathers all the elements generating power
- The blades that spin

The tower part is a support structure, made as high as possible to enable the blades to harness winds as strong as possible. This will not be reviewed because it presents very low interest to describe. The nacelle part gathers all the elements generating power. It mainly includes gearboxes, a rotor and a stator. However, the generating power principle is common to most power plants. The rotor rotates around the stator which is supplied by AC current. This will generate a rotating magnetic field that will induce a current. Research try to improve the properties but this principle is also applied in nuclear, hydropower and fossil fuel power plants. The nacelle component will consequently not be reviewed. Blades are the key part of a wind turbine and will be studied to understand their main parameters, advantages and drawbacks.

1) Principle

Blades use aerodynamic properties to spin such as airplanes wings to fly. A blade is more curved at the rear than at the front. This results in a pressure differential between the rear and the front when the air crosses the blades, that creates a drag and a lift force, the latter making the blades spin [16]. The nacelle can rotate around the tower axis in order to perfectly face the wind. Captors placed on the nacelle collect precious wind measurements to set the best direction to face, in order to maximize the production.

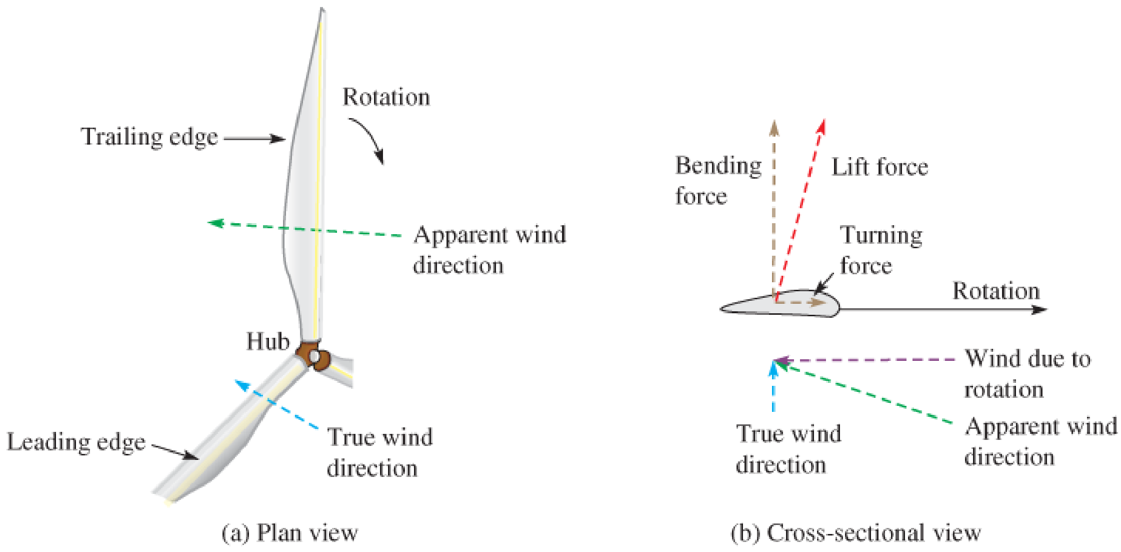


Figure 11: Blades spinning principle [17]

However, heavy mechanical strain can be induced with high wind speed, being dangerous for the turbine. Hence, engineers use a sailing technique called furling to tackle this issue [18]. In sailing, it consists in reducing the area of the sail, usually by folding a part of the canvas, to improve the vessel stability and to reduce the risks of damage. In wind turbines, this same technique is achieved by decreasing the blade's angle of attack.

Furling enables to have a great control on the rotation speed of the blades. This is essential to efficiently generate electricity and to safely keep components within designed speed limits. Indeed, turbines are designed for a specific range of wind speed, according to the environment in which they will be implemented to. According to several parameters of the blades, turbines have cut-in and cut-out speed

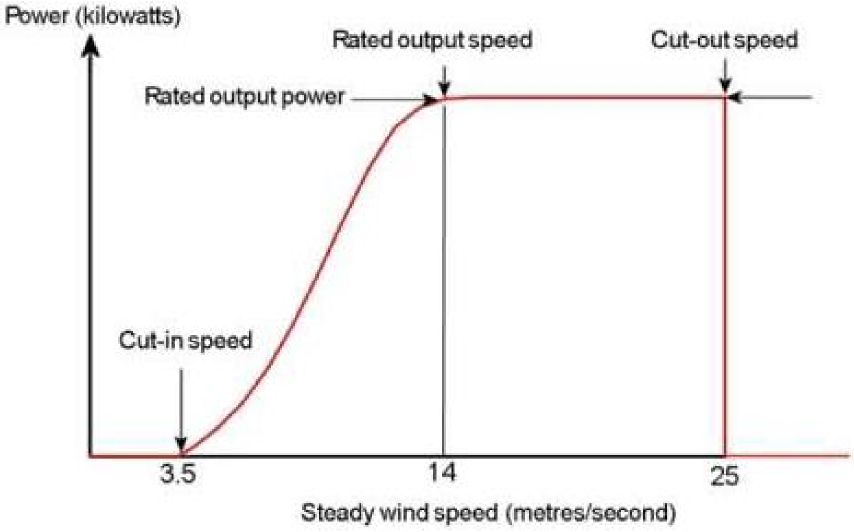


Figure 12: Produced power according to wind speed for a typical wind turbine [19]

In this example above, the cut-in speed is around 3.5 m/s while the cut-out speed, also called the survival speed, is 25 m/s. This means when the wind blows stronger than 90 km/h, the turbine has to stop and no power is generated. This is a crucial reliability issue as it is difficult to predict if the wind will blow at 85 km/h or 95 km/h. Sudden strong wind gusts can also occur and exceed this limit. It makes power generation unpredictable in certain conditions, the recurring drawback of renewable energies.

2) Limits

Over the years, scientists have constantly searched for improving the energy harnessing of wind turbines. However, they can't capture more than $\frac{16}{27}$ (59.3%) of the kinetic energy of the wind. This Betz limit has been found in 1919 by the physicist Albert Betz. This law is derived from the principles of conversion of mass and momentum of the air steam flowing through an idealized turbine [20] [21].

The power obtainable from a cylinder of fluid with cross-sectional area S and velocity v is: $P = C_p * \frac{1}{2}\rho S v^3$. C_p being equal to the Betz limit and ρ to the fluid density [20] [21].

Betz's law applies to all Newtonian fluids, including wind. The idea is that if all the energy coming from the wind through a turbine was extracted, the wind speed afterward would drop to zero. If the wind stopped moving at the exit of the turbine, then no more fresh wind could get in; it would be blocked. In order to keep the wind moving through the turbine, there has to be some wind flow on the other side of the turbine. Betz's law shows that as air flows through a certain area, and as wind speed slows from losing energy to extraction from a turbine, the airflow must distribute to a wider area. As a result, geometry limits any turbine efficiency to a maximum of 59.3%. Turbines currently produce around 80% of the Betz limit [22].

3) Number of blades

If one carefully looks to wind turbines, they all have three blades. Why it is so? In fact, there is no perfect number of blades, it is all about finding an optimal compromise. One can think that the more blades there are, the more powerful the rotation. However, the drag is a huge parameter to consider. Increasing the number of blades from one to two yields a six percent increase in aerodynamic efficiency, whereas increasing the blade count from two to three yields only an additional three percent in efficiency [23]. Adding more blades would only increase the aerodynamic efficiency by a tiny margin, which is not cost-efficient.

Figure 13: Envision 3.6 MW 2-blade turbine [24]

Hence, one-blade and two-blade turbines must be considered. The first option is not viable as there would be equilibrium issues. Moreover, having a second blade helps the first one to go up against gravity. However, two-blade turbines face the gyroscopic precession issue, which results in a wobbling, leading to stability issues [25]. Besides, blades must be longer to match the power output of a three-blade turbine, also making higher towers necessary. Cost of a two-blade turbine is almost similar to a three-blade turbine. Three-blade turbines are thus the most cost-effective option, with a great power output, this is why almost every turbine in the world are three-bladed.

4) Blade materials

The blade material is a key parameter that requires several conditions in a general, mechanical and environmental aspects:

- a large availability and easy processing to reduce cost and maintenance
- a low weight to reduce the impact of gravity forces
- high strength and high fatigue resistance to withstand strong forces applied by wind gusts and the weight of the blade for several years

- high stiffness to ensure stability of the optimal shape and orientation of the blade
- the ability to withstand harsh environmental conditions: lightning strikes, high erosion environment or typhoons [26]

This narrows down the list of acceptable materials. Metals would be undesirable because of their vulnerability to fatigue. Ceramics have low fracture toughness, which could result in early blade failure. Traditional polymers are not stiff enough to be useful, and wood has problems with repeatability, especially considering the length of the blade. In contrast to the above materials, fibre-reinforced composites have high strength and stiffness and low density, thus being a very attractive class of materials for the design of wind turbines.

In addition, a key issue for any material is the resistance to erosion, in particular in a marine environment. Wind charged with particles, sand dust, rain and hailstone can have a major impact on the blade in particular at the leading edges, dramatically reducing the blade performance. A study [27] analysed the impact of erosion on the turbine performance, and results were quite outstanding. With few tips of 2.54 mm on the blades, which was one of less eroded analysis, they calculated a drag increase of 80%, which results in a 5% loss in annual energy production. Blades heavily damaged by erosion showed a drag increase of 500%. Hence, erosion is major parameter to consider as it greatly diminishes the power production and increases the maintenance costs.

Figure 14: Impact of the erosion on a blade [28]

Recycling is another crucial criterion in selecting a material. As wind power is expected to be one of the major suppliers of energy needs, in particular in Europe. There are already 140,000 wind turbine blades that will be decommissioned in the next five years [29]. However, the median lifespan of a wind turbine is expected to be around 20 years before it needs to be decommissioned. As the offshore wind market really started to grow in the 2000s, many wind farms will have to be decommissioned or replaced in the decade to come. This will result in an increasing number of blades to deal with.

Turbine blades are made out of composite materials, as described above. These materials are extremely difficult to recycle because of the complexity of their structure. Therefore, conventional recycling methods need to be adapted. There is currently no proper recycling method that fully recovers the glass fibre. The WindEurope association has set this recycling issue as the top priority for wind industry [29].

Choosing the right material is thus a complex task, considering all the parameters that need to be considered. For now, Glass Fibre Reinforced Polymer (GFRP) is the best compromise but a lot of research is ongoing to enhance effectiveness properties, while ensuring an easier recycling process and a better resistance to erosion.

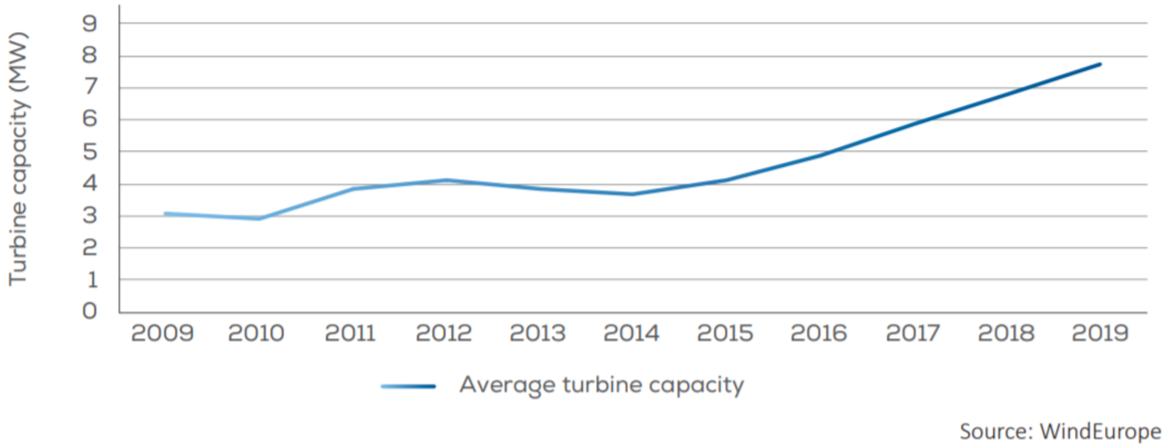


Figure 15: Average turbine capacity newly installed per year in Europe [4]

Hence, developing a sustainable wind turbine is a very complicated task to achieve. Unfortunately, the major part of research is dedicated to build higher and stronger wind turbines, as highlighted in the figure 15. On the one hand it enables to generate more power which increases the part of renewable energies in the energy mix. But on the other hand, recycling wind blades remains impossible. This will be a great issue when the time of decommissioning wind farms will come in the years to come.

C. <u>The process: from development to the decommissioning</u>

Developing an offshore wind farm is a very long process. It is one of the main disadvantages of this technology. It usually takes around 10 years before the wind farm is fully commissioned, an eternity in our modern world. This first issue comes from the regulatory process. The State needs to consider all tenders from different developers which can be time consuming. The second issue is the offshore environment. On one hand it enables to harness more powerful wind. But on the other hand, much more studies to develop a safe wind farm in this complex environment. The construction schedule is also much longer than onshore wind farms.

The ensuing timeline represents the different steps for most wind farms and highlights which steps are time consuming. This timeline is used at Spinergie, a start-up that track the vessel positions to leverage market insights, where the internship take place. The events describe what are the most important steps and allows to quickly understand at what stage of development currently is a wind farm.

Tender Open (Year 0): The State (e.g. the Crown Estate in England) identifies a suitable site for an offshore wind farm and launches a tender process.

Environmental Impact Assessment (Year 1): Companies interested in the tender process must conduct an EIA; a report assessing the environmental impact of the future wind farm.

Tender submission due-date (Year 1): Limit date for the companies to submit their offer. Propositions must contain the likely layout of the wind farm, estimated price of electricity produced, Environmental Impact Assessment…

Winning developer announced (Year 2): After several months, when propositions have been studied, a winning developer is announced.

Subsea Survey (Year 3-5): They are conducted by the lessee (winning developer) to have a deep understanding of the wind farm area, in particular the seabed properties. With all the information gathered, the developer then submits a Construction & Operation Plan, that describes the characteristics of the future wind farm.

Consent authorised (Year 6): The Construction & Operation Plan (COP) has been approved by the State. The winning developer has all legal authorisations to begin construction.

FID (Year 7): The Final Investment Decision means the company has reached the final agreement on the project.

Sub-contract awarded (Year 7): The winning developer signs a contract in which it delegates a part of the project to a subsidiary company (cable installation, foundation manufacturing, turbine installation…).

Construction start (Year 8): The offshore installation begins.

First power (Year 9): The first turbine has started to generate power.

Construction end (Year 10): The last turbine has been installed.

Fully Commissioned (Year 10): The wind farm has been fully commissioned and is fully operational.

Decommissioning (Year 30-40): The wind farm is usually decommissioned after 20 to 30 years of service. Turbines are uninstalled and brought back to shore.

Hence, developing an offshore wind farm is a long work that must be done with extreme precision. Small mistakes can cause delays and complex issues in a harsh environment. Although, ten years minimize the risk of mistakes, this amount of time can be deemed too long. Usually, when a wind farm is inaugurated, more powerful and cheaper turbines have been released since. Reducing the time needed to develop a wind farm has thus become an important issue to tackle.

Offshore wind turbines need to be rooted into the seabed with fixed foundations, as floating foundations are not quite mastered yet. Several types exist and research tries to extend their water depth ability. Shallow water conditions in a windy environment are two conditions required but rarely gathered. This leads to several inequalities across the world regarding the development of the technologies. The following part will detail which countries utilized their assets or which ones overlooked the technology despite benefiting from great conditions.

II. Current state of offshore wind power in the world

Climate change started to become a matter of general concern 10 years ago. Reducing greenhouse gas emission became a major priority, especially for countries relying on coal. Countries had to change their energy mix towards a greener one. Research and citizen's will for greener power plants enabled to foster renewable energies. Offshore wind benefited from this momentum, becoming one of the most promising and growing energy technologies.

In 2010, the technology hit a milestone with global capacity additions representing more than 1 GW in a single year [30]. Since then, annual installed capacity has increased by 30% per year, reaching 4.3 GW in 2018, as pointed out by the figure below.

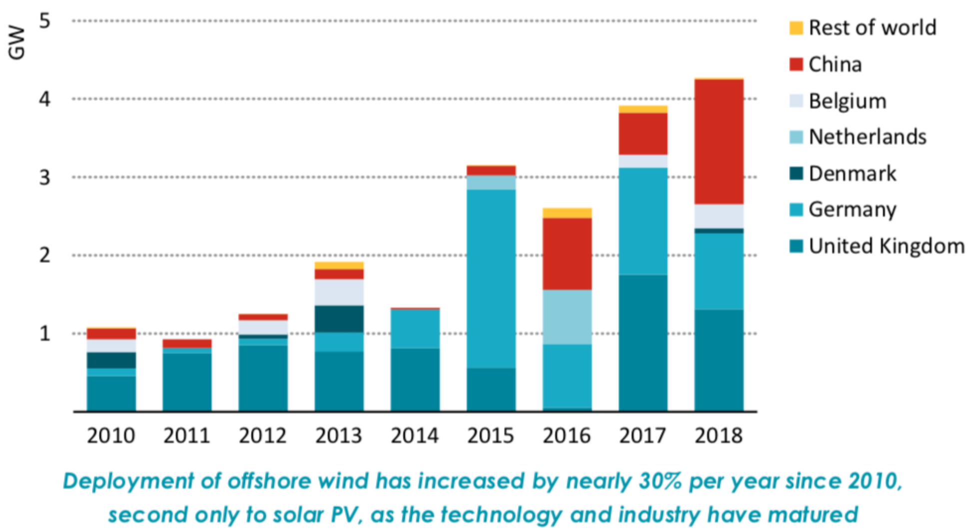


Figure 16: Gigawatts of offshore power installed per year and per country [30]

However, this growth is concentrated in European countries bordering the North Sea, where strong winds and shallow water provides exceptionally good conditions to develop offshore wind farms. Only China recently started to implement the technology, becoming the leader of capacity deployment in 2018 with 1.6 GW offshore wind power added to its grid. Today, Europe and China are leaders for several reasons. They are among the most developed countries and their governments start to make decisions encouraging sustainable projects. Yet, the main reason is their access to shallow-water areas where a strong wind blows.

Firstly, floating foundations are not mastered yet. This decade will be dedicated to the first large scale floating wind farms. Hence, wind turbines need fixed foundations rooted into the seabed. As described in the part above, jacket foundation cannot go deeper than 60 meters. This means that only places where the water depth is lower than 60 meters can welcome a wind farm.

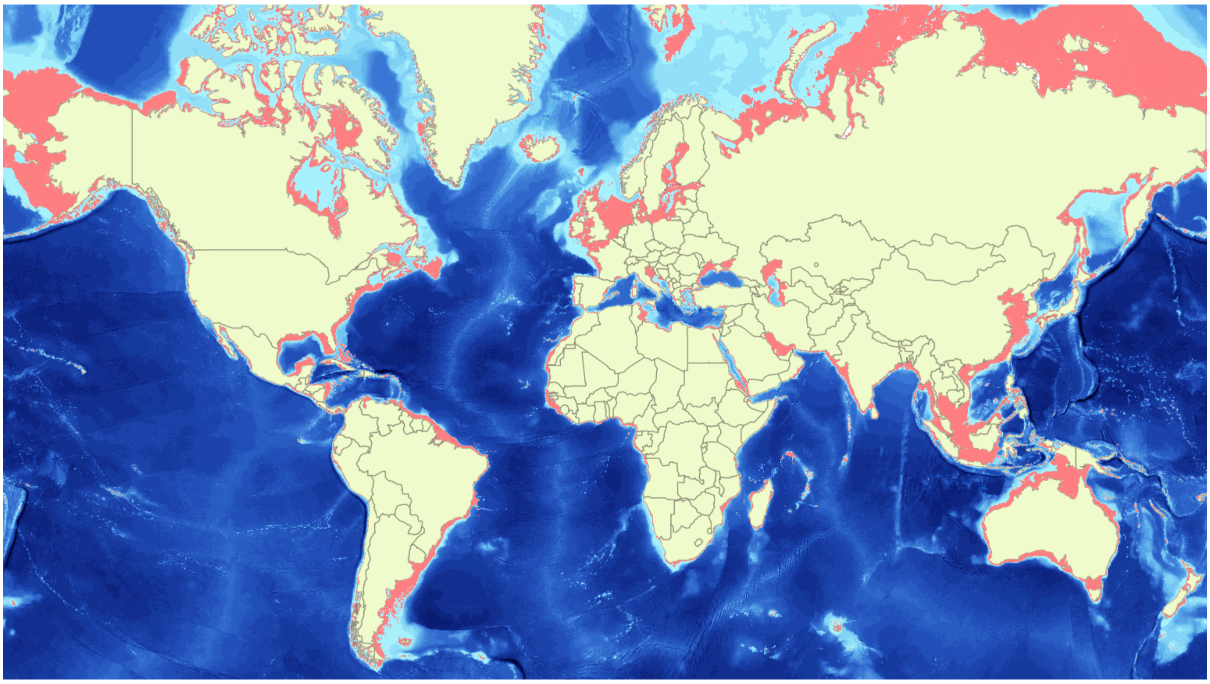


Figure 17: World's bathymetry, in red the water depth is lower than 100 meters [31]

The above map (and all the following ones) highlights in red the places where the water depth is lower than 100 meters. This explains why certain regions developed easily the technology. The North Sea and the China's coast offer large areas of shallow water. Some shallow water areas have not been used around Alaska, Russia, Argentina, USA eastern coast, Indonesia, Australia… One should be careful when analysing this map regarding the projection's issues: Brazil is actually four times larger than Greenland. Australia's and Indonesia's areas are incredibly large and could welcome many wind farms while Alaska's shallow water areas are much smaller in glacial conditions.

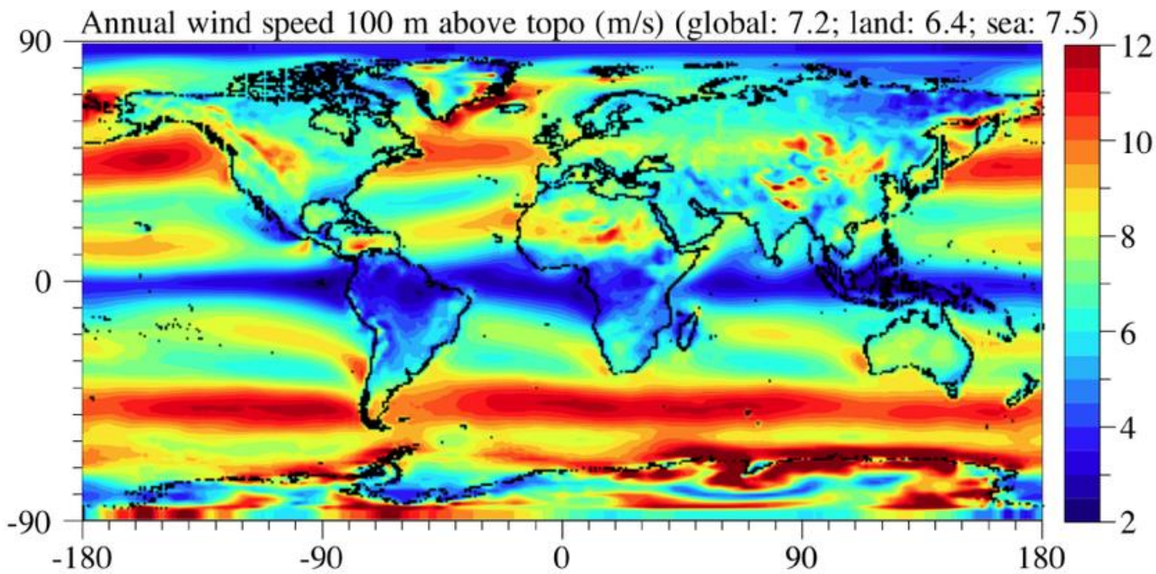


Figure 18: Average wind speed 100 meters above the topography [32]

Water depth is not the only environmental aspect to consider when developing a wind farm. Indeed, wind unequally blows around the world and this can prevent some countries from developing any wind farm. The figure below illustrates the average wind speed 100 meters above the ground. As an example, Indonesia doesn't have the sufficient wind resources to implement wind farms, despite having large shallow water areas.

Hence, even though offshore wind power is increasingly implemented, large disparities exist between the different regions of the world. Europe and China drive the technology benefiting from both wealth and excellent environment. Nevertheless, a closer look at the different regions is needed to understand why large disparities exist in Europe and Asia, while America, Oceania and Africa only built a single wind farm so far.

A. Europe: a leader with important inequalities

European countries represent more than 80% of global installed capacity. However, this global percentage does not account for large disparities in the use of offshore wind in all Europe. Indeed, the top 5 countries (UK, Germany, Belgium, Netherlands, Denmark) concentrates 99% of the cumulative wind power in Europe [4]. These countries benefit from excellent environment with the North Sea, but other suitable environments exist and were barely utilized. A specific review of every countries will help to understand taken and missed opportunities.

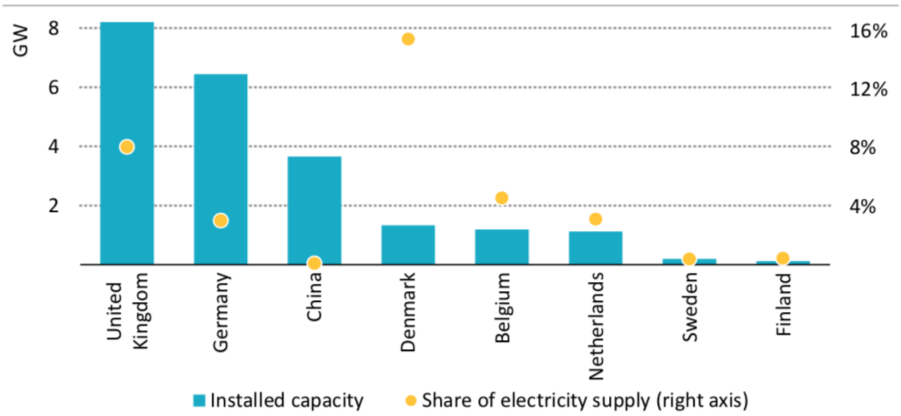


Figure 19: Total gigawatts installed and share of electricity supply per country [30]

1) Two undisputed leaders: UK and Germany

UK and Germany are two undisputed leaders of the offshore wind power technology. They represent 79% of the global capacity in Europe (17.4 GW out of 22 GW) [4]. Besides, they maintain their leadership as they account for 79% of the net capacity connected in 2019 (3 GW out of 3.6 GW) [4]. Both countries want offshore wind power to become a major electricity supplier.

Table 3: Information on offshore wind farms installed per country [30]

COUNTRY	NO. OF WIND FARMS CONNECTED[1]	CUMULATIVE CAPACITY (MW)	NO. OF TURBINES CONNECTED	NET CAPACITY CONNECTED IN 2019 (MW)	NO. OF TURBINES CONNECTED IN 2019
UK	40	9,945	2,225	1,760	252
Germany	28	7,445	1,469	1,111	160
Denmark	14	1,703	559	374	45
Belgium	8	1,556	318	370	44
Netherlands	6	1,118	365	0	0
Sweden	5	192	80	0	0
Finland	3	70.7	19	0	0
Ireland	1	25.2	7	0	0
Spain	2	5	2	0	0
Portugal	1	8.4	1	8	1
Norway	1	2.3	1	0	0
France	1	2	1	0	0
Total	110	22,072	5,047	3,623	502

Several reasons explain such a domination. The first one is their unique geographical situation. As described, North Sea offers excellent conditions to implement wind farms and they perfectly utilized this asset. The map below shows that a large part of the North Sea has water depth below 50m, where it is possible to implement wind farms.

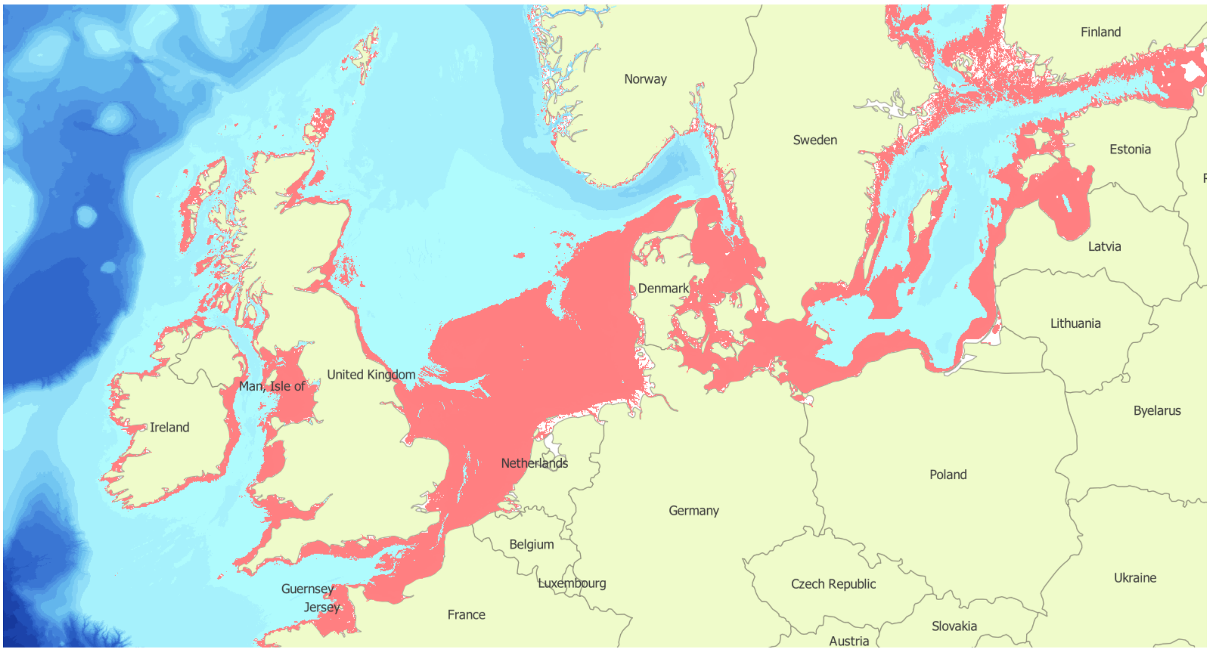


Figure 20: North Sea bathymetry [31]

Secondly, their governments have expressed a political determination to foster greener power plants. Back in 2010, these two countries had very polluting power generation sources as highlighted by the figure 21. The UK were relying on their large production of natural gas in the North Sea and coal [33]. Germany were mainly utilizing their coal resources [34].

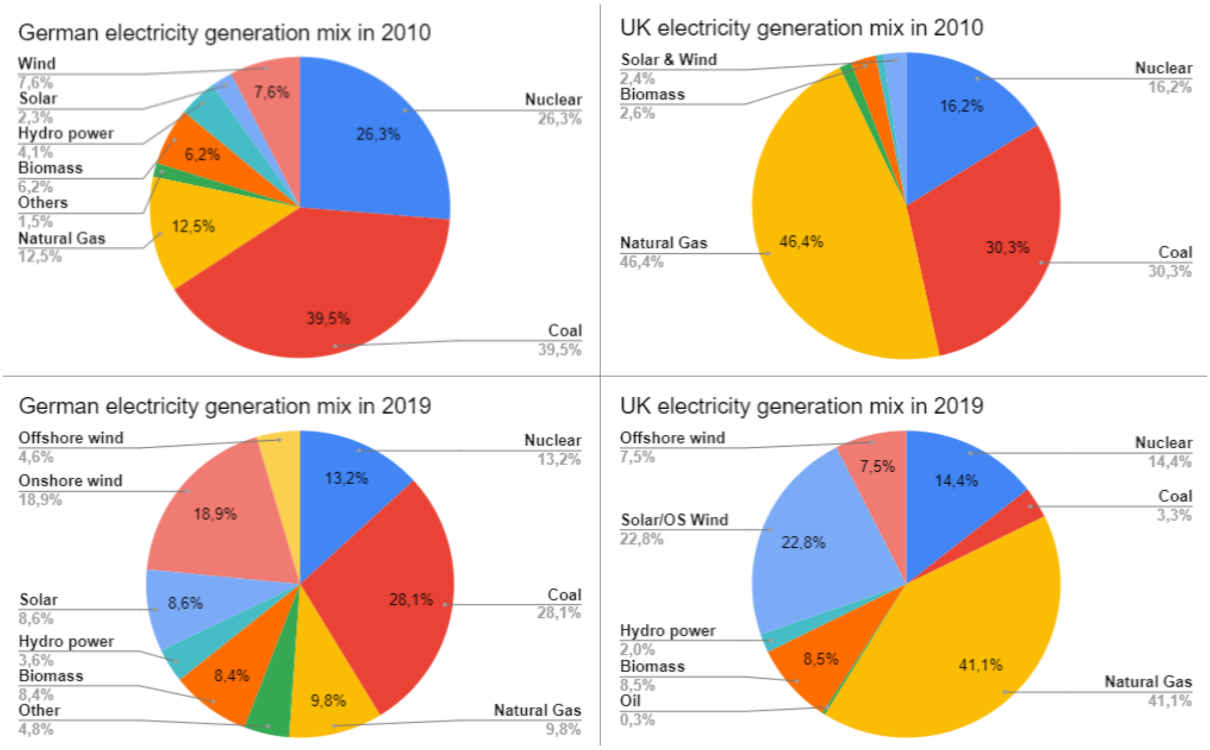


Figure 21: Energy mix evolution of UK and Germany between 2010 and 2019 [33] [34]

UK and Germany successfully improved the part of renewable energies in their power generation mix. In 2019, they accounted for 44% in Germany and 41% in the UK. Onshore wind represents the major part of this improvement, being much cheaper and more mature technically than offshore wind (the comparison between different renewable energies will be made in the third part -from page 46-). However, suitable onshore wind areas are limited by cities, worse wind conditions and local complaints against noise and visual pollution which can slow down the development process. Governments now try to develop the offshore wind power as costs are decreasing and as turbines are more powerful. Hence, the excellent environment offered by the North Sea and policies encouraging renewable energies enabled Germany and UK to become offshore wind world leaders.

2) The three followers: Denmark, Netherlands and Belgium

Denmark (1703 MW installed), Belgium (1556 MW installed) and Netherlands (1118 MW installed) form a solid group of followers [4]. They are excellent examples because they are much smaller countries than UK and Germany. Indeed, even though their global capacity installed is lower, the part it represents in their energy mix is higher. As shown in the figure 19, Denmark is the leader with about 15% of its power needs met by offshore wind power. UK is second (7.5%) but Belgium is third (4.7%), and Netherlands share fourth place with Germany (3.6%) [30]. In comparison, China's 4 GW only meet 0.1% of their energy needs. The three countries also benefited from the North Sea asset.

Belgium is the perfect example of utilizing assets at its maximum potential. Despite having a shore length shorter than 70 km and an Exclusive Economic Zone (EEZ - Sea zone where the state is sovereign) of 3347 km² [35], they successfully installed 398 turbines.

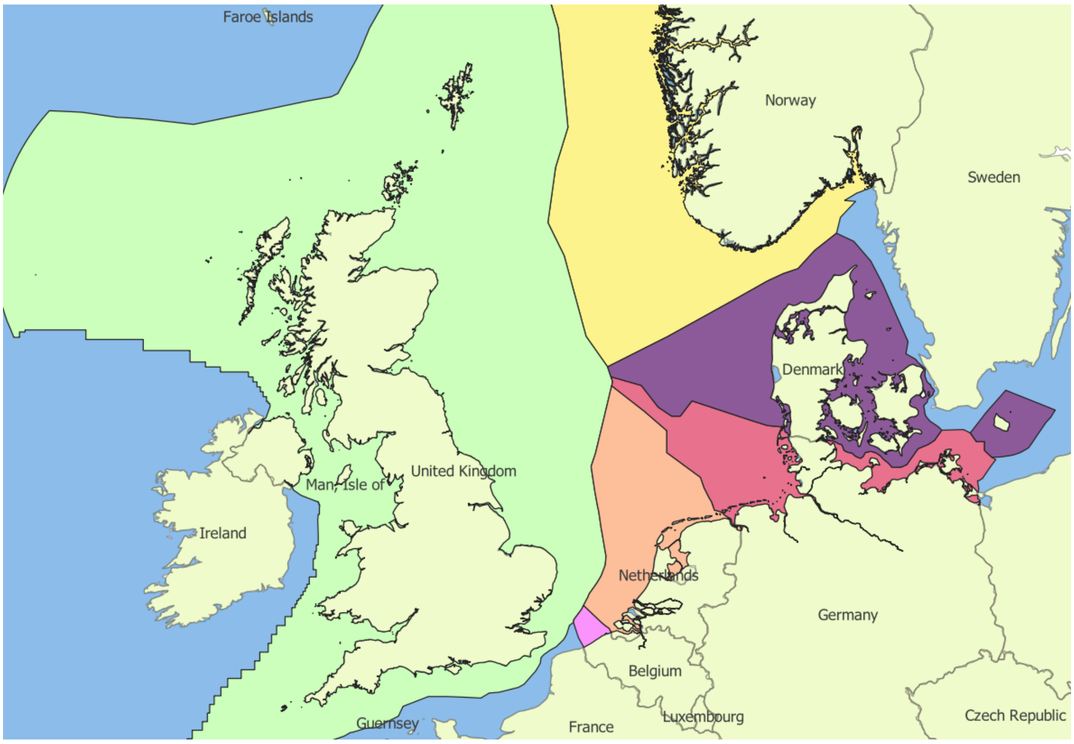


Figure 22: North Sea Exclusive Economic Zone (EEZ) [35]

Unlike Belgium, Netherlands have a large EEZ in the North Sea (64328 km²) [35]. Despite this much larger EEZ, Netherlands have installed 400 MW less than their neighbour. This is likely to be due the large gas resources harnessed by the Netherlands in the North Sea for more than 70 years. Hence, they are slowly developing renewable energies to utilize their gas resources in the North Sea until depletion.

Denmark also benefits from a large EEZ in the North Sea (105021 km²) [35]. Yet, they only installed 150 MW more than Belgium. However, due to a smaller population and industry, Denmark has a smaller energy consumption. Indeed, their 1.7 GW installed represents 15% of the electricity supply grid while 1.5 GW represents 4.5% of the electricity supply grid in both Belgium and Netherlands. Furthermore, 69% of its electricity generation already comes from renewable energies [36]. However, renewable energies have common drawbacks which makes difficult for a country to 100% rely on them. Hence, Denmark keeps developing offshore wind power but slowly as a large part of its electricity generation already comes from renewable energies.

Table 4: Belgium, Netherlands & Denmark comparison

	Belgium	Netherlands	Denmark
EEZ Area (km²)	3347	64328	105021
Offshore wind capacity installed (MW)	1556	1118	1703
Share of electricity supply coming from OWP	4.7%	3.6%	15%

Belgium, Netherlands and Denmark benefit from the North Sea assets and they utilize it to install more than 1 GW of offshore wind power each. Nevertheless, important disparities exist between these three countries. Belgium have a much smaller EEZ but manages to be the fifth largest world producer of OWP. Netherlands benefits from large gas resources and harness them, waiting for offshore wind prices to further decrease. Denmark already has a large part of its electricity generation coming from renewable energies and slowly keeps developing offshore wind farms.

3) Other countries lag far behind their neighbours

If this top 5 countries are world leaders, other European countries lag far behind their neighbours. Ireland, France, Norway, Portugal and Spain have large EEZ but they only gather a global capacity installed of 52 MW (200 times less than the UK) [4]. Why are these countries so far behind?

Norway had three main reasons not to fully commit on OWP. First it borders the part of the North Sea where the water depth is high, as illustrated in the map below. Secondly, more than 95% of their electricity generation comes from hydropower [37]. Thirdly, Norway only has a population of 5 million inhabitants while having the largest oil reserves of Europe, with over 5 billion oil barrels reserves proven. Hence, it was not a necessity for Norway to develop offshore wind farms.

However, as climate change has become an urgent issue, Norway has turned into a leader of floating wind farms. Equinor, formerly Statoil, is one of the biggest energy company of Norway. They want to develop greener power plants, like their changed name suggests. Equinor's website provides a timeline of their floating projects [72]. In 2009, they commissioned the first floating wind turbine: Karmoy - Hywind Demo. It was only composed of a single 2.3 MW turbine, but this represented a milestone for the technology. The test was successful, so they developed Hywind pilot park - Scotland, commissioned in 2017, still the largest floating offshore wind farm in the world. Another big leap forward, as the floating foundations carried 6 MW turbines. Lastly, Equinor is currently developing Hywind Tampen, expected to be commissioned for late 2022. This wind farm will feature 11 8MW-turbine, an unprecedented feat. Hence, Norway is late but it is also catching on leaders by developing innovating solutions.

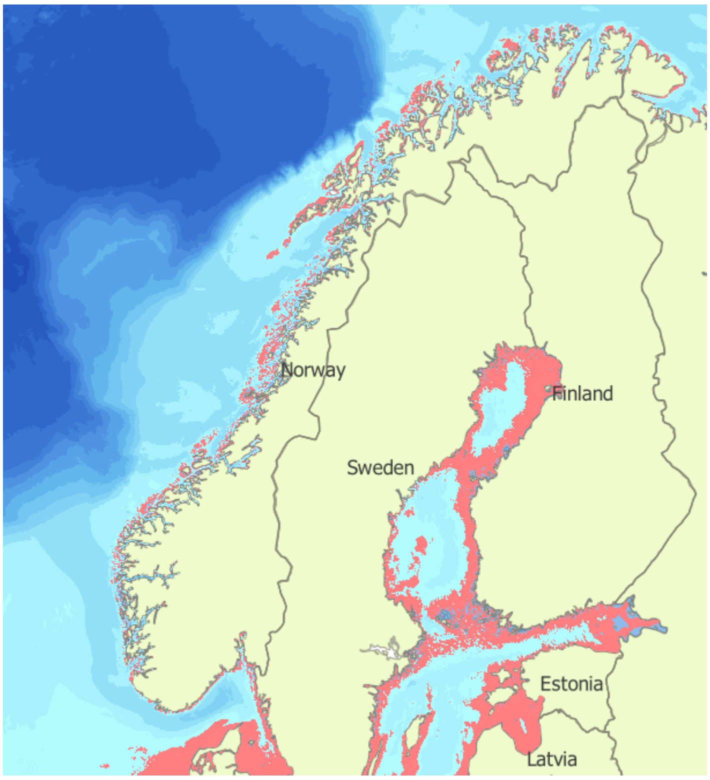


Figure 23: Norway's water bathymetry [31]

France benefits from the largest EEZ in the world [35]. This is mainly due to its pacific islands but metropolitan France still has a large EEZ with generous shallow water areas as illustrated by the map below. Yet, France still has not built any wind farm. Several reasons can explain such delay.

Firstly, its energy production relies for 70% on the nuclear power [38], a cheap and low carbon emissions technology well rooted in the country. Secondly, France has chosen to develop onshore wind power, being the largest European country (550000 km² while Germany is 350000 km² large) with a relatively low density of 107 inhabitants/km² (233 for Germany). France is the third largest onshore wind power developer in Europe with over 16 GW of capacity installed. But the decrease in the cost and the increase reliability of the OWP technology have pushed France to catch the gap, with 4 GW planned to be constructed before 2027 in 8 wind farms [39]. Furthermore, France is alongside Norway, one of the floating solutions leaders. France welcomes the most floating projects in the world with 6 different ones. Hence, France changed its energy roadmap to catch the gap and become a major player in the offshore wind sector.

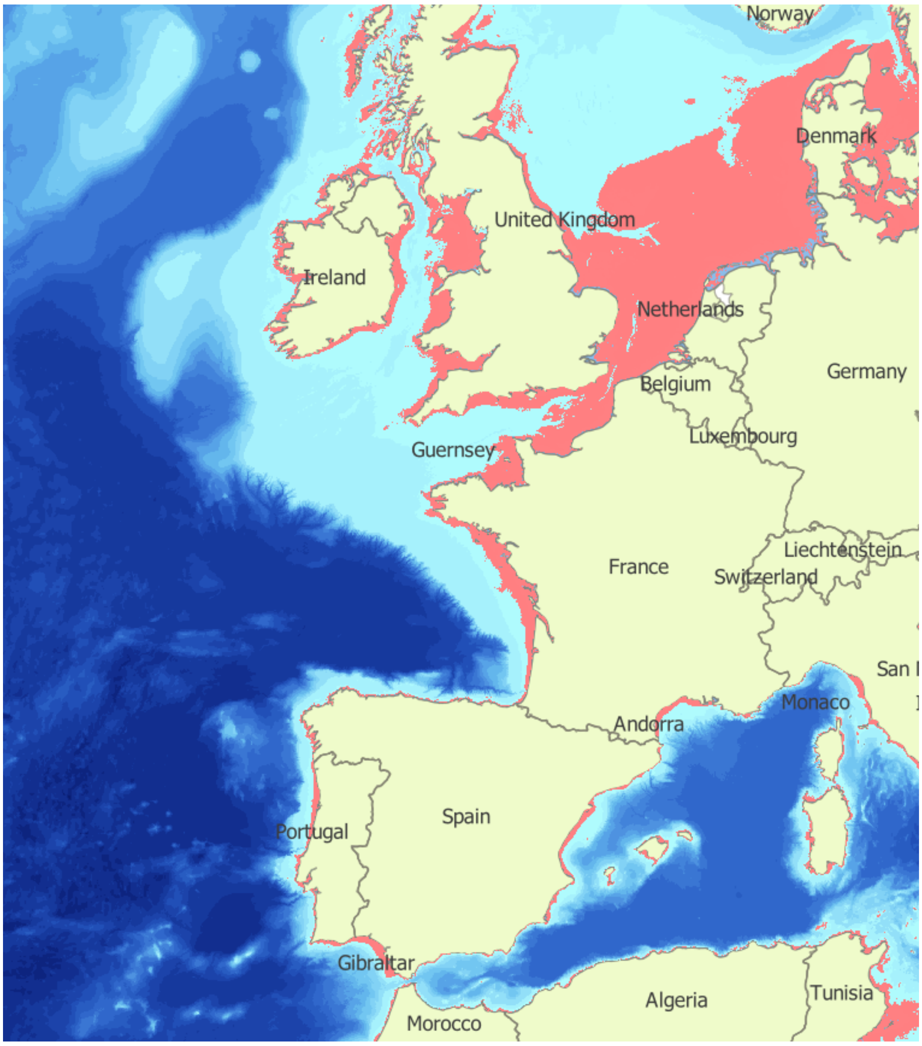


Figure 24: Atlantic bathymetry [31]

Ireland has been one of the pioneers in the offshore wind technology. They commissioned the 25 MW "Arlow Bank I" wind farm in 2004 which remains the only offshore wind farm they ever built. Yet, Ireland benefits from shallow water areas allowing many wind farms implementations. Several projects are on their way but only one is expected to be commissioned before 2025 [39]. The National Offshore Wind Association of Ireland announced that €50 billion was due to be invested in the offshore wind farms aiming to catch the gap but no confirmation has been made yet [40]. Indeed, with the benefits from a strong onshore wind and a low population density (74 inhabitants/km²), Ireland may not be as stimulated as France and Norway to catch the gap.

Portugal and Spain have developed only 4 offshore wind turbines so far [39], despite benefiting from large Exclusive Economic Zones (EEZ) on the North Atlantic. This can be explained by the water depth of the surrounding sea. It quickly increases when further from the shore (Figure 24), barely leaving space to develop OWF. Besides, the wind quality around Spain and Portugal is not as good as in the North Sea (Figure 25).

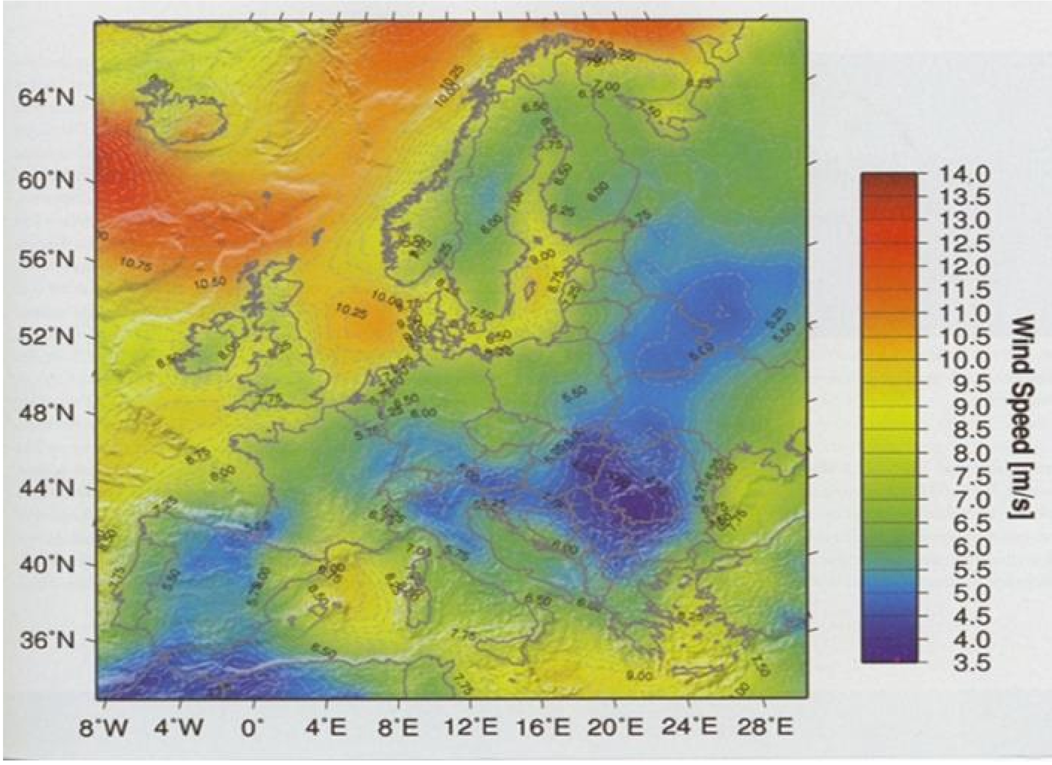


Figure 25: Average wind speed in Europe [41]

Despite these conditions, Portugal and Spain aware of the benefits of this technology, are trying to catch the gap by investing on the floating solutions. Portugal developed one of the first floating offshore wind farms, "WindFloat Atlantic", commissioned in 2020. Spain is currently developing a floating wind turbines research area in the Canary Islands where the wind is stronger and more consistent.

Countries around the Baltic Sea also starts to invest the OWP technology. Poland, Finland, Estonia and Latvia all planned to develop at least one wind farm before 2030. These countries combine great shallow water areas (Figure 20) and good wind conditions (Figure 25). Except Poland, they are sparsely populated countries. Large offshore projects could thus skyrocket the part of renewables in their energy mix.

Hence, Europe is the crux of the offshore wind technology. It gathers the two world leaders of the technology (UK and Germany), three small countries that managed to become important players (Belgium, Netherlands and Denmark) and the floating foundations leaders (Norway, France, Spain and Portugal). Europe is the place where the first offshore wind farm was commissioned in 1991 but also concentrates the major part of the research on the future wind farms. Europe definitely constitutes the epicentre of the technology.

B. Asia and the USA to catch the gap

Asia and the USA constitute alongside Europe the three biggest players in today's economy. Offshore wind power is a rare example of a technology well developed in one of the players and largely underdeveloped in other two. Asia, leaded by China, started to develop large scale wind farms in 2016. The USA have only commissioned four offshore wind turbines so far [39]. What may explain such a gap between the three biggest players in today's economy?

1) China & Taiwan

China and Taiwan are the two leaders of the technology in Asia. China had the third world largest global capacity installed in 2018, with 3.6 GW. Most importantly, they are massively investing the technology to catch their lateness. In 2018, they added 1.6 GW of OWP to their grid, which was more than any country [30].

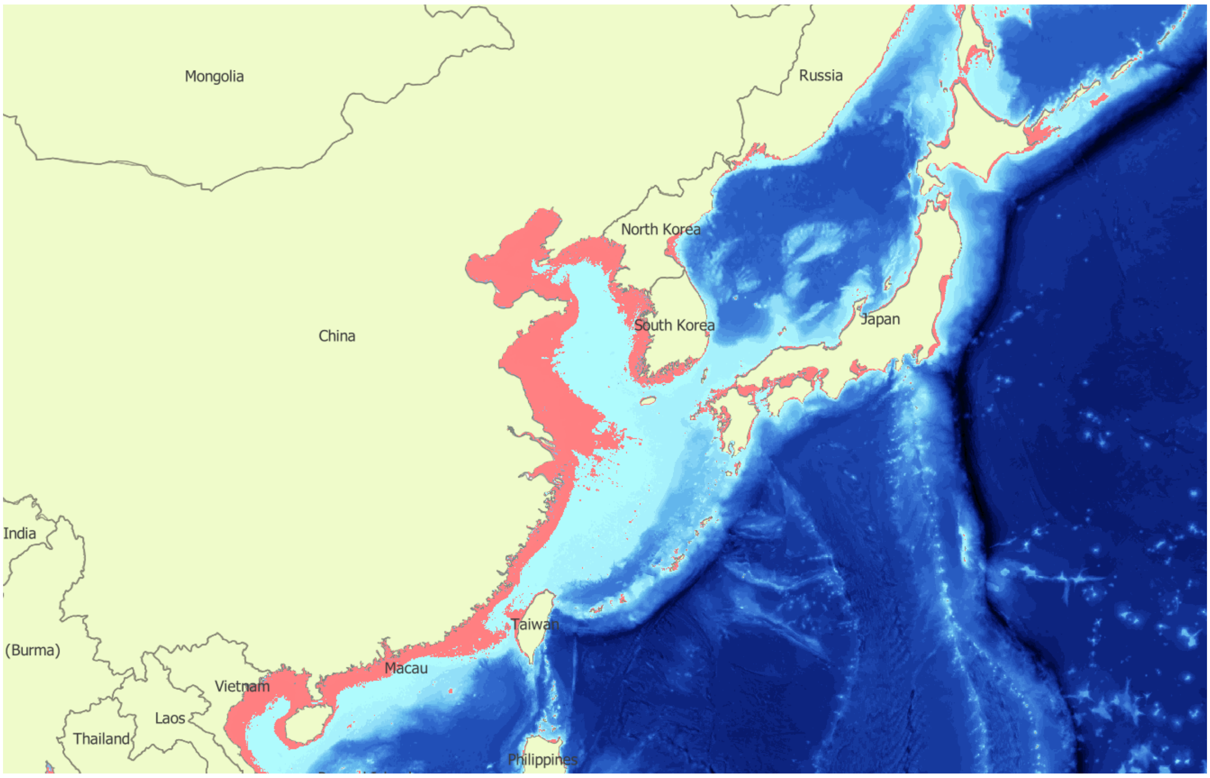


Figure 26: Bathymetry of the Asian seas [31]

This was made possible by large shallow water areas all along their coast, as illustrated on the map above. Besides, strong and consistent wind blows on these areas, making OWF perfectly suitable in the red areas. Nevertheless, the China's involvement in the technology can be deemed disappointing when the global installed capacity is related to the size and consumption of the country. The following table helps to put numbers into perspective.

Table 5: Belgium & China comparison

	Belgium	China
Population	11.5 million	1.4 billion
EEZ	3,350 km²	877,000 km²
Capacity installed (2018)	1,550 MW	3,600 MW

Hence, there is an important growth of the OWP in China but this remains paltry compared to the size, energy consumption and wealth of China.

Taiwan, the 36,000 km² island situated 180 km east of China, wants to follow the Belgium example. Like China, Taiwan benefits from shallow water areas and great wind conditions. The map below illustrates how Taiwan plan to fully utilize the shallow water areas to implement offshore wind farms.

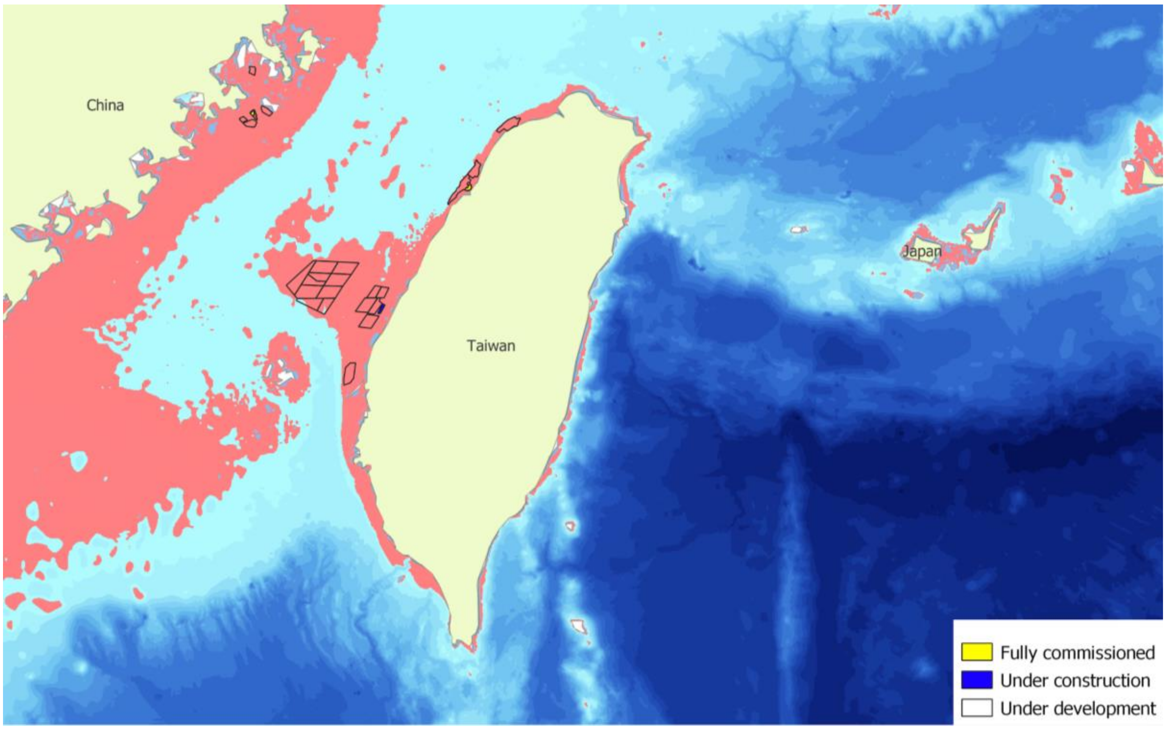


Figure 27: Taiwan's water bathymetry and wind farms [31]

For now, a single 128 MW wind farm has been developed by Orsted, commissioned in November 2019. But 15 projects totalling more than 5 GW are expected to be commissioned before 2028 (Annex A) [39].

Hence, China and Taiwan constitute the two leaders of OFP in Asia. If China's recent installations seem impressive, the real feat comes from Taiwan, a small country that plan to install over 5 GW in less than decade.

2) Japan / South Korea

Japan and South Korea are alongside China, the most developed countries of Asia. Yet, South Korea has only commissioned two wind farms while Japan has only conducted tests for now. Why these countries seem to be even late compared to China?

Japan is populated country (125 million) on a relatively small area (378,000 km²) that has a large industry. This makes the country the fourth largest electricity consumer (964 TWh in 2017) [42]. In order to meet these gigantic energy needs, the State chose to mostly rely on fossil fuel energies. In 2018, they represented more than ¾ of their energy mix. In March 2011, the Fukushima nuclear disaster had a tremendous impact on the Japan society. This crisis enabled to develop a great number of renewable energy projects across the country.

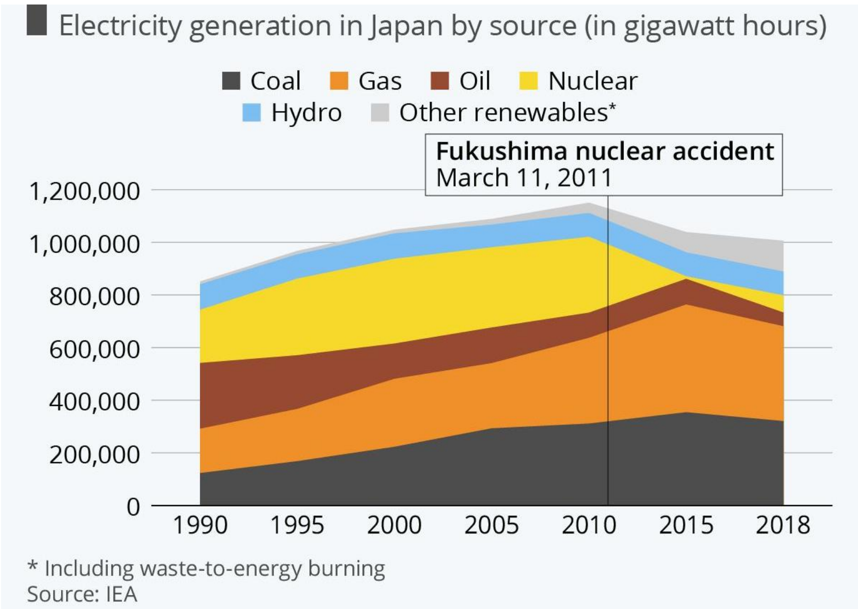


Figure 28: Japan's electricity generation mix evolution [43]

Unfortunately, Japan has very few shallow water areas available. Most of the red areas are situated between the main islands where there are many ship transits occurring. This drastically limits suitable areas for classical OWF. But Japan wants to exploit the technology and planned several projects nearshore to catch up China and Taiwan. Japan also becomes interested in the floating foundations. The "Fukushima Floating Offshore Demo" and other demonstration projects are testing the feasibility of the technology to further improve the part of renewable in their energy mix.

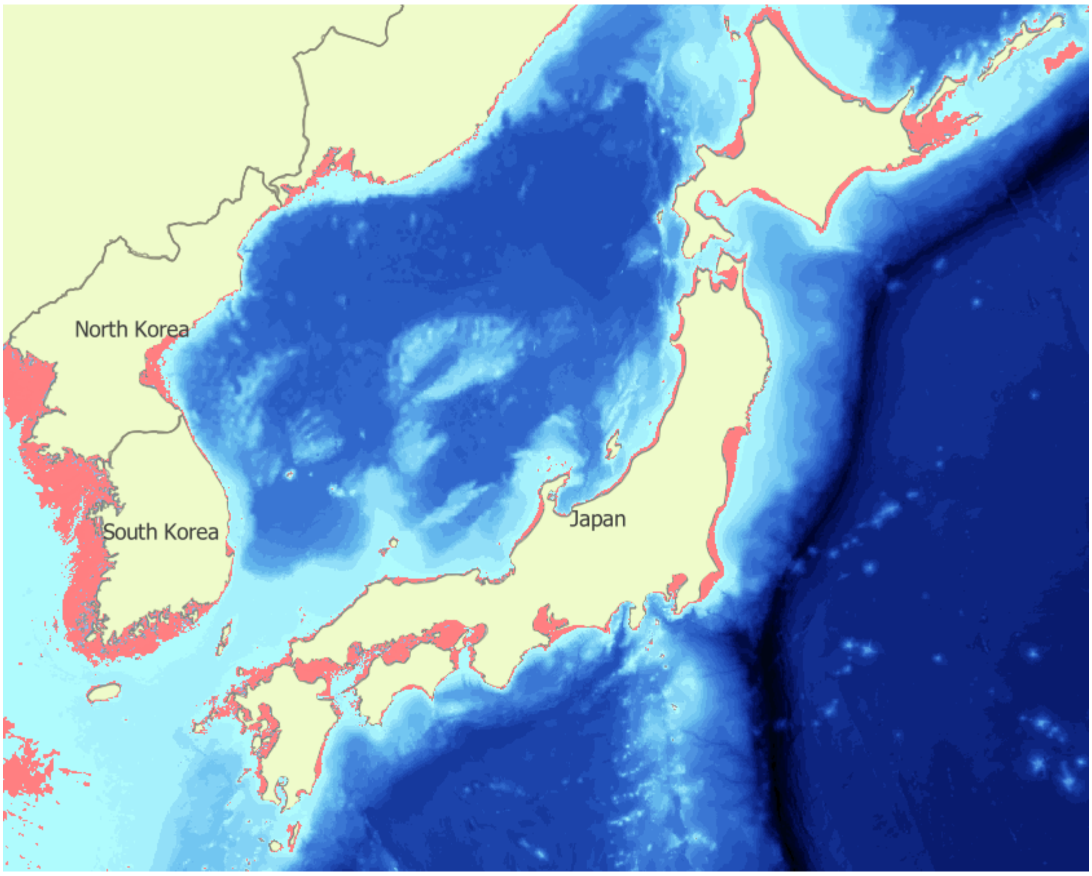


Figure 29: Bathymetry around Japan and South Korea [31]

Hence, Japan is among the largest electricity consumer in the world while having a tiny part of renewables in their energy mix. The Fukushima nuclear accident helped to advocate renewable energies but Japan still has a long way to go before becoming a major player in renewable energies, in particular in the offshore wind sector.

South Korea can be described as the smaller version of Japan. It is a populated country (51.7 million) on a small area (only 100,000 km²), making it one of the densest countries in the world (526 inhabitants/km²). There is a large industry, as South Korea is one of the largest exporters in the world. This makes the country the 6th largest electricity consumer in the world (523 TWh in 2017) [42]. In order to meet such large energy needs, the government decided to mostly rely on fossil fuel energies, as indicated on the graph below.

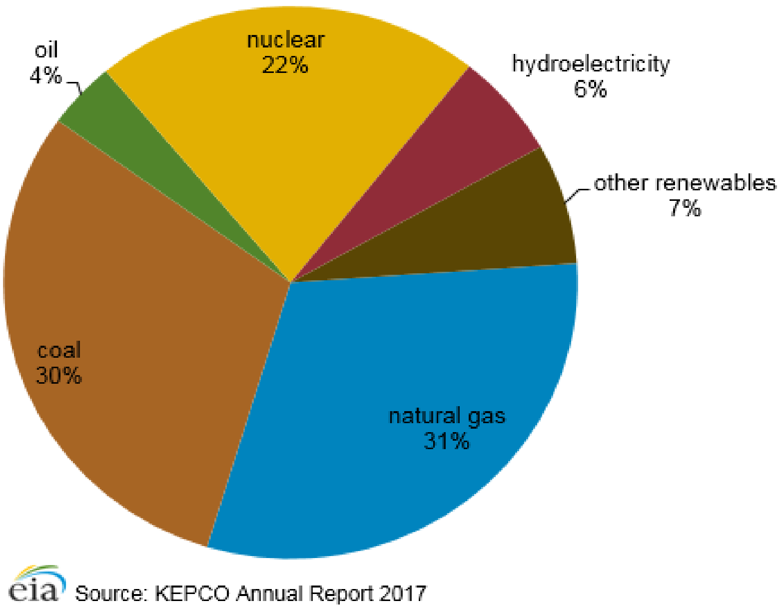


Figure 30: South Korea electricity generation by source in 2016 [43]

South Korea benefits from great shallow water areas on its western and south coasts. However, the water depth quickly increases on the eastern coast making the installation of OWF impossible with fixed foundations. They utilized these western and south areas by developing small wind farms to test the technology. The "Tamra" wind farm featuring 10 turbines of 3 MW each was commissioned in 2016. Four years later, the "South West Offshore - Phase I", featuring 20 turbines of 3 MW each, was inaugurated. South Korea thus slowly started to develop the technology but plans to speed up the process during this decade. South Korea's government defined an energy plan in 2017 to have at least 20% of electricity produced by renewables by 2030. New wind capacity is expected to make 16.5 GW, with nearly 12 GW being offshore [44].

Most importantly, South Korea wants to become a major player in the floating wind farms. Equinor is currently conducting tests to build an impressive 800 MW floating wind farm [45]. Local companies also want to improve their knowledge on the technology with the "Ulsan 5 MW Pilot" expected to be commissioned shortly.

Hence, South Korea was late but planned to catch on China and European countries. Large projects will be commissioned before 2030 to reach the goal of 20% of their electricity produced by renewable energies [44]. South Korea also took interest in the floating technology to implement wind farm in their eastern shores where the water depth is important.

3) The USA

The USA are the country of superlatives. They are among the most populated and largest countries in the world. They also are the second largest energy consumer in the world behind China (3738 TWh in 2017) [42]. They benefit from one of the largest shallow water areas in the world, as illustrated by the map below.

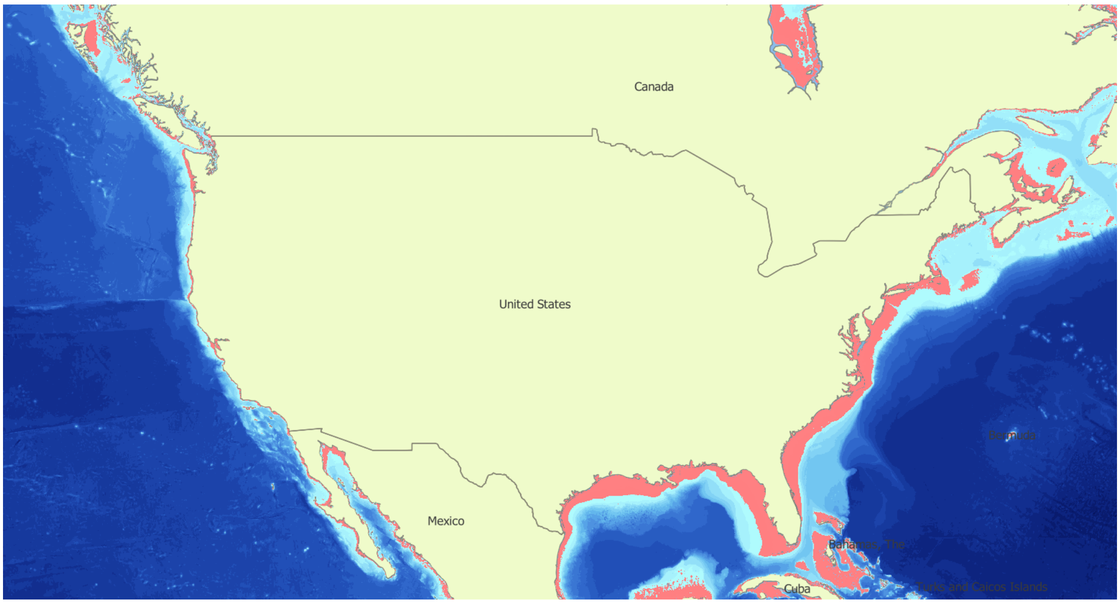


Figure 31: USA bathymetry

Yet, only four turbines have been built so far. One main reason is the election in 2016 of Donald Trump as the president. He has been known to be one of the fervent protesters of the wind power. Back in 2014, he massively strove against the European Offshore Wind Deployment Centre (EOWDC) in the Aberdeen Bay, saying it would “ruin the view from his golf” [46]. During meetings and the 2016 campaign, Donald Trump kept arguing against wind farms: “Darling, please. There is no wind. Please turn off the TV quickly!” [47].

However, the States of the USA have a large decision power and they used it to develop large projects in the decade to come. Very large projects featuring giant turbines will be developed, such as the 2.6 GW “Virginia Wind Energy Area” where Dominion plans to install hundreds of the largest wind turbine: the 14 MW Siemens Gamesa [39].

The Western coast of the USA does not benefit from the same shallow water asset as the eastern coast. No wind farm is currently planned to be built in the decade to come. Besides, no floating projects have been studied so far in this region. They prefer to develop other renewable sources such as the photovoltaic as they benefit from exceptional sun conditions.

Hence, the USA was already late on the OWP compared to Europe and the election of Donald Trump in 2016 only increased this gap. But different States have decided to take their responsibilities themselves and planned giant projects on the eastern coast. As always, the USA will most likely become one of the major players in the offshore wind market, so dominant their economy is in the world.

III. Offshore wind power: global comparison to other power plants

Offshore wind power offers great promises: renewable, low environmental footprint, no sound and visual pollution for the neighbourhood. But there are also hidden drawbacks that can backfire and totally negate the positive effects. Other renewable power plants are also very promising in particular the solar power. Hence, it is important to precisely compare the main parameters of different renewable energy power plants thanks to figures and studies.

A. Cost

The first main parameter is the cost. As the world's economy is based on capitalism, companies' main goal is to make profit. If an offshore wind project doesn't make money or only barely, developers will cancel the project, even though the C02 impact would be positive compared to another source of energy. This is why researchers have worked the past decades to make offshore wind farm less expensive. It is now essential to study the evolution of the price and to understand where it currently stands.

Levelized Cost Of Energy (LCOE) is a fundamental key to compare costs of energy. It corresponds to the sum of all the costs over the lifetime of the powerplant divided by the amount of energy produced by the power plant. This ratio expressed in cents € per kWh is the best tool to understand the difference of cost between renewable power plants.

$$\mathrm{LCOE} = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

It: Investments expenditures in the year t
Mt: Operations and maintenance expenditures in the year t
Ft: Fuel expenditures in the year t
Electrical energy generated in the year t
Discount rate: r
Expected lifetime of system of power station: n [48]

It is worth mentioning that the LCOE is an estimation and not a perfect calculation. However, it is a quite accurate estimation, that scientists deem credible enough to use it for comparison.

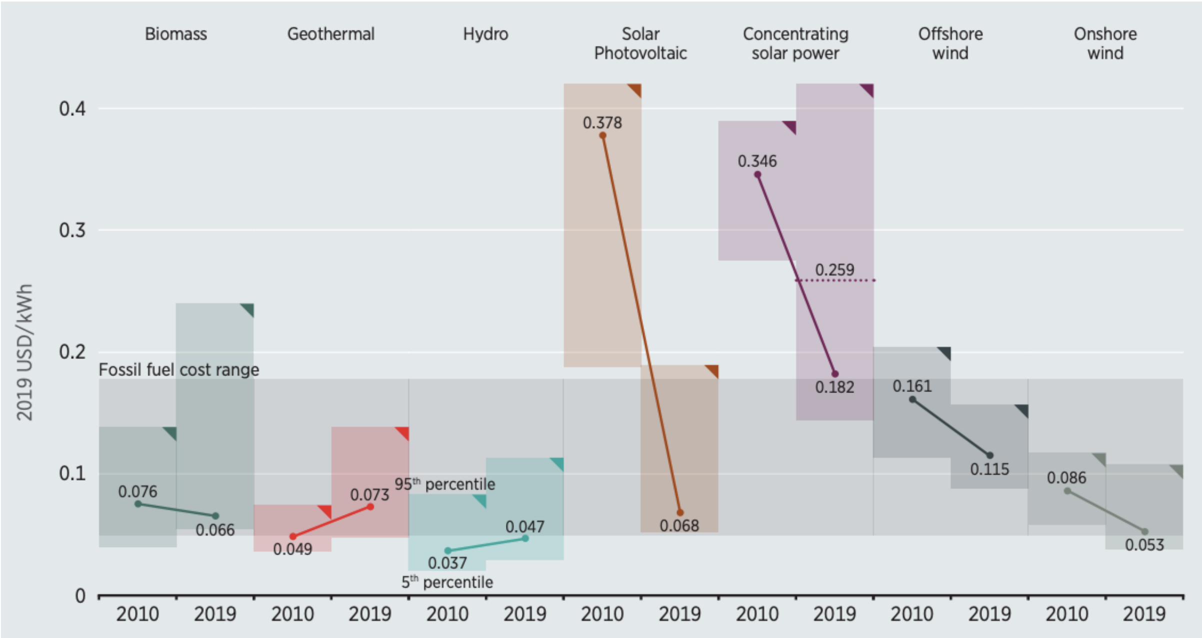


Figure 32: Evolution of the LCOE for different renewable energy technologies [49]

The graph from the figure 32, points out the evolution of the LCOE of different renewable power generation technologies [49]. Two very key insights must be studied. The first one is the actual LCOE of each technology. Offshore wind is among the most expensive mean of power generation with 115$/MWh. A large gap separates offshore wind from onshore wind as the latter is half expensive, with a LCOE only equals to 53$/MWh. This can be explained by the costly foundation needed in the offshore wind. Operation & Maintenance (O&M) is also much more expensive. Onshore wind is currently the second cheapest renewable power generation technology behind hydro, which displays an LCOE of 47$/MWh. Except offshore wind and concentrating solar power, prices are all concentrated around 60$/MWh with small differences. Hence, offshore wind power is a quite expensive choice among the renewable power generation technologies.

However, a second key is essential to analyse in this figure 32: the trend. If geothermal and hydro technologies seem attractive due to their low-price, the trend is not as satisfying. Hydro power LCOE increased by 27% in 9 years [49]. It is a mature market which means it is a reliable and cheap option. However, it also means that costs are most likely to never decrease again, as technologies improvements or breakthroughs are nearly impossible. Geothermal technology follows the same pattern. It is a mature, reliable power generation technology, its LCOE increased by nearly 50% during the last decade. Biomass belongs to this same mature technology category, even though LCOE decreased along the decade, it was only by a tiny margin. Hence these technologies are currently great and cost-effective but they won't be the technology that will replace all current power plants.

Nevertheless, solar and wind power could very well constitute this technology. Their LCOE have impressively dropped, as highlighted in the figure 32. Solar photovoltaic (PV) has seen the biggest drop, LCOE has been divided by 5, going from 378$/MWh in 2010 to 68$/MWh in 2019. A lot of research has been conducted by the scientific community on this technology since the XXIst century and it paid off. The graph also highlights the fossil fuel cost range, which is between 50$/MWh and 180$/MWh. This means that photovoltaic is now almost cheaper than any fossil fuel power generation. This constitutes a tremendous step forward for renewable energy. Concentrating solar power has also seen an incredible drop of its LCOE, divided by 2 in the last decade and now entering the fossil fuel range, with its 2019 LCOE being at 182$/MWh [49]. This technology based on the concentration of the sun rays thanks to their reflection on mirror, shows great promises, and could fit very well in desertic areas.

Figure 33: Concentrating solar power plant [50]

Finally, both offshore and onshore wind technology display promising results. Onshore wind LCOE decreased by 38% from 86$/MWh in 2010 to 53$/MWh in 2019. It now constitutes the second cheapest renewable power generation technology behind hydro power. But as described above, hydro power LCOE is on an increasing slope. Onshore wind is thus expected to become the cheapest renewable power generation technology, alongside the solar photovoltaic.

Offshore wind also shows great progress. Its LCOE decreased by 29% from 161$/MWh to 115$/MWh. It now stands in the middle of fossil fuel cost range which is a milestone. Furthermore, a more detailed evolution of the LCOE shows that PV LCOE plummeted in the early 2010s and now decreases slowly. However, offshore wind power LCOE increased in the early 2010 until its peak of 183$/MWh in 2014. Hence, it actually decreased by 37% in only 5 years.

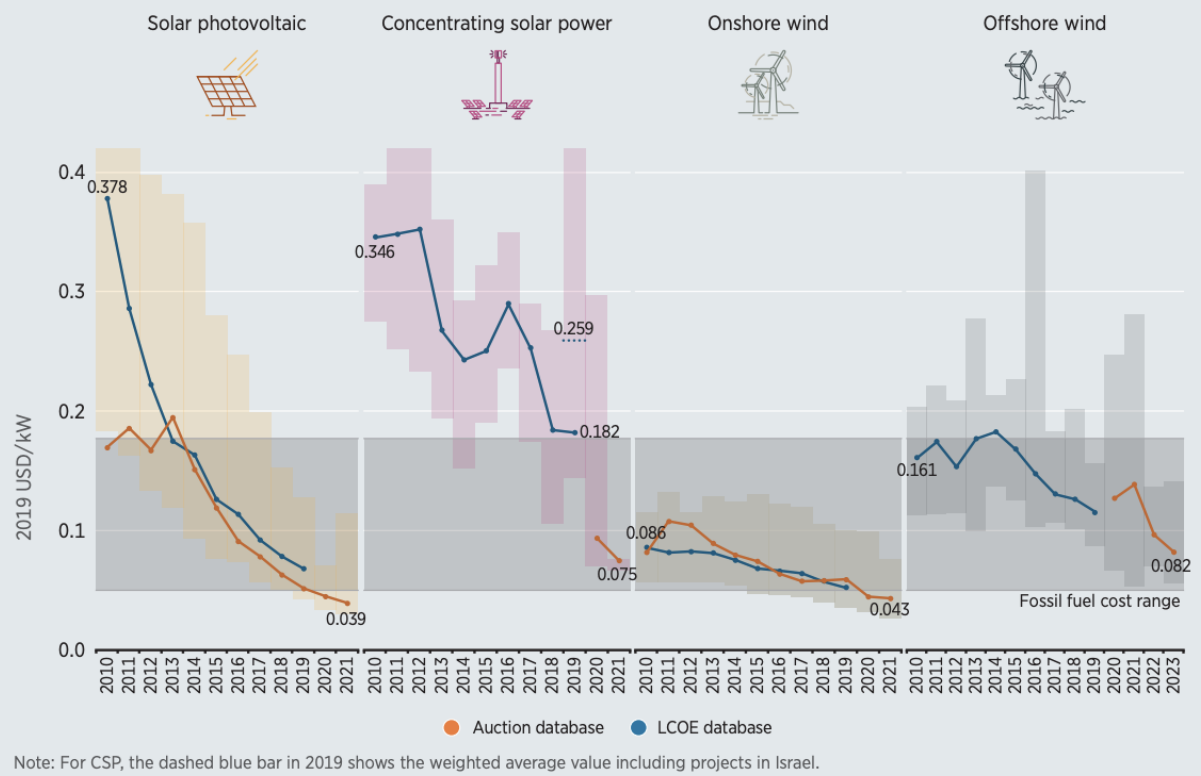


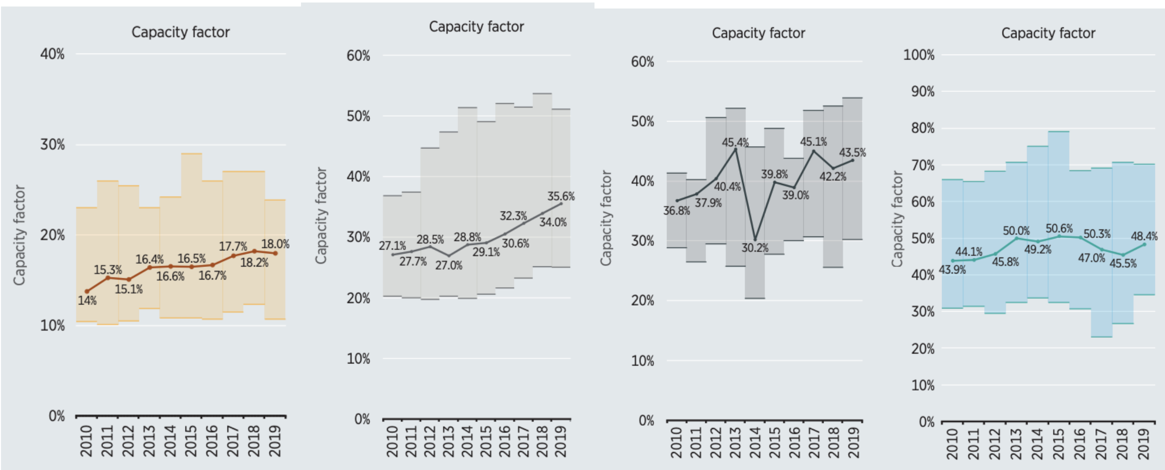
Figure 34: Detailed evolution of the LCOE for four renewable energy technologies [49]

Offshore wind power surprisingly displays an increase of its LCOE between 2010 and 2014. Europe was aiming at deeper waters project to harness more powerful wind and limit the visual pollution. This increased the cost of materials needed, but also the cost of construction and developing process. For instance, installation vessels were not designed to lift such large wind turbines and were multitasks to be used in the oil and gas sector. But the market overcame these difficulties and it is now maturing. 2020s decade could represent a milestone for this technology to become a reliable, cost-effective renewable energy.

Another parameter interesting to study is the standard deviation. It is illustrated in the figure 34, by the coloured columns. The top of the column represents the 95th percentile while the bottom represents the 5th percentile. The exact standard deviation would be complex to derive. But dividing the 95th percentile by the 5th percentile can be a useful hint to evaluate the standard deviation. For the offshore wind, the ratio is roughly equal to 1.7, while onshore wind displays a ratio of 2.3 and PV a ratio of 3.8. This points out that the standard deviation of the offshore wind technology is low, thus making it a reliable power generation technology.
Offshore wind is among the most expensive renewable power generation technology. However, the market has not yet arrived to maturity and its trend is excellent. Its LCOE plummeted over the last 5 years and this drop is expected to continue, until the maturity of the market. It is expected to be even cheaper than gas power plants in UK by 2023 [51]. Furthermore, cost is only one criteria and renewable energies cannot be ranked only according to this one. Capacity factor and CO_2 are also two main parameters and will be studied in the two following parts.

B. Capacity factor

The capacity factor can be defined as the ratio of the power generated by a power plant in a given period of time and the power that would have been generated if the power plant worked at full power without any interruption during the same amount of time. For instance, if a coal power plant is closed for maintenance during 36 days in a year (~10% of the year), while working at full power the rest of the year, then its capacity factor is about 90%. This criterion is essential to estimate the reliability of a power generation technology. Power suppliers are looking for safe and reliable power plants, so that they can be able to supply power at any time, regardless the weather conditions.



Solar PV | Onshore wind | Offshore wind | Hydro power

Figure 35: Evolution of the capacity factor for four renewable energy technologies [49]

The figure 35, highlights the evolution of capacity factor for four renewable energies. PV has by far the lowest capacity factor of all renewable power generation technologies, lagging far behind at only 18%. This is mainly due to the high-dependence of the sun conditions: a solar panel don't produce at night (which represents already about 50% on average on a year) and clouds can make the production drop. Hopefully, searchers are improving the panels, making the capacity factor increasing by 28% going from 14% in 2010 to 18% in 2019 [49].

Wind farms display better capacity factors, as the wind is a more reliable source of energy than sun. Onshore wind farms had an average capacity factor of 36% in 2019, with an excellent trend, thanks to the use of more powerful turbines that can harness the wind more easily. Offshore wind is quite better than onshore wind as its capacity factor was 44% in 2019 [49]. This is due to larger turbines and being on the sea, far from shore, where the wind blows stronger and more consistently.

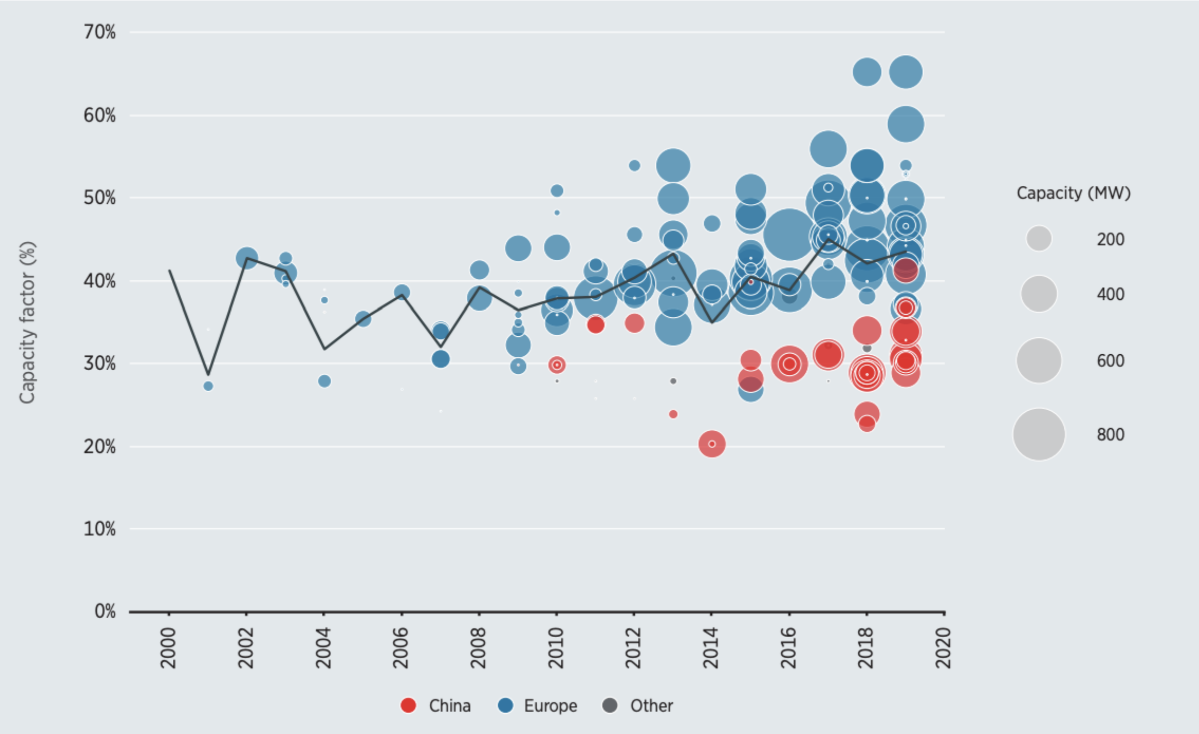


Figure 36: Detailed evolution of the offshore wind capacity factor [49]

The trend from the figure 35 needs some explanation as the capacity factor curb of the offshore wind power displayed a surprising drop in 2014. The figure 36, explains why it occurred. China’s arrival on the market in the second half of 2010s decade quite shook the statistics. They build wind farms with very low capacity factors. Even though they are new on the market and inexperienced, Europe never reached such low capacity factors, even when they were inexperienced themselves [49]. One of the problems is China’s closure to foreign companies. As they want to keep control on their energy power plant, they refuse foreign developers to install wind farms, which means they refuse to receive great know-how from more experienced developers. EDF has become one of the first foreign co-developers, only in 2019 for the Dongtai IV & V wind farms [52]. They also typically use older and smaller turbine models that are cheaper but that can’t harness as much wind as the latest models [30].

Furthermore, the figure 37 highlights the immense gap between Europe and China. It displays the number of days needed to install 1MW for different wind farm in the world. China’s wind farm are the pink circles and they display poor figures. The average days needed to install a single megawatt is around 3 days for China, while Europe does it in only 0.5 days [39].

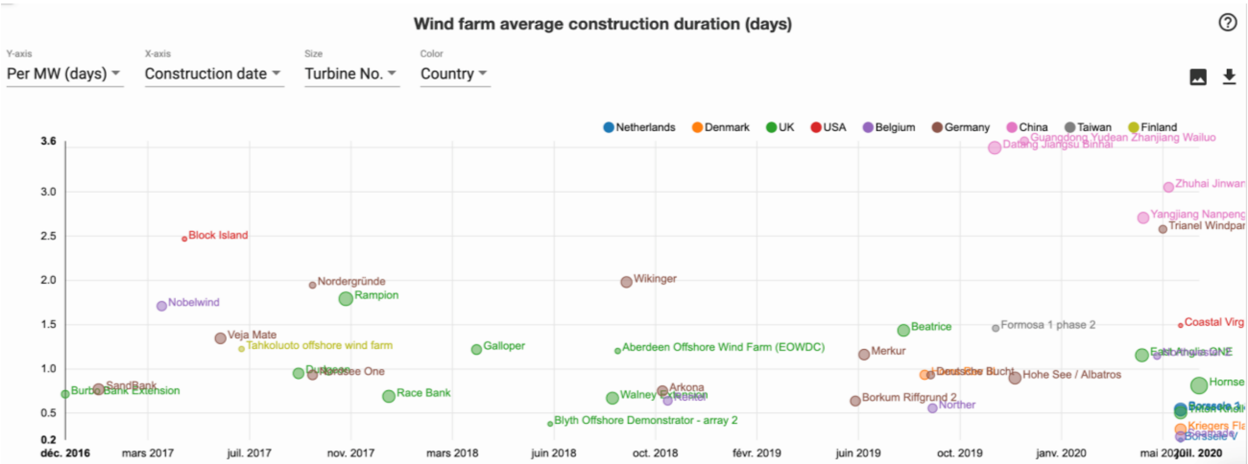


Figure 37: Average days needed to install 1 MW per wind farm [39]

Hence, China's arrival on the market is a great news for the technology as it will help the market to become mature. However, they start from scratch and do not really learn from the European's developers. As a result, the average capacity factor in China was 33% in 2019, while Europe's was 47 [49]. Forecasts are bright and predict that capacity factor will continue to increase, particularly if floating wind farms are successful. Indeed, floating foundations enable to have wind farms increasingly further from shore where winds are stronger and more consistent, thus increasing the capacity factor.

C. Environmental footprint

The main advantage of renewable energies is that they do not release greenhouse gas in the atmosphere while generating electricity. However, their construction, operation & maintenance, and decommissioning have a footprint that needs to be quantified. Climate sceptics and fossil fuel energy advocates often claim that renewable energy induce large life-cycle greenhouse gas emissions. It is thus important to study this footprint parameter in order to understand how renewable these technologies really are.

The first parameter to consider when studying footprint is the emission of CO_2 equivalent per kWh expressed in gCO_2 eq/kWh. This describes how much CO_2 equivalent green-house gas (GHG) emissions will be released in the air to produce 1 kWh of energy. The carbon dioxide equivalent (CDE) represents, for a polluting gas, how much CO_2 is needed to have the same harmful effects. For instance, a power plant can release few CO_2, but a lot of methane which is also very polluting. The scale based on CDE makes thus comparisons between different technologies easier.

Table 6: Emissions of selected electricity supply technologies (g CO_2 eq/kWh) [53]

Options	Direct emissions	Infrastructure & supply chain emissions	Biogenic CO_2 emissions and albedo effect	Methane emissions	Lifecycle emissions (incl. albedo effect)
	Min/Median/Max	Typical values			Min/Median/Max
Currently Commercially Available Technologies					
Coal—PC	670/760/870	*9.6*	*0*	*47*	**740/820/910**
Gas—Combined Cycle	350/370/490	*1.6*	*0*	*91*	**410/490/650**
Biomass—cofiring	n.a.	–	–	–	**620/740/890**
Biomass—dedicated	n.a.	*210*	*27*	*0*	**130/230/420**
Geothermal	0	*45*	*0*	*0*	**6.0/38/79**
Hydropower	0	*19*	*0*	*88*	**1.0/24/2200**
Nuclear	0	*18*	*0*	*0*	**3.7/12/110**
Concentrated Solar Power	0	*29*	*0*	*0*	**8.8/27/63**
Solar PV—rooftop	0	*42*	*0*	*0*	**26/41/60**
Solar PV—utility	0	*66*	*0*	*0*	**18/48/180**
Wind onshore	0	*15*	*0*	*0*	**7.0/11/56**
Wind offshore	0	*17*	*0*	*0*	**8.0/12/35**
Pre-commercial Technologies					
CCS—Coal—Oxyfuel	14/76/110	*17*	*0*	*67*	**100/160/200**
CCS—Coal—PC	95/120/140	*28*	*0*	*68*	**190/220/250**
CCS—Coal—IGCC	100/120/150	*9.9*	*0*	*62*	**170/200/230**
CCS—Gas—Combined Cycle	30/57/98	*8.9*	*0*	*110*	**94/170/340**
Ocean	0	*17*	*0*	*0*	**5.6/17/28**

The table 6, shows how much more polluting are fossil-fuel power plants. Offshore wind is the second least polluting energy technology just behind onshore energy. But the most interesting information is the gap between renewable energies and fossil fuel-based power plants. To produce a single kWh, coal will release about 70 times more CO_2 in the atmosphere than renewable power plant. Note that nuclear has a very low lifecycle emission of CDE, one of the benefits of this technology.

A second parameter can be very useful to describe power plants footprint: the Energy Return On Investment (EROI). The latter expresses the ratio of the quantity of energy E_a to the quantity of energy E_b that was needed to produce E_a. For instance, if a power plant over its lifetime has produced 20 GWh, and that 1 GWh was needed to generate those 20 GWh (to import the fuel, to construct the plant, to make the power plant work daily), then its EROI equals 20. The inverse of EROI also called the embodied energy can be studied. In this case, 5% of the total energy produced was used to produce the total energy the embodied energy would equal 5%.

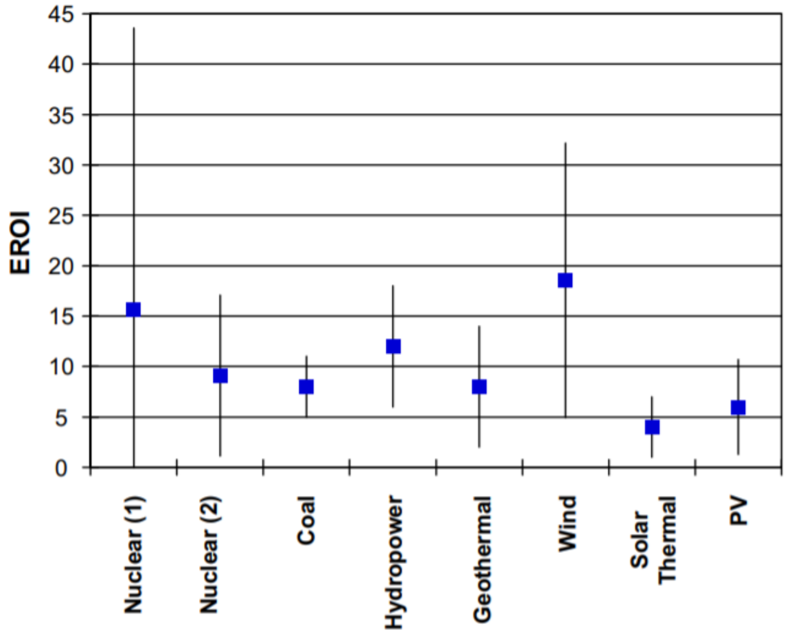


Figure 38: EROI of different power plants [54]

A study [54] was performed in 2010 and showed a comparison of EROI of different power plants. The figure 38 illustrates that wind power has an excellent EROI. However, PV appears to have one of the lowest EROI. It is essential to understand that EROI is a complex indicator to calculate and that different estimations can lead to different results. One study [55] claims that offshore wind has a lower EROI than onshore wind while another claims the opposite [56]. One must be careful and compare different studies, point of views and estimations.

Table 7: EROI of different power plants

Source of energy	Optimistic EROI	Pessimistic EROI
Coal	17	17
Oil	7	7
Gas	7	7
Biofuels & Waste	10	10
Nuclear	14	14
Hydropower	84	59
Wind	18	5
Solar PV	25	4

This table displays values from a study made in 2018 [57]. They are once again different from the figure 38. It is thus complicate to compare the different energy sources, with values being so different. However, one can detect a common point in all these studies: solar and wind power are not lagging far behind fossil-fuel energies. Renewable energies are expected to have increased EROIs in 2050 as highlighted in the figure below [58]. Wind power is predicted to have an EROI of 44 (embodied energy of 2.2%) and solar power an EROI of 26 (embodied energy of 3.8%).

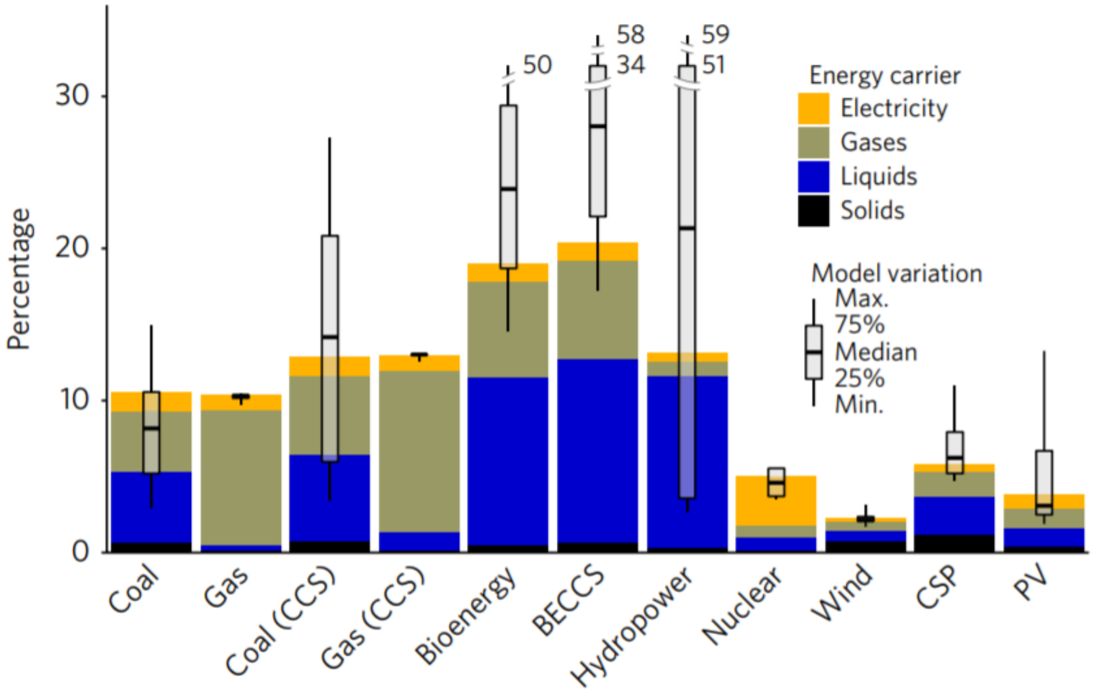
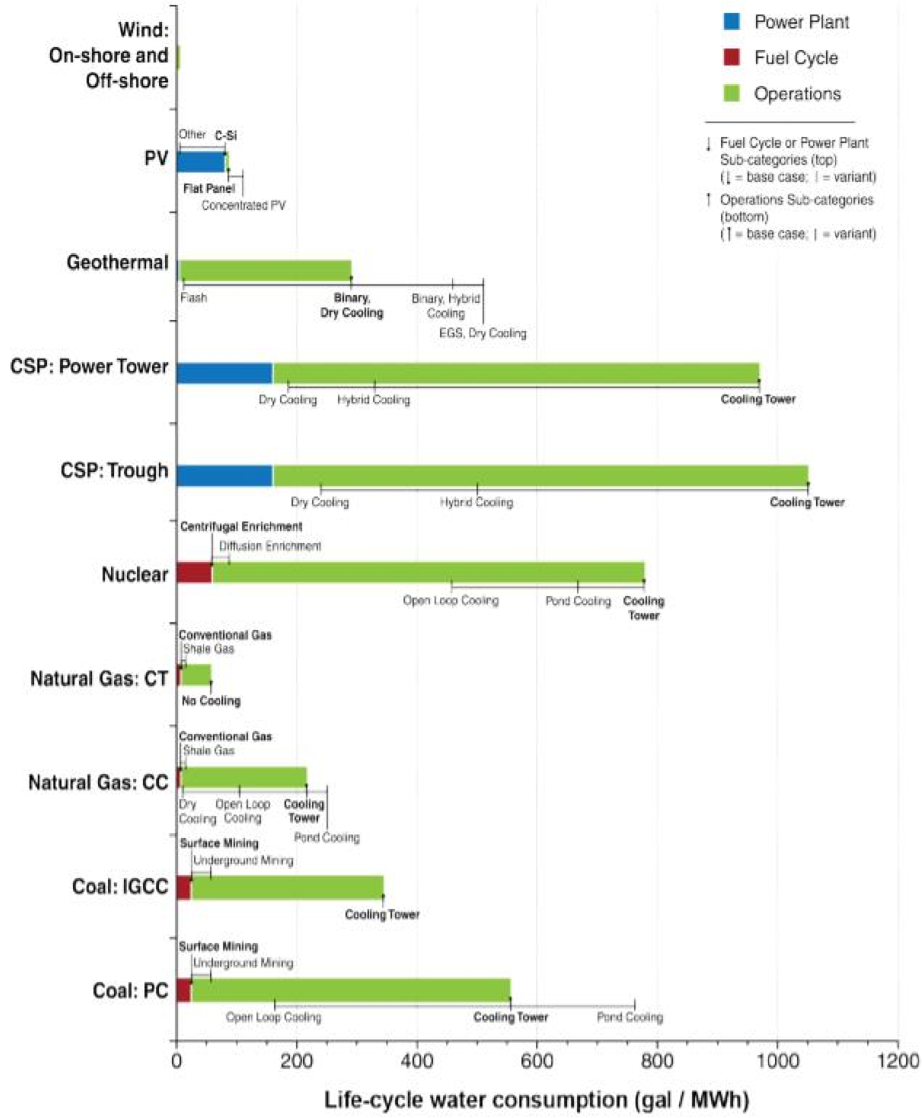


Figure 39: Estimated embodied energy of power plants in 2050 [58]

The water and material quantity a power plant needs to produce electricity are also two key parameters. A study made by the US department of energy [59] found very interesting results, presented in the figure 40.



Notes: Not all cooling options are shown; for instance, more expensive, dry cooling (with zero water consumption and withdrawal) is an option for most plants. Key: **PV** = solar photovoltaic; **C-Si** = crystalline silicon; **EGS** = enhanced geothermal system; **CSP** = concentrating solar power; **CT** = combustion turbine; **CC** = combined cycle; **IGCC** = integrated gasification combined cycle; and **PC** = pulverized coal, sub-critical.

Figure 40: Life-cycle water consumption of different power plants [59]

There are tremendous gaps between the different technologies. Wind power is by far the least consuming technology with a value close to zero. There is a big difference between the two solar technology. PV actually consumes far less water than Concentrating Solar Power (CSP) which is the most consuming technology.

Table 8: Quantity of materials needed to produce 1 TWh for different technologies [59]

Materials (ton/TWh)	Generator only				Upstream energy collection plus generator			
	Coal	NGCC	Nuclear PWR	Biomass	Hydro	Wind	Solar PV (silicon)	Geothermal HT binary
Aluminum	3	1	0	6	0	35	680	100
Cement	0	0	0	0	0	0	3,700	750
Concrete	870	400	760	760	14,000	8,000	350	1,100
Copper	1	0	3	0	1	23	850	2
Glass	0	0	0	0	0	92	2,700	0
Iron	1	1	5	4	0	120	0	9
Lead	0	0	2	0	0	0	0	0
Plastic	0	0	0	0	0	190	210	0
Silicon	0	0	0	0	0	0	57	0
Steel	310	170	160	310	67	1,800	7,900	3,300

Key: **NGCC** = natural gas combined cycle; **PWR** = pressurized water reactor; **PV** = photovoltaic; **HT** = high temperature

The table 8 points out how renewables energies need more materials. For instance, wind power needs about 8500 tons of materials to produce 1 TWh while coal, gas or nuclear power plants need about 1000 tons. However, the type of materials needed is probably even more important than the quantity.

Table 9: Summary of power sources parameters

	LCOE	Capacity factor	EROI	Life-cycle C02 emissions	Life-cycle water consumption	Materials needed
Off. Wind	115	44	-	12	~0	-
On. Wind	53	36	18	11	~0	8450
Solar PV	68	18	25	44	400	8550
CSP	182	-	-	27	3800	-
Hydro	47	48	84	24	-	14050
Biomass	66	-	10	480	1150	1100
Nuclear	-	-	14	12	3000	750
Coal	-	-	17	820	1700	1200
Gas	-	-	7	490	475	550

In this section, several parameters were studied but drawing a conclusion is complex. Costs might be the only parameter relevant to conclude on. Indeed, cost is a simpler and more concrete parameter to study: how much more does it cost to benefit from clean wind power compared to a nuclear power plant? Conversely, capacity factors and environmental footprint are much more complex parameters to analyse. The solar PV technology harnesses the solar energy which is much more volatile than the wind energy, so it does not make sense to compare them. Besides, if a technology has a low capacity factor but produces a lot of power at low cost with a low environmental impact, it remains a technology to use. Environmental impact is even more complex to analyse. It was shown that different studies could lead to very different results. Furthermore, comparing the material needs of different power plants is heavily complex. Is it better to use less concrete but lead instead? Is nuclear waste more polluting than building solar panels using silicon and glass? Consequently, the cost analysis allows to understand where the offshore wind power stand among the other technologies. The capacity factor analysis only allows to understand that offshore wind power has a better capacity factor thanks to better wind conditions and larger turbines. Finally, the environmental footprint analysis allows to understand how complex this question really is. A whole thesis on this subject would be needed to properly answer the questions raised.

IV. Floating wind farms: the future of offshore wind?

Floating foundations could be the game changer for offshore wind power. This technology would enable to install larger wind farms, further from shore, where the wind is stronger and more consistent. The consistency, is an essential parameter to improve because it is one main flaw of renewable energies. Most importantly, floating foundation would allow countries with deep surrounding waters to install their first offshore wind farm.

A. History

The idea was first conceptualized by William E. Heronemus at the university of Massachusetts Amherst in 1972 [61]. However, first offshore wind farms were built on bottom-fixed foundations, as they were much cheaper. Besides, European countries displayed many shallow water areas in the North Sea, postponing the need for floating foundations. At the end of the 2000s, the need for larger wind farms in more windy areas started to appear. Besides, some countries could not build any offshore wind farm because of the high-water depth of their waters.

This is the case for Norway, where water depth of the ocean greatly increases when moving away from their shores, as displayed in the figure 23 (page 34). This explains why they were the first to aim at floating foundation. They inaugurated the first floating large-scale turbine in 2009. Hywind-Karmoy is constituted of a 2.3 MW turbine, 10 km from shore, where the water depth exceeds 200m [56].

Figure 41: Hywind, the first large floating wind turbine [62]

This represented a huge milestone for the floating wind technology. The 2010s decade was dedicated to the improvement of the floating foundation to carry more powerful turbines. A floating turbine demonstration was successfully developed in Japan in 2016 but the real step forward was made once again by Equinor, when they inaugurated their 30 MW floating wind farm: Hywind

Scotland. The wind farm featured 5 turbines of 6 MW each, on which the nacelle alone weighs already 360 tons [39]. This success made people realize that this technology was trustworthy and it triggered many research projects that will be commissioned in the 2020s.

Table 10: All floating wind farms commissioned or under project featuring more than 1 turbine [39]

Name	Country	Status	Nb of turbines	Turbine capacity (MW)	Expected commissioning
Hywind pilot park Scotland	UK	Fully commissioned	5	6	Done
Hywind Tampen	Norway	In development	11	8	2022
Kincardine	UK	Partial generation	6	9.5	2020
Goto Sakiyama Oki Oki	Japan	In development	11	2	2021
New England Aqua Ventus I (Maine)	USA	In development	2	Undecided	2020
WindFloat Atlantic	Portugal	Partial generation	3	8.4	2020
Les éoliennes flottantes de Provence Grand Large	France	In development	3	8.4	2021
EolMed	France	In development	4	6.15	2021
Les éoliennes flottantes du Golfe du Lion	France	In development	3	10	2022
Les éoliennes flottantes de Groix & Belle-Île	France	In development	3	9.5	2022
Fukushima Floating Offshore Demo	Japan	Fully commissioned	3	Undecided	Done
Flocan 5	Spain	In development	5	Undecided	2021
Parque Eólico Gofio	Spain	In development	4	Undecided	>2023

The table 10 shows how this technology is booming. Ten wind farms are expected to be commissioned within 3 years, when the last decade witnessed the development of only 3 wind farms. Hence, 2020s will be a decisive decade for this technology. If the wind farms developed are successful, then it might make offshore wind the best renewable energy on the market.

B. Technologies

To understand how wind turbine can float is very interesting. Indeed, turbines can weigh over 1000 tons [63], they must not only float but stand as immobile as possible, while facing wind that can reach 150 km/h. So how those mastodons can float? Major developers are actually using different techniques as none has been proved to be better for now. This report will review the most promising one and address advantages and drawbacks of each one.

1) Semisubmersible (Eolink)

Eolink is a French company that redesigned the wind turbine concept. Their idea is based on a completely different support system. Usually a large cylinder called tower goes up in the sky to put the blades as high as possible. Eolink split this cylinder into 4 smaller arms linked to a bottom square structure.

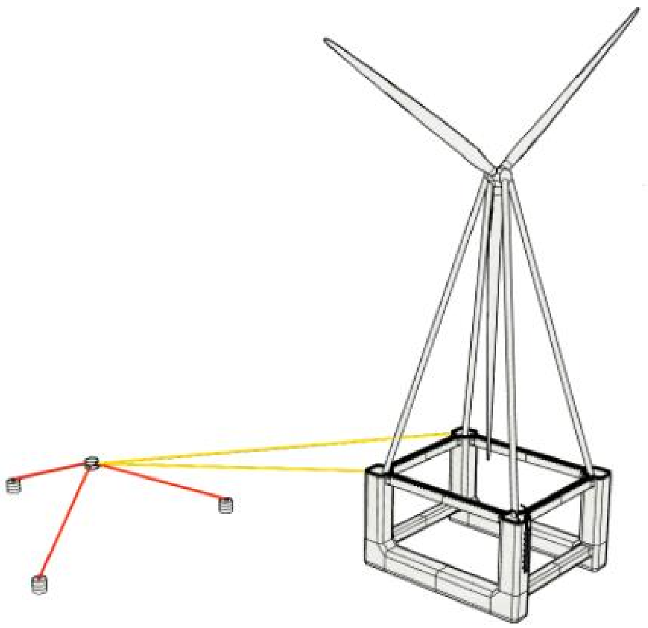


Figure 42: Eolink's structure scheme [64]

As described in the figure 42, the four arms are connected at the top on the nacelle and tied on the same parallelepiped structure at the bottom. This structure is then anchored to the ground thanks to three large cables.

The 4-arm top structure allows great advantages. First of all, there is a better weight repartition across the bottom structure. It means the whole structure is much more stable, a crucial parameter for floating wind turbines. It enabled Eolink to build a more compact bottom structure: their 66 meters long and 2100 tons bottom structure can hold a 12 MW turbine, while the average floating foundation that can hold an 8 MW turbine (smaller) needs to be over 75 meters long and weighs over 2500 tons. [64]

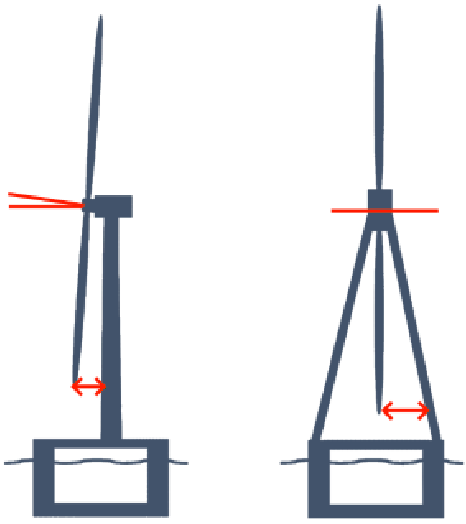


Figure 43: Vertical cross-section of Eolink's structure [64]

Secondly, the 4-arm top structure enable the bladed to be perfectly perpendicular to the wind. Indeed, a security space is needed between the blades and the tower. In traditional wind turbines, the large cylinder tower is too close from the blades, forcing the blades to be slightly aimed upwards, as shown by the figure 43. Not only the Eolink's blades are perfectly perpendicular to the wind, but they can also be longer. Thanks to larger security distance and a more stable structure, longer blades and thus more powerful turbines can be installed on a smaller structure.

Thirdly, the offshore installation of the structure is extremely simple. The turbine is fixed to the structure in the harbour and then it is tugged until its offshore location. This is a common advantage to all floating turbines but this is even more accurate as the Eolink's structure is more compact, thus easier to tug.

Figure 44: Eolink's 1/10 scale turbine test [64]

Finally, Eolink announces an impressively low LCOE of 60€/MWh for their 12 MW turbines, expected to commissioned in 2023. This is very impressive because the predicted global offshore wind LCOE for 2023 is 73€/MWh whereas floating wind is supposed to be more expensive. It can be deemed over confident by some, but Eolink is for now right on schedule. They successfully released a 1/10 scale turbine test in 2018. A multi MW test is scheduled for 2021, and if everything works fine, the 12 MW turbine should be launched in 2023 [64].

However, existing turbines on the market cannot be used and this can constitute an issue. Indeed, turbines that have been on the market for several years are very reliable. Developers that want to use existing turbines might choose a floating solution that enables to pick those turbines.

Floating foundations have less constraints and Eolink exploited this by redesigning the structure. Their structure displays great qualities that make it one of the most promising floating foundation options. However, developers might pick floating foundations with existing turbines for reliability. EOLFI must succeed perfectly in their testing phases in order to acquire the trust from developers.

2) Damping pool (Ideol)

Floatgen is a floating wind turbine project involving 7 European countries. The foundation's conception was attributed to Ideol, a French company specialized in floating structures. Their foundation concept lies on the damping pool technique. The turbine is placed on a square structure, as illustrated below. The structure is made out of concrete and acts like a giant floating square pool.

Figure 45: Ideol's damping pool structure [65]

Floatgen project featuring a 2 MW turbine was inaugurated in 2017. The electricity production of the project went beyond expectations when it reached a 6 GWh production in 2019. This company uses a different foundation type than Eolink's structure: what are its benefits?

The pool absorbs easily the wave loads by being in an opposite phase than the sea around. If a high wave is coming to the floating structure, the pool level automatically goes down, as illustrated in the figure below. This principle grants excellent stability and allows the structure to be compact. The structure is only 36 meters long for the 2 MW turbine. 6 cables are tied to the seabed to strengthen the stability of the structure and to immobilize it [65].

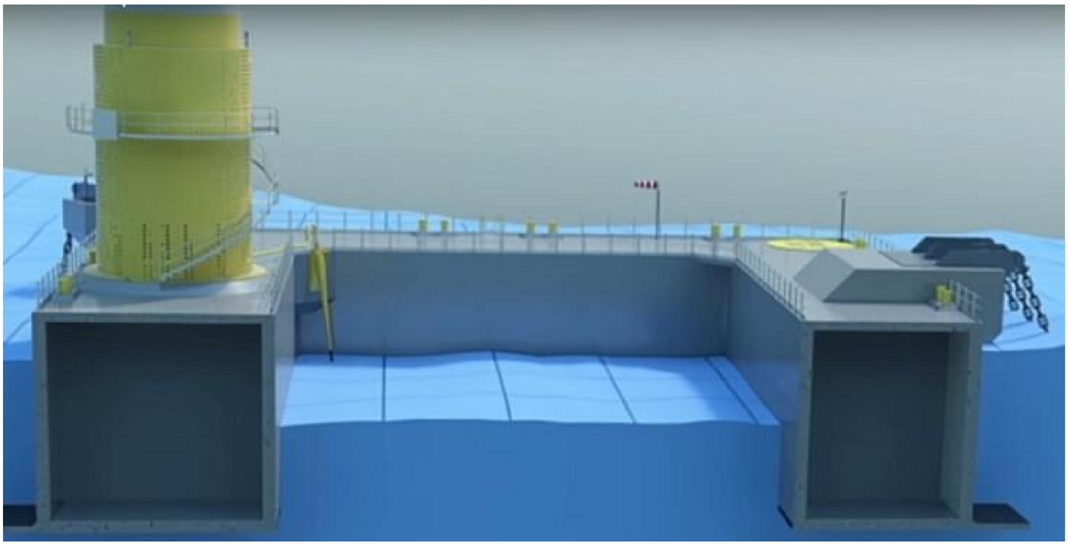


Figure 46: Damping pool's opposition phase absorbs wave load [65]

Another great advantage of the technology is that every wind turbine on the market can be placed on Ideol's damping pool. Of course, the structure's size must be adapted but this is an important quality that EOLFI's structure does not have. The Floatgen project featured an MHI Vesta 80-2.0 turbine, one very reliable that was largely implemented around the world. Finally, it is a plug and play structure meaning that it can be constructed in the port and then towed to its final offshore location.

3) Flowocean

Flowocean AB is a Swedish company that based its floating foundation on Tension Leg Platform (TLP) and semi-submersible techniques. They are well known types of foundations because they are widely used by the oil companies. Indeed, oil wells can reach depths over 2500 meters nowadays. Hence, oil companies had to develop techniques to implement offshore platform in ultra-deep environment.

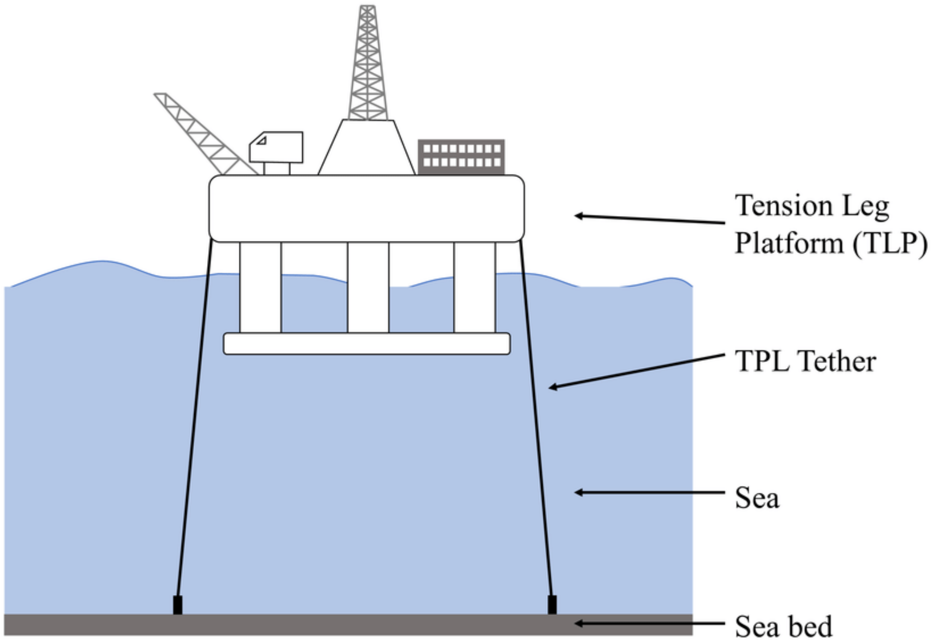


Figure 47: Tension Leg Platform scheme [66]

The principle of a Tension Leg Platform (TLP) is the cables, here called TPL Tether, that link the platform to the seabed. But these cables are special, they are more than cables that simply prevent the structure from drifting. They are extremely tight in order to make the platform sunk a bit, as illustrated in the figure below. This greatly improves the stability of the structure [67].

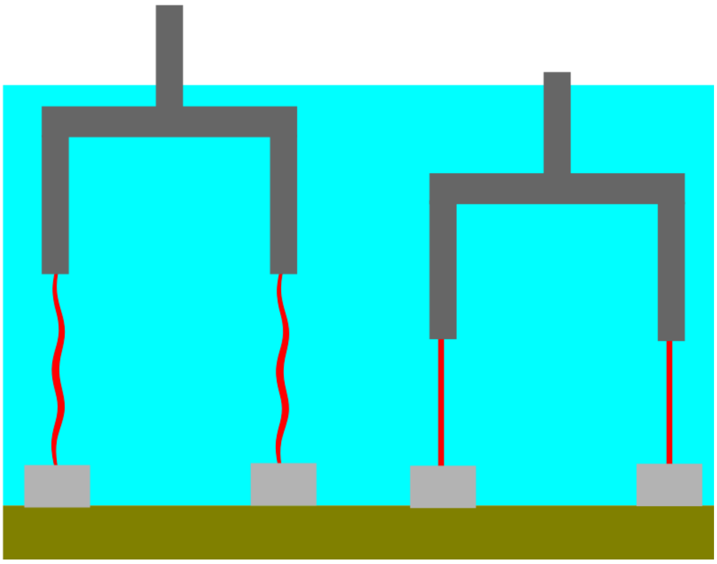


Figure 48*: Structure free floating on the left and pulled down by the cables on the right* [68]

Semi-submersibles are a specific type of vessels used by the offshore oil business for drilling operations as their main quality is their excellent stability. This is why Flowocean's design was also inspired by this technique. This quality comes from giant ballasts that can be filled with water to sink the vessel into the sea, improving the stability. This is basically the same principle as TLP: sink the vessel to reduce wave loads' impact on the structure.

Figure 49: Semi-submersible vessel [69]

Flowocean uses the techniques that proved in the past to be effective and reliable. However, using them to carry wind turbine was never done before. A lot of research is needed to understand how these technologies can be transposed for renewable energies. Nevertheless, the interesting part of this concept is that they want to implement two wind turbines on a single floating foundation, as illustrated below. The aim is to implement two smaller turbines that would have the same power generation or more than a large one.

Figure 50: Flowocean 2-turbine concept [67]

This patented design present beneficial qualities. First of all, the structure is very light. It is thus easier to install it but also cheaper as less materials are needed. Secondly, it has a plug and play feature. Like all floating foundations, the installation of the turbine can directly be made in the harbour and then tugged until its location. Thirdly, the foundation mixes two reliable techniques that works well in harsh environment. Finally, Flowocean uses two smaller turbines to benefit from the lightness of smaller turbines. It is easier to install and to perform maintenance on them [67].

For now, only a 1/50 scale test has been conducted and was successful. The idea seems great on paper, but is also counter-intuitive. Putting two turbines on a similar foundation can involve more risks because of the proximity of the two turbines. The aerodynamics of one can interfere with the aerodynamics of the other one. This could be a serious drawback for Flowocean, as people might not trust their concept. Once again, successful small-scale tests will be necessary to earn trust of wind farm developers.

4) WindFloat

WindFloat is a concept developed by Principle Power, an American company specialised in the floating wind foundations that was created in 2007. In 2011, a 2-MW prototype was installed offshore Portugal. For 5 years, Principle Power collected data to understand issues and to improve their structure [70]. In 2016, the WindFloat 1 was decommissioned, after successful results. Then, they developed WindFloat Atlantic, a three turbines project of 8.4 MW each [71]. The first turbine was installed in December of 2019 and produced power in January 2020. The last turbine was currently under installation in June 2020. It is early to call this project a success or not, but until now there was no issue encountered, neither in the installation phase or the operation phase. Besides, the technology was chosen for the four-turbine project "Les éoliennes du Golfe de Lion" in France, and the six-turbine project "Kincardine" in the UK. This seems to be a very successful technology, so what is the technology behind it?

Figure 51: WindFloat Prototype in Agucadoura [71]

WindFloat is based on the semi-submersible technology. The foundations are composed of three giant semi-submersible cylinders placed in a triangle. As explained for the Flowocean concept, semi-submersible foundations were used in the past and thus quite reliable. This is one reason why the WindFloat technology has been already chosen for several projects. Besides, static and dynamic stabilities are excellent which enables the use of turbines already commercialized for fixed-foundations. Furthermore, WindFloat displays the same "Plug and Play" technology which allows developers to install the turbine onshore and to tug the whole structure offshore [71].

WindFloat presents classic floating foundations qualities using a reliable semi-submersible technology. Most importantly, it was the second real-scale floating turbine tested behind Hywind but it is also the currently second most-used technology for floating wind farms behind Hywind once again. It is thus a very safe choice for developers in a yet unknown market.

5) Hywind

Hywind is a technology developed by Equinor. This company, formerly named Statoil, is one of the largest oil and gas companies in the world. However, they started to largely divest the oil and gas market in the 2010s to invest towards greener energy. They are currently developing 18 projects in Europe and in the USA. Most importantly, they are pioneers in the wind floating foundations. In 2009, they inaugurated the first floating turbine in the world. In 2017, they inaugurated the first floating wind farm, Hywind Scotland Pilot, featuring five turbines of 6-MW each. Hywind Tampen is a project that features 11 turbines of 8-MW each. The wind farm is expected to be commissioned for 2022 and will be the largest floating wind farm in the world [72].

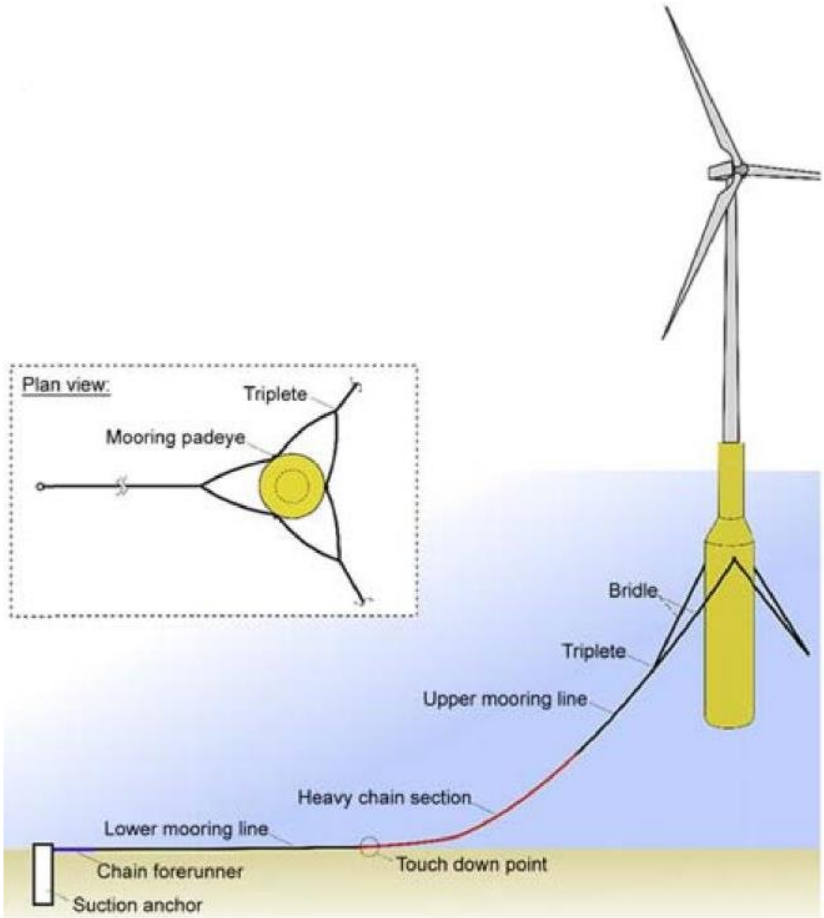


Figure 52: Hywind floating foundation scheme [73]

The Hywind foundation is different from the ones previously studied. It is based on a single floating cylindrical spar buoy moored by cables to the seabed. The substructure is largely ballasted with water and rocks in order to maintain the turbine perfectly perpendicular to the sea level. This substructure is moored thanks to three large cables rooted in the seabed that split into six bridles strongly attached to the foundation, as illustrated by the figure 52. The latest version has a draft of 90 meters and a displacement of 12000 tons, tremendous numbers. The diameter is relatively small, being only equal to 15 meters [72].

This unique solution presents several advantages. First of all, it appears to be very reliable as two projects are successful. Also, it is based on a well-known technology which can reassure developers. Secondly, it is adapted for turbines already commercialized for fixed foundations. This prevents from adding more cost of developing new turbines.

However, its installation is more complex than competitors. Indeed, most other foundations offers a "Plug and Play" features that enables to fully install the turbine on the foundation in the pier. In the Hywind case, the large cylinder is towed horizontally to the location where the ballasts are filled with 8000 tons of water and rocks. With this manoeuvre, the foundation goes vertically and only then the turbine can be placed on the foundation. This process is relatively simple compared to fixed foundation's process but it is more complex that the majority of other floating foundations' process.

Table 11: Comparison of floating technologies

Technology	Structure	Plug & Play	Usual turbines	Schedule
Eolink		Yes	No	12 MW turbine in 2023
Ideol	Damping pool	Yes	Yes	4x6MW turbines in 2021
FlowOcean	Semi-submersible/TLP	No	Yes	1/50 scale model tested
WindFloat	Semi-submersible	Yes	Yes	WF commissioned
Hywind	SPAR	No	Yes	WF commissioned

Floating wind farm could be revolutionary as countries that do not benefit from shallow water areas would be able to implement wind farms. Furthermore, it would harness more consistent and more powerful winds. Several technologies are under testing either at small scale or large scale. What is interesting is the plurality of the technologies developed. For now, it is complex to properly compare them as they are all under testing with only small information communicated. However, first results from all of them seem extremely promising. Three technologies are well advanced with wind farm already or soon commissioned. Eolink is still testing smaller scale models but predicted a surprisingly low LCOE of 60€/MWh. It is almost half the current average LCOE price, presented in the figure 32. Flowocean is more behind but its technology is incredibly different from the other and requires more developing time.

Floating foundations are thus full of promises but will need some time before being used for very large-scale wind farms. Research is needed to ensure a better reliability while decreasing the costs.

Conclusion

Global warming caused by excessive consumption of fossil fuels through human activities has prompted us to rapidly find alternatives to reduce CO_2 emissions. Renewable energy technologies have emerged as one of the best assets to strive against this issue. The goal of the thesis was to bring the light to offshore wind power, explain what was this technology, understand its advantages and drawbacks, and study its potential.

Wind offers a large and clean resource of power, available all over the world. Wind power plants have first been developed onshore in 1980 as it is an easy and cheap technology. However, onshore wind is limited in terms of capacity suffering from volatile wind conditions and limited acceptance from the population.

Conversely, offshore wind power allows very large-scale development, featuring larger turbines in areas where a stronger and more consistent wind blows. This allows to generate more power and to have better capacity factors, explaining why offshore wind power has recently emerged as an excellent asset to develop renewable energies at large-scale.

Yet, this technology also suffers from several drawbacks. The first part highlighted how crucial was the foundation part. Different types of fixed foundation exist, each one having a different advantage but they all have in common one major disadvantage: they are not suitable in water depths higher than 60m.

This major issue was illustrated in the second part. Different maps pointed out how benefiting from shallow water areas was essential to develop these offshore wind farms. This requirement explains the large development inequalities of the technology. Europe greatly took advantage of the North Sea which offers exceptionally large shallow water areas in a windy environment. Conversely, certain countries in America and in Asia have barely developed the technology, despite benefiting from great shallow water areas.

In the last years, there has been a phenomenal progression of renewable energies regarding their costs and capacity factors. Costs have plummeted, particularly for solar PV and onshore wind that have become cheaper than any fossil fuel-based power plant. Offshore wind power remains expensive but offers higher capacity factors. Research needs to be conducted to further decrease the costs but most importantly to remove the constraining shallow water requirement.

Floating wind farms could overcome both of these issues. Floating foundations are suitable for any reasonable water depth, thus completely resolving one issue. For now, this technology is more expensive than traditional offshore wind farms because of large research and testing costs. Once the reliability proved, the costs lowered and the production means adapted, the technology will be mature enough to be implemented at very large-scale. This might require a decade but it will surely be worth the wait as it would help many countries to largely replace their actual polluting power plants.

Several aspects of the offshore wind power have been studied, conclusions have been drawn on some of them, but other ones remain undecided. A first glance on the environmental footprint of different power generation sources has been made. This is a thorny question that requires a lot of work. It would allow a better understanding of renewable energies’ impact on the planet to see what characteristics could be improved (for instance their recyclability). Finally, floating foundations were introduced. As most of them are under testing, only few data are available to understand the different structures tested. A more detailed analysis would be useful to compare the benefits and issues of each foundation type.

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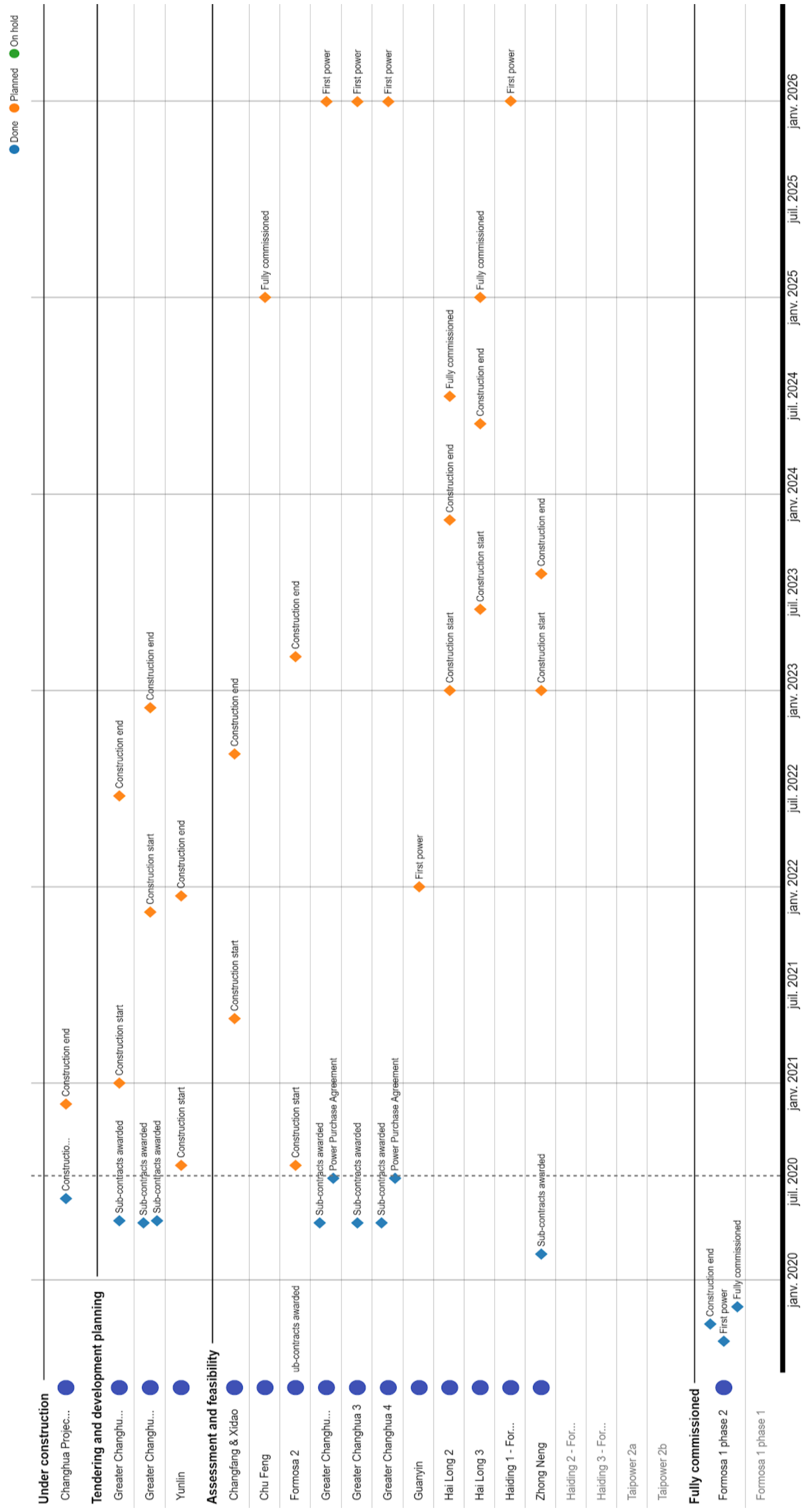
Annex A



Done
Planned
On hold
Under construction
Changhua Projec...
Tendering and development planning
Greater Changhu...
Greater Changhu...
Yunlin
Assessment and feasibility
Changfang & Xidao
Chu Feng
Formosa 2
Greater Changhu...
Greater Changhua 3
Greater Changhua 4
Guanyin
Hai Long 2
Hai Long 3
Haiding 1 - For...
Zhong Neng
Haiding 2 - For...
Haiding 3 - For...
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Taipower 2b
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Formosa 1 phase 2
Formosa 1 phase 1
Sub-contracts awarded
Construction start
Construction end
Power Purchase Agreement
First power
Fully commissioned
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