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Will Europe achieve its Offshore Floating Wind energetic targets for 2050?

Kleyver Mijares

Acknowledgements

Dedicated to my grandmother and the Maritime University of the Caribbean.

Special thanks to my family, especially my brother, Joalbert Mijares, for being there advising me most of the time and to my mother for encouraging me to always go forward. Thanks also to my supervisor, Associated Professor Charlotte Obhrai for her help, and lastly, to the person who accepted my application to course this Master`s degree. Without his/her decision I would not be here today doing this Master Thesis.

Abstract

The objective of this master's thesis is to investigate the feasibility of assembling and installing the expected capacity of offshore wind farms. The focus of the study will be solely on the installation of Offshore Floating Wind Turbines. Disregarding other factors such as grid connection, cabling installation, substation refurbishment or installation, and supply chain considerations. The study employs a modeling tool called *Shoreline*, to determine if offshore wind hub ports strategically situated in critical locations across Europe can meet the estimated installed capacity indicated in governmental and European association projections for the decades to come, specifically up to 2050. These hub ports are chosen based on established parameters. The assembly process involves the assemblage of the wind turbines (including the tower, nacelle, and blades) and floating substructures (such as spars or semisubmersibles) for posterior mating and hook-up with their respective anchoring and mooring line systems. The study aims to give insights into the feasibility of reaching future offshore floating wind capacity objectives, with a particular emphasis on installation issues within the chosen hub ports.

7 hub ports were assigned across Europe and progressively modified the assets involved in the installation process of the wind farms expected to be deployed in the future. At first, the most optimal installation asset combination was found for both types of hub ports (hub ports installing semi-submersible wind turbines and only Norway using spar-buoy floaters) in terms of the completion time of one single project. In the case of semi-submersible hub ports, adding an extra set of tugs and an extra floater assembly crane (two in total for both assets) turned out to be considerably beneficial for the completion of this pilot wind farm. On the other hand, for the spar-type hub port, adding two extra sets of tugs and an additional anchor handling vessel (three sets of tugs and two AHVs in total) significantly reduced the completion time of the project. Subsequently, other cases were considered since the limiting criteria for the allocation of hub ports per country is the integration crane (crane used to assemble the wind turbine to its floater). First, an ideal case where each hub port had its own integration crane was made in order to have a reference target achievement date for further comparison; this ideal case showed that most of the countries were relatively close to reaching their targets on time. Thereafter, the number of cranes was periodically reduced with the intention of showing how this will affect the total installed capacity of the hub ports and make a more realistic estimation of the total installed capacity. A sensitivity study was carried out, so as to determine non-arbitrary crane transfer criteria among the countries, giving as a result that a more equitable outcome will be obtained if the integration crane is transferred by proximity between nations and by elapsed time rather than installed wind capacity. Successively, the comparison between fully operating hub ports and interrupted ones by crane transfer operations was carried out and showed that most of the countries decrease their installed capacity by approximately 50% in most of the instances. This decrease significantly extends the target achievement date of the nations. Based on a comprehensive analysis considering all the assumptions made in this master thesis, and after the results obtained, it is strongly recommended that governments enhance their policies if they aspire to achieve their targets by 2050; in aspects such as licensing, investment in power grids, substations, and port facilities, and lastly, prioritize the development of technologies associated with integrations cranes in order to enhance the number of hub ports per country.

Abbreviations

MW Mega-Watt

GW Giga-Watt

OW Offshore Wind

OFWT Offshore Floating Wind Turbine

AHV Anchor Handling Vessel

WTG Wind Turbine Generator

SWATH Small Water plane Area Twin Hull

AHTS Anchor Handling Tug and Supply

AHV Anchor Handling Vessel

PRS Polyester Rope Section

CTV Crew Transfer Vessel

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1. Introduction

1.1 Background

The necessity of finding new sources of energy has increased over the last decade as a consequence of global warming. Across the world, different technologies have been implemented to reduce CO_2 emissions and dependency of fossil fuels. However, the problem lies in the necessity to find alternative ways to produce energy. The use of fossil fuels and/or nuclear power plants might be appealing to some countries, while others (like in the EU), are transitioning to exploit alternative energy sources in an effort to limit the global temperature increase to below 2 degrees Celsius by 2050. For that, the use of renewables is highly prioritized, which is where wind turbines seem like a good alternative. As the population grows, so does the demand for power [24], which in turn necessitates expansion of wind turbine installations. Moreover, considering the issues and the tendency to build larger (sized) wind turbines, in-land projects seem to become less feasible and increasingly challenging to install due to the opposition to wind farms from local populations. This has led to a proposal of offshore wind-turbines.

The distribution of already installed offshore wind turbines tend to be close to shore. [23] In recent years, the offshore wind turbine industry has been exploiting the *"low hanging fruit*" of shallow waters while using monopiles foundations. Floating concepts start to become more appealing for multiple reasons, one of which, is that it is easier to exploit larger areas of sea surface farther away from the coast, at water depths greater than 60 m. Secondly, from an environmental perspective, compared to offshore fixed structures, floating concepts offer less invasive activity with respect to the seabed during the installation process compared to offshore fixed structures. [99]

In recent years, the wind energy industry has experienced significant progress and shows no indications of slowing down. According to the Global Wind Energy Council, the global wind market will surpass 100 GW for the first time in 2023, with a 15% compound annual growth rate. Despite obstacles such as regressive policies, logistics costs, and supply chain pressures, the deployment of wind energy is accelerating in major industrialized nations, and surplus in the manufacturing sector is likely to be eliminated by 2026. Large corporations from outside the energy industry are increasing their investments in wind development, and it is anticipated that wind and solar will be the primary sources of additional electricity generation between 2022 and 2023. The wind industry is preparing for a forthcoming acceleration, and policymakers must take action to facilitate the required level of trade while expanding domestic supply chain opportunities. In this context, it is impossible to overstate the significance of political action to strengthen renewable energy supply chains. Specially for the upcoming years, when a certain amount of Offshore Wind farms are expected to be installed by the next decades. [22]

1.2 Research Question

Governments worldwide are trying to find solutions to mitigate the effects of global warming while maintaining their production levels. As a commitment to reduce emissions and limit the temperature increase for this century to 2°C (ideally keeping it below 1.5°C), 194 parties across the world signed the Paris Agreement (2015). The agreement also provides funding, particularly to poor nations, to reduce climate change, increase resilience, and boost skills to adapt to climatic consequences. When thinking about the offshore wind industry in Europe. [108]

Which, then yields the following question:

"Is it possible to reach the targets on time?"

2. Theory

2.1 Why go towards offshore wind production?

One of the main reasons to opt for offshore projects, apart from the constant conflicts that this kind of inland projects will generate with local communities, (e.g., the Fosen wind project, in Norway [4]) is how the wind profile behaves regarding its closeness to the earth's surface. By wind profile, it is meant to describe how the wind's velocity and other properties develop according to the height at which it is studied. As seen in figure 2.1, it is possible to appreciate how the wind speed changes between inland surfaces and offshore ones (the red ones being the fastest and inversely with the green ones). This wind profile development occurs in the *atmospheric boundary layer* (which is the lowest section of the atmosphere). As it is close to the earth's surface it is expected that wind velocity at this point will be slightly close to zero and that will very likely increase vertically. This variation of speed, called *vertical wind profile* or *wind shear*, is a very important magnitude hence, it can determine the productivity of any Wind Turbine Generator (WTG) and could potentially help to determine the lifetime of the rotor due to the constant addition of cyclic loads towards the structure. [5].

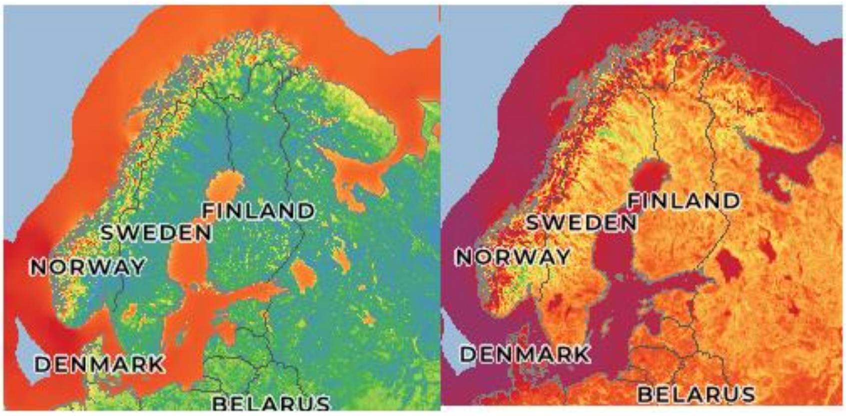


Figure 2.1: Wind speed atlas at 10m (left) & 100m (right) height. [6]

Considering that with respect to time, engineering allows WTG to increase their size and therefore their production capacity [7] as seen in figure 2.2. Offshore wind power seems more appealing for two main reasons, as wind turbine are getting bigger, installing wind parks offshore will not have an impact of any source to locals of any community, and secondly but not less important, wind speeds offshore are greater due to the lack of interference, such as surface roughness. [8]

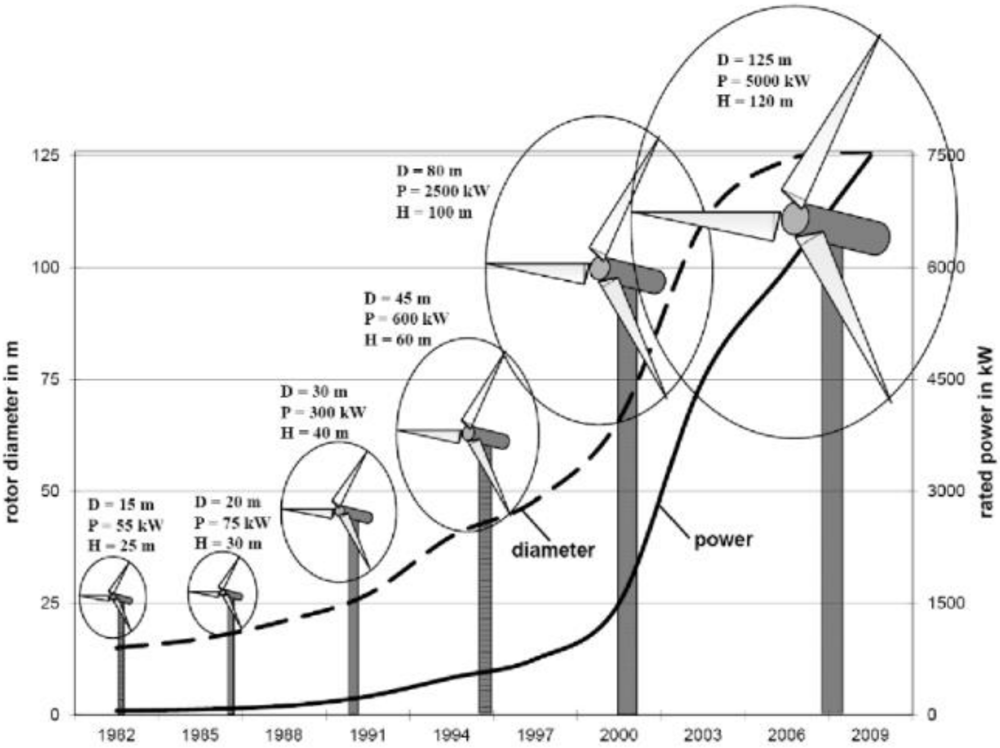


Figure 2.2: Size and Power output of Wind turbines over the years. [7]

2.2 Components of a wind turbine

Over the ages wind turbines have been going through a series of variations, comprising modifications of the rotor's axis positioning, and the number of blades used. (See figure 2.3) Both modified according to different considerations, like for instance, costs, noise production, fatigue, and most importantly, power coefficient, the power coefficient (C_p) is the ratio between mechanical power produced by the WTG and power available in wind. As seen in figure 2.4 drag force wind turbines, typically VAWTs have less power coefficient than lift force wind turbines or HAWTs, which is why nowadays it is more common to see this type of wind turbines and not the others. Regarding the number of blades, (also seen in the same figure, 2.4), a three bladed WTG will have less tip speed ratio or *TSR* (which is the speed experienced at the end of the blade) and a higher C_p compared to a two and a one bladed WTG, resulting in a more efficient power production and less noisy operation. The rotor, nacelle, tower, and foundation are shown as the key elements of a contemporary horizontal-axis wind turbine (HAWT) in Figure 2.5. [9] [10]

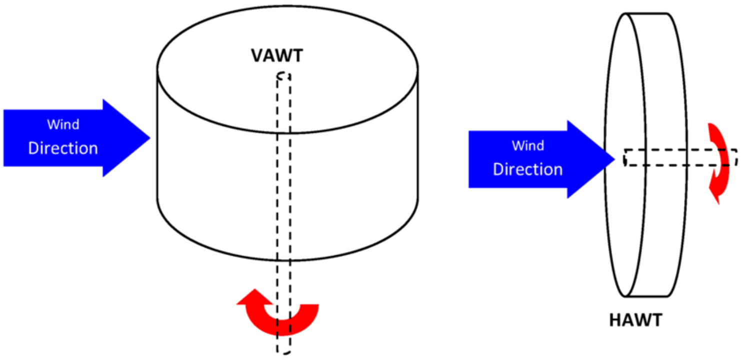


Figure 2.3: Differences between VAWT and HAWT. [9]

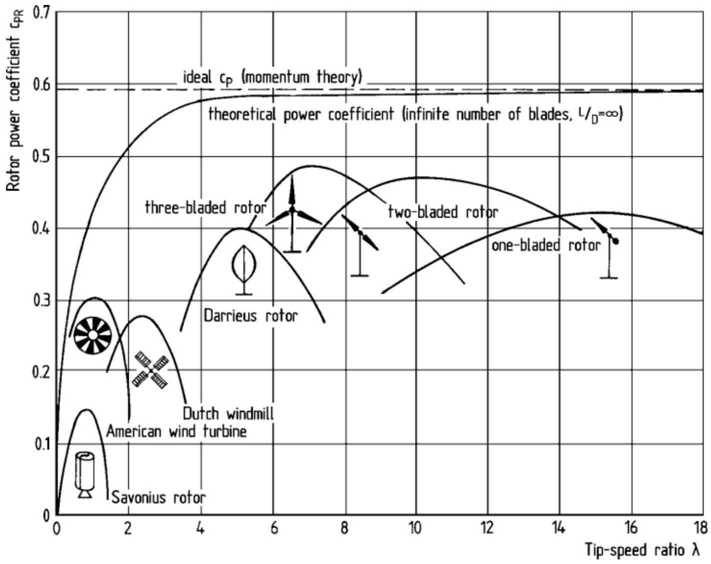


Figure 2.4: Relation of rotor power coefficient vs TSR for different wind turbines [10]

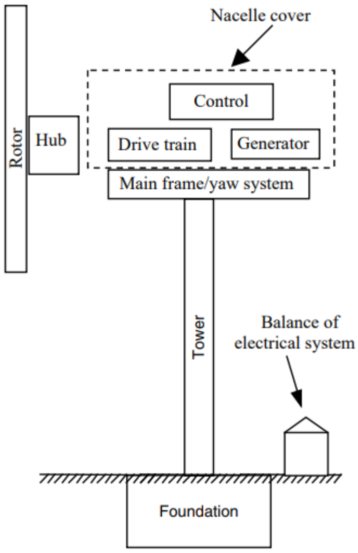


Figure 2.5: Major components of a HAWT. [5]

2.2.1 Rotor

Modern horizontal-axis wind turbines (HAWTs) have a rotor that primarily comprises the hub and the blades. It is considered to be one of the turbines' most important components, both in terms of performance and costs, it is considered as one of the most important components. Regarding the blades, these elements are frequently made of expensive composite materials, such as fiberglass or carbon fiber, and therefore, tend to be costly to build, especially for longer blade lengths above 50 meters. When it comes to the hub, it is important to notice that is normally constructed of steel, and its main function is to serve as joint point for the wind turbine's blades to its central shaft. The hub also enables the blades to rotate or pitch with respect to their own axis, allowing them to alter the lift force when the wind speed hits specific levels. Particularly under high wind conditions, this pitching mechanism is essential for maximizing the effectiveness and safety of the wind turbine. The total effectiveness and energy output of the WTG can be considerably impacted by the rotor's design (including construction materials). [5] [11]

2.2.2 Nacelle

The nacelle refers to the area where the equipment responsible for generating electricity, such as the drive train, generator, and control systems, are located. This space is typically designed to protect the components from weather conditions. [5]

2.2.2.1 Drive train

The energy converted from the wind by the rotor is transferred to the generator using the drive train, which typically includes the rotor shaft, gearbox, and braking system see figure 2.6. The rotor shaft is a cylindrical axis that transmits the rotations from the hub to the gearbox. The gearbox converts the rotor's high torque, low spinning velocity into the generator's shaft much quicker rotation. The braking system serves as a mechanism used to ensure the stopping position of the wind turbine once that this one has reached the "*cut out speed*" (which is the point at which the blades are pitched to stop the rotor from rotating due to excessively high wind speeds) refer to figure 2.7. This mechanism will be addressed in a more specific way in the section below. [12] [14]

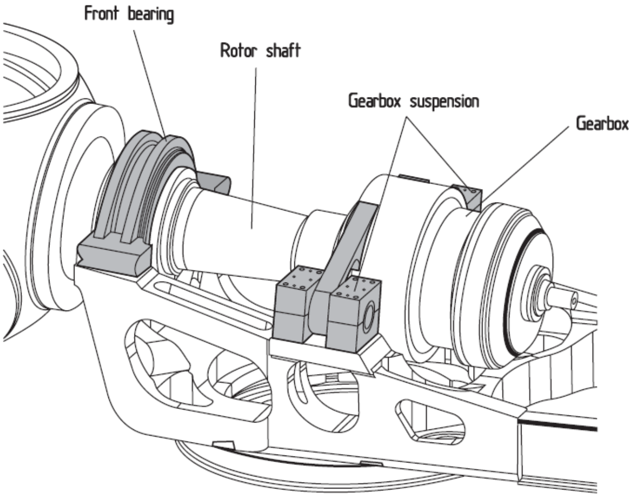


Figure 2.6: Rotor Shaft – Gearbox assembly, the hub at the very beginning. [10]

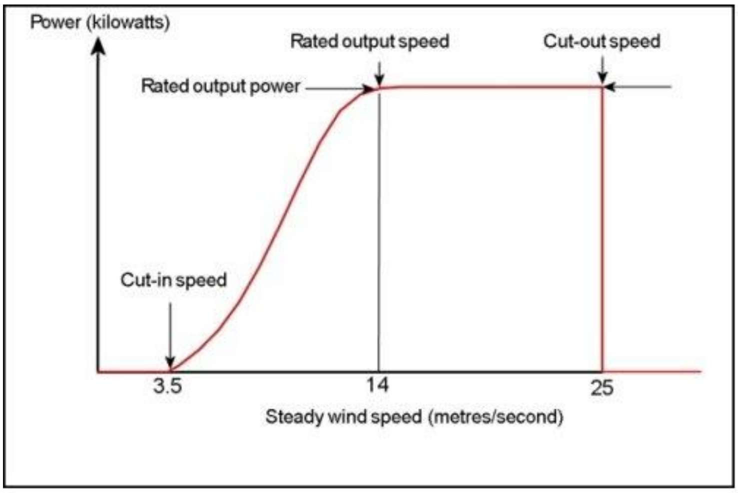


Figure 2.7: Typical wind turbine power output curve. [13]

2.2.2.2 Generator

First, the generator set covers two important elements, the *"stator"* and the "*rotor"*. See figure 2.8. Where the stator acts as a housing that contains coils of wire assembled in a predetermined pattern, while the rotor is the moving part that has an integrated magnetic field either by means of permanent magnet or induced magnets, that when rotates, induces voltage to the stator and generates consequently, electricity.[12]

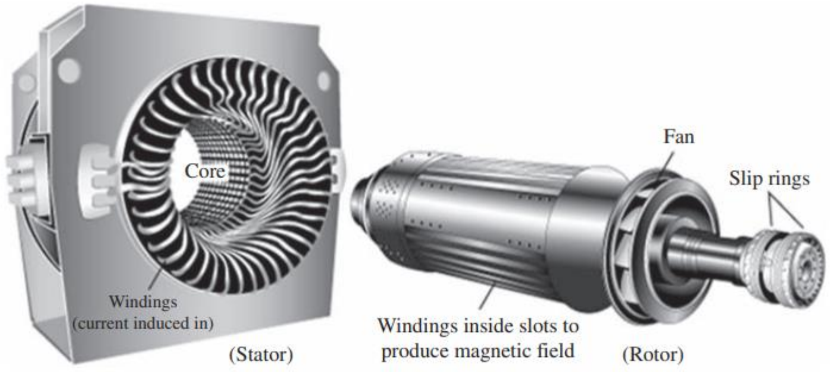


Figure 2.8: A typical generator with its stator and rotor. [12]

2.2.3 Control system

Although WTGs are built to withstand inclement weather, they are not intended to operate with high wind speeds or high aerodynamic rotating torques. The reason is that the force experienced by the blades during these conditions could potentially lead to mechanical failure of the gearbox, generator, and other components due to excessive loading. Therefore, the main task of the control systems is to ensure safe operations and power production of the wind turbine. The way to achieve it is by stopping the WTG when the output power reaches a maximum value which can be directly related to the wind speed perceived by the rotor. The control techniques used to accomplish this task are stall control and pitch control. (Influence of the stall control on the power curve can be seen in figure 2.9 and can be classified as active or passive). It is worth mentioning that active stall mechanisms scarcely differ from pitch angle control systems, but the pitch-controlled blades provide lower power and load peaks, which is the main reason why nowadays it is mostly used in wind developments. To reduce torque and rotational speed in strong winds the pitch control systems incorporate an active control system that changes the pitch angle of the turbine blades' orientation in relation to the wind to stabilize the output power around its nominal value. On the other hand, stall control systems use the aerodynamic designs of the turbine's blades to stall or stop the turbine from turning while also implementing the rotation of the blades when the wind speed exceeds the turbine's rated wind speed. [10] [15]

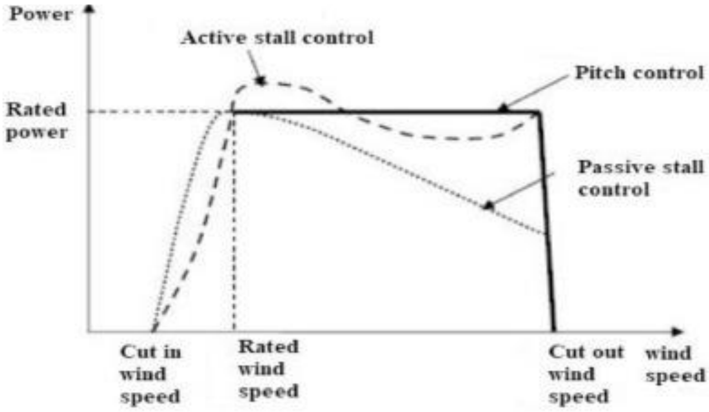


Figure 2.9: Power curve of a WTG. Active and Passive stall control and Pitch control techniques [15]

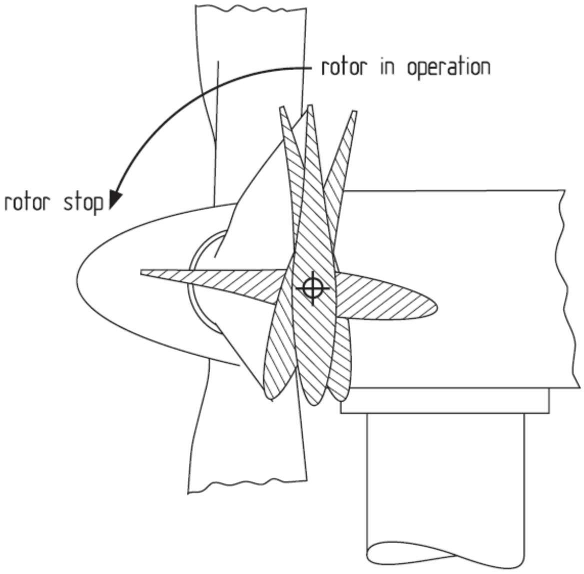


Figure 2.10: Active stall control mechanism with different sets of pitch angles. [10]

2.2.4 Yaw system

The yaw control system’s main objective is to make the turbine rotor always face the wind to enhance power, reduce the stresses brought on by the yaw misalignment, and alleviate the wake effect in wind farms. The process starts when a deviation between the nacelle and the wind’s direction, also called a *Yaw error* occurs and is detected by any of the three different methods employed nowadays for this functionality (using a traditional wind direction sensor, estimating wind direction, or without using a wind direction sensor) triggering afterwards a response in the logical control module, or a Proportional Integral Derivative (PID) controller that will activate an electric drive motor and will allow therefore the relocation of the tower’s head relative to the wind’s direction. This yawing mechanism comprises elements such as the before mentioned electric drive motor, in charge of generating the mechanical power to operate a pinion gear coupled to the bull gear and a set of other components that from a structural point of view constitute the transition section from the tower to the nacelle. See figure 2.11. [10][16]

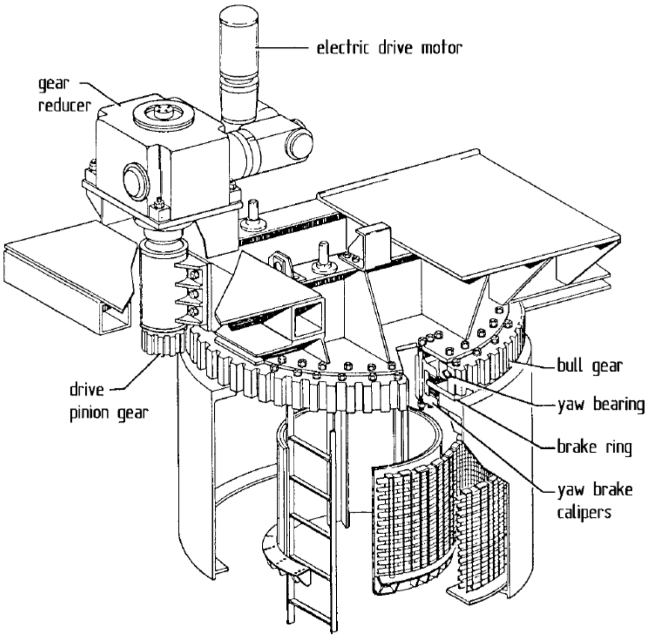


Figure 2.11: Yaw system assembly. [10]

2.2.5 Tower

A structural piece, generally designed as a tubed-type element, serves as the major support structure for the rotor, power transmission, and control systems, as well as the intermediate component between the foundation piece or substructure and the nacelle. The tower provides enough height for the rotor to be outside the surface boundary layer and its successful design should guarantee the safe, effective, and economical design of the entire wind turbine system. Specifically providing easy access for maintenance purposes of the rotor’s components, transportation, and upending/lifting operations. [18]

2.2.6 Foundations and substructures

When it comes to offshore wind turbines the foundations constitute one of the most important considerations to be taken into account, first of all, the foundation represents between 15% – 40 % of the total capital expenses of the project and the selection of the concept will depend on the site conditions as for example, water depth, wind speeds, wave height, current and ground profile, seabed condition and the WTG power output capacity. There are in general two types of foundations, one that is *grounded type* which is when the structure is “anchored” to the seabed. Grounded type foundations can then, be divided into two sub-categories according to the foundation/geotechnical engineering; *shallow foundation* is mostly related to gravity-based structures (which have added dead load to prevent overturning), while suction caisson or suction bucket solutions basically consists of an open end circular cross section that buries into the soil as seen in figure 2.12 and provides sufficient stability to the structure. The *deep foundation*, like monopiles structures, as seen in figure 2.13. Monopile structures are a large steel pipe driven into the seabed with a penetration of about 25 to 40 meters. This foundation piece will be coupled with the tower via a transition piece which also provides a surface and ladder for technicians to use during installation, commissioning, and maintenance operations. [12][25]

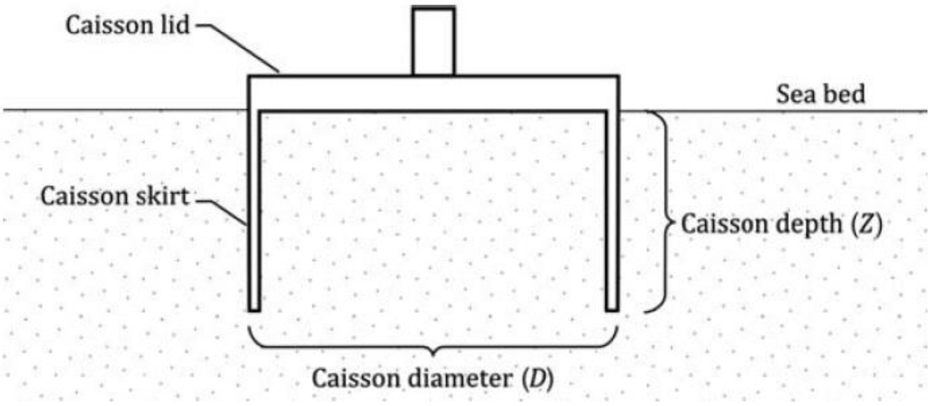


Figure 2.12: Suction Caisson or Suction Bucket Foundation. [12]

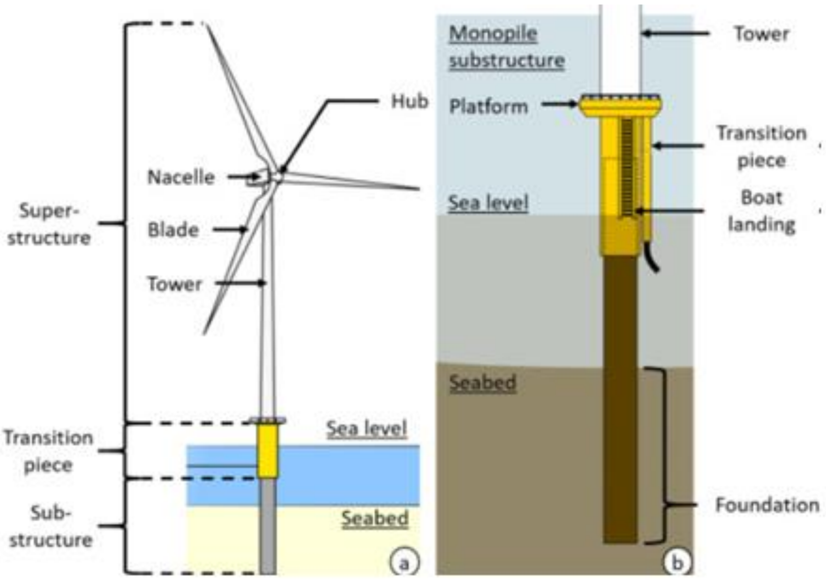


Figure 2.13: Monopile WTG Foundation and substructure. [26]

Based on previous experience from the offshore oil and gas industry, it was possible to apply an already known and well-studied method of a mooring system into the floating wind turbines field, generating what is known as f*loating system*, this kind of foundation represent certain “ecological” advantage, as it is seabed footprint is smaller than the grounded type`s, which makes the whole facility easy to decommission and maintain. Via a mooring mechanism that could be made out of wires, polyester ropes or chains, anchored to the seabed using either suction piles, driven piles or gravity installed anchors, it is possible to keep the offshore floating structure in place, despite wind forces and current. The mooring systems include spread catenary or taut mooring system lines, tensioned leg system and single point mooring concepts, The selection of the mooring concept (lines and anchors) will depend on several factors, as for instance, conditions such as: water depth and soil type, overall costs, country regulations and floater type. The latter is described further in this master thesis. As seen in figure 2.14, there are different combinations of mooring systems with different floating substructures. [12][27]

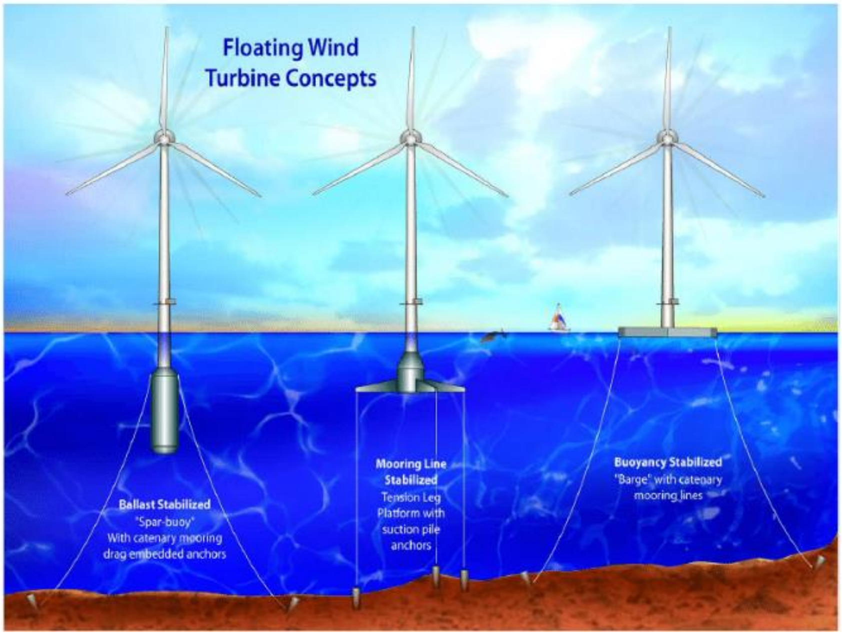


Figure 2.14: Different Floating concepts with different mooring concepts. [28]

2.3 Floating wind turbine concepts

In recent years, offshore wind turbine development has advanced rapidly. Earlier wind farms were built in shallow waters with jackets or monopiles substructures mostly. Nonetheless, as wind farm development continued to progress into deeper waters, fixed structures became expensive to produce and Floating Offshore Wind Turbines (FOWTs) became the preferred solution. See figure 2.15. There have been “demos” of FOWTs, including the *Hywind* (spar type) off the coast of Norway in 2009 and the WindFloat (semi-submersible type) in the coast of Portugal in 2011. In 2019, *Hywind Scotland* became the first wind farm of this kind to operate commercially, and in 2020, *WindFloat Atlantic* became the second floating wind farm to feed an electrical grid. *WindFloat Kincardine* and *Hywind Tampen* are two additional wind farms currently under construction. FOWTs can mainly be categorized into three primary types of spar-buoy, semi-submersible, and tension-leg platform (TLP). A fourth type can be also considered as a floating wind turbine concept; the barge type. It has a damping pool similar to those used in the offshore oil and gas industry. [23][31]

The classification of the stability methods used to prevent overturning of the structure or *capsizin*g. Will vary depending on the chosen concept of the floater, some of the use a *ballast stabilized* principle which means that adding seawater into certain compartments of the structure will modify the stability conditions of the structure and will help them to get back to their initial status (when non disturbed), some others are *buoyancy stabilized*, meaning that the stabilizing moment is contributed by the water plane area of the floater and finally, *Mooring stabilized*¸ which receives most of its stability from mooring lines as seen in figure 2.16. [40]

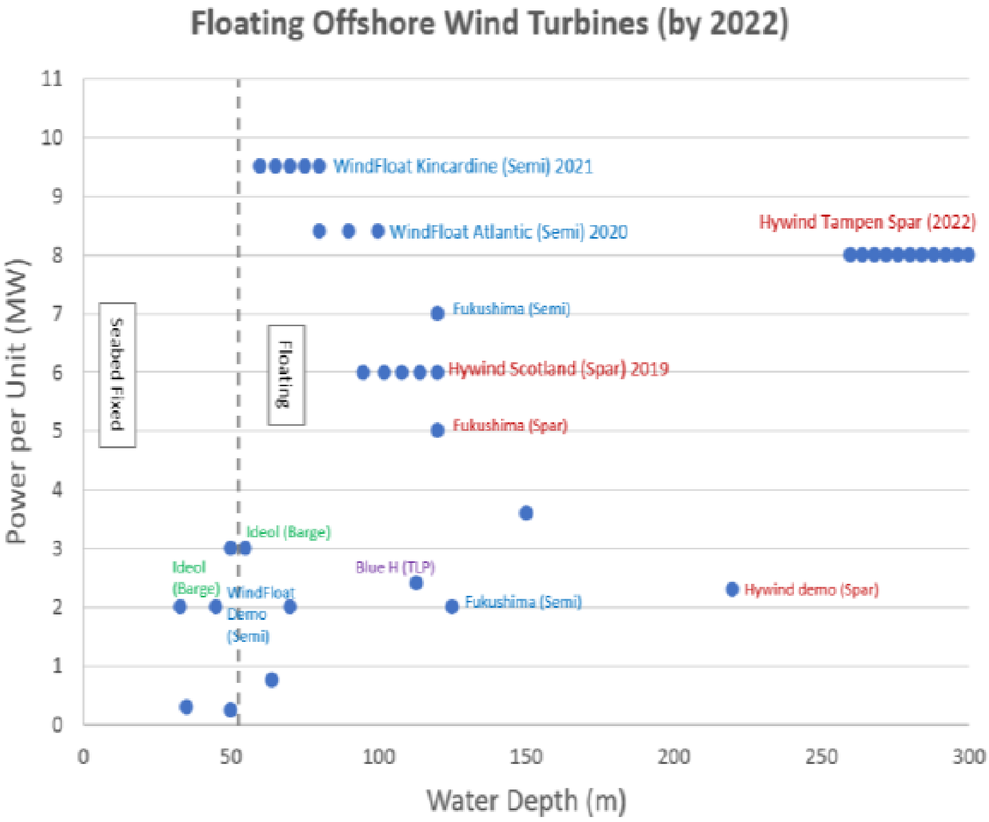


Figure 2.15: Fixed and floating Wind turbines already installed. [31]

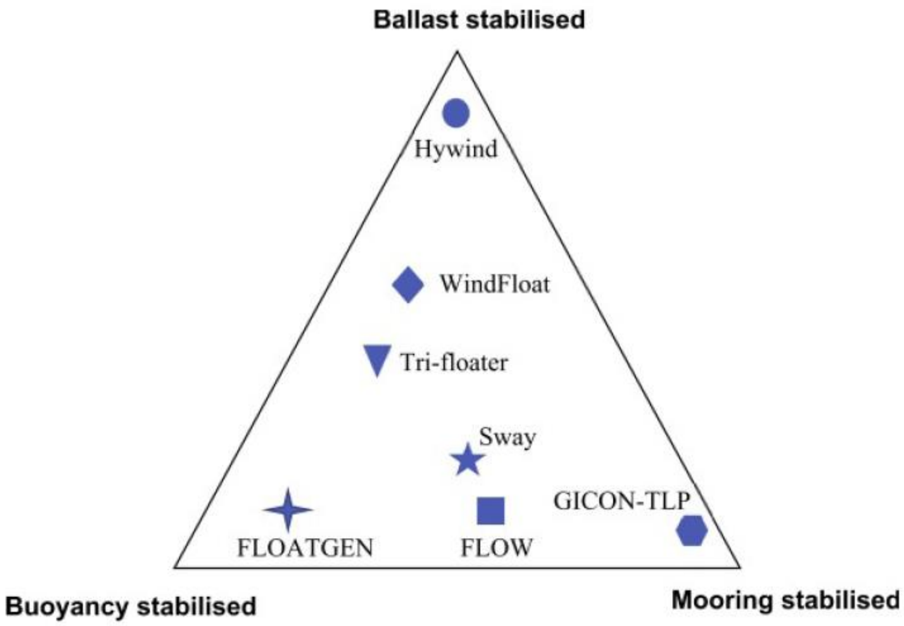


Figure 2.16: Classification of the stability methods of floaters. [40]

2.3.1 Spar

This type of floating substructure requires a deep draft floater, i.e., a cylindrical structure that could be made of steel or concrete, that when ballasted (filled with sea water) places the center of buoyancy (the center of the submerged volume of the object) above the center of gravity (center of mass of the object) so as to make it stable and capable to redress whenever its original condition is altered. This concept requires mooring lines and anchors to keep it at a certain position and keep it from drifting [12]. It is worth mentioning that the first spar type wind turbine *"Hywind"* was installed in Norway, by Statoil (currently known as Equinor) in conjunction with Siemens in 2009. Hywind was a 2.3 MW power output wind turbine with a hub height of 65m and a rotor diameter of 82.4m [29].

2.3.2 TLP (Tensioned Leg Platform)

The TLP design consists of a floating foundation that supports the WTG. The TLP wind turbine can be commissioned and assembled onshore, thereby avoiding the logistical challenges related with the assembly offshore. Vertical tendons, also known as *tethers*, secured by suction piles, driven piles, or a template foundation hold the floating platform in place, as seen in figure 2.17. Pre-tensioning of the tethers provides the necessary righting moment and therefore, stability. [30]. One Early design was *Eolomar*, a ring-shaped buoy attached to the soil via tendons which had two main advantages; it was possible to build it onshore and then tugged and hooked up with the tendons, and that there was an absence of humongous foundations. The floater was conceived to be built in concrete, but this idea was discarded in favor of steel because it is more flexible when considering circular shapes [32].

2.3.3 Semisubmersible

As for the oil and gas industry, the semisubmersible floater consists of a set of watertight columns that can be loaded or unloaded with seawater (*ballasted or deballasted*) in an effort to maintain the stability of the structure. This concept involves a mixture of both, ballasting and tensioning mooring lines and can be defined as a *buoyancy stabilized* concept. A prototype model, the "*WindFloat 1"* was installed in Portugal in 2016 using this kind of floating substructure. During its lifecycle, this prototype generated around 17GWh into the Portuguese power supply. This type of substructure basically consists of 3 vertical columns joint by truss beams, where, once the floater is built the turbine can be placed on top of one of the columns as seen in figure 2.18. [12][33][34].

2.3.4 Barge type

FloatGen, a concept designed by a company called IDEOL in France, proposes a moonpool barge floater that consists of a squared-like substructure with a moonpool in the middle that dampens the motions of the barge-type floating wind turbines, see figure 2.19. This concept seems very promising not only in manufacturing costs but also as a concept capable of improving hydrodynamic performance. The floater is made from concrete (but can also be made of steel or mixed concrete) and the installation can be carried out onshore, which will eventually save costs of mobilizing offshore vessels [35][36].

In table 2-1, a comparison of different fixed type and floating concepts have been carried out in terms of certain advantages/disadvantages such as installation, transportability, scour level (*Scour* is when sand particles are moved away by the interaction of wave and currents with the structure, causing holes between the substructure and the seabed altering its dynamics characteristics. [82]) and other aspects presented below.

Table 2-1: Advantages and disadvantages of different substructures. [21]

Comparison points	**Type of Foundations**			
	GBS	Monopiles	Jacket Structure	Floating
Design methods	Available	Available but for less than 6m diameter	Available	Research work in needed
Installation	Difficult	Moderate	Moderate	Easy
Manufacturing	No on site	Easy	Easy	Easy
Transportability	Difficult	Moderate	Moderate	Easy
Scour	Very high	Moderate	Less	Less
Dependency on subsoil condition	Very high	Moderate	Low	Low
Self-Weight	High	Less	Moderate	Less
Depth application	5-10m	25-30m	Around 50m	+50m

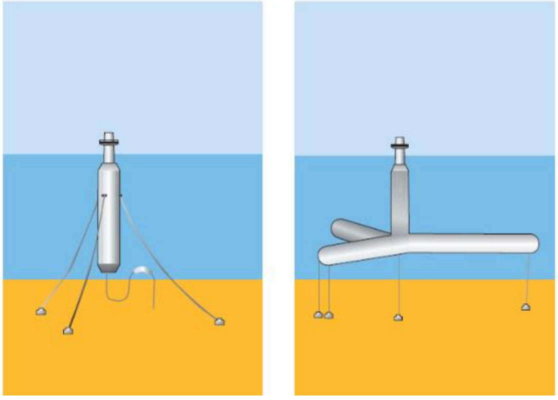


Figure 2.17: Left to right Spar, TLP, floating substructures. [34]

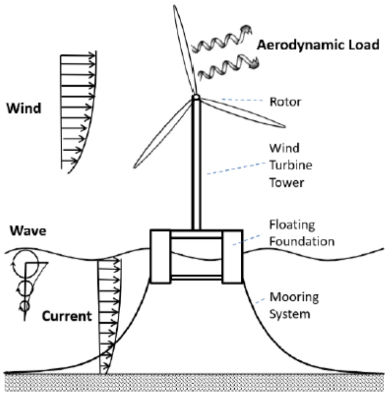


Figure 2.18: A semisubmersible floater type for an offshore wind turbine. [31]

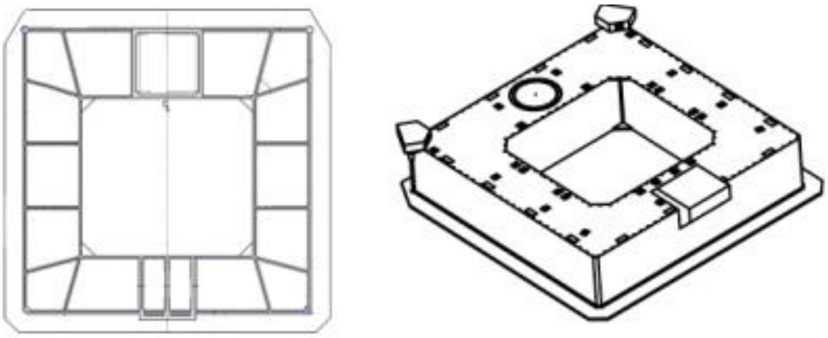


Figure 2.19: FloatGen Substructure or Hull. [36]

2.4 Installation methods of a floating wind turbine concept

The variation of the installation processes relies on the specific type of floater that is chosen. In addition to that, any floating wind installation process necessitates a larger number of vessels than those used for offshore fixed wind ones, but the vessels are less expensive to hire and more readily available. Despite the fact that numerous floating wind concepts have been conceived, only some of them have been successfully deployed and have been incorporated on a commercial level and this are the following.[40]

2.4.1 Installation of a Spar type Wind turbine

In the case of the first spar type wind turbine installation, the process went as follows, see figure 2.20. Considering the geographical conditions that Norway has, the installation of the substructure subsequently occurred this way, the foundation must be towed first, in a horizontal position up to the desired location, right after that, the *"upending"* must be done, the upending consists on ballasting the substructure via pumping water and also adding dry ballast (magnetite rocks) using a rock installation vessel till it's completely vertical and has the correct draft for the next step, which was the assembly of the mooring lines to the substructure, then the last stage, assembling the wind turbine to the already moored substructure (tower, nacelle and rotor were previously assembled inland and towed by a heavy lift crane vessel) this step it's called *"mating"*. [37]

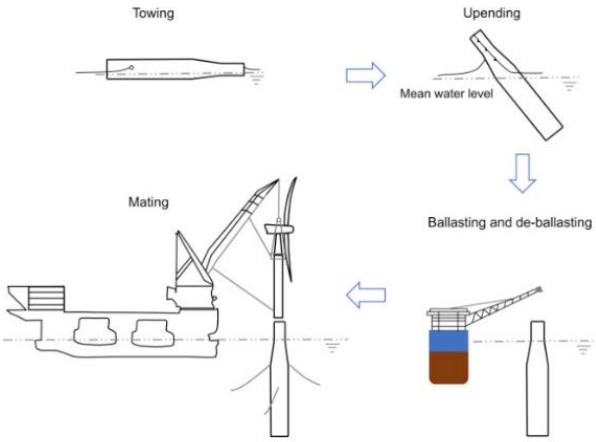


Figure 2.20: Descriptive process of the first spart type wind turbine installation. [37]

Although there is a different procedure, that considers mating the WTG with the substructure in sheltered areas to avoid wave/wind induced responses. First, the foundation must be upended, then it's towed to the dock, after that the wind turbine components are installed one by one, i.e., first the tower, then the nacelle, and finally the blades, all of this is done on top of the substructure, then is disconnected from the dock and afterwards towed to its final position where pre-installed mooring lines (with anchors) are hooked up as can be seen in figure 2.21. [36].

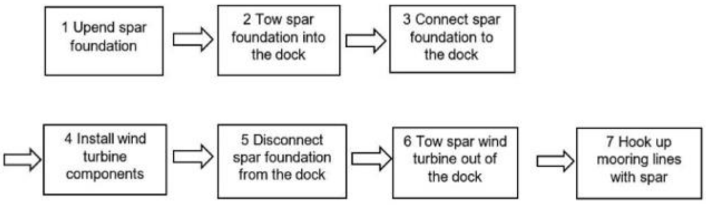


Figure 2.21: Alternative installation process of a Spar WTG. [36]

2.4.2 Installation of a Semisubmersible Wind turbine

In the case of the WindFloat concept, there were two different shipyards building the floaters, one in Setubal, Portugal and another one in Fene, Spain. In the case of Setubal, the floater was built on a dry-dock. The three vertical columns were built and joined with the water entrapment plates (WEP's) or heave damping plates (plates used to reduce horizontal motions of the structure or as called in the marine engineering field, *heave responses*), see figure 2.22. Once the truss-beams were welded among the columns and the coating was added, the dry-dock was then flooded and tugged the substructure to Ferrol, Spain for posterior assembly of the wind turbine components. Meanwhile, in Fene, the columns were built in two sections and assembled horizontally. Right after that, the hull was upended and coated, the WEP's and trusses were welded to the columns and afterwards dry-towed onto a semi-submersible vessel to Ferrol, Spain for the wind turbine assembly, see figure 2.23. Once in Ferrol, the hull was ballasted, and the wind turbine assembled piece by piece. The tower was assembled in three sections, then the nacelle and the 3 blades. Leading to the final step which was the towing on site of the complete structure (floater and wind turbine). [2]

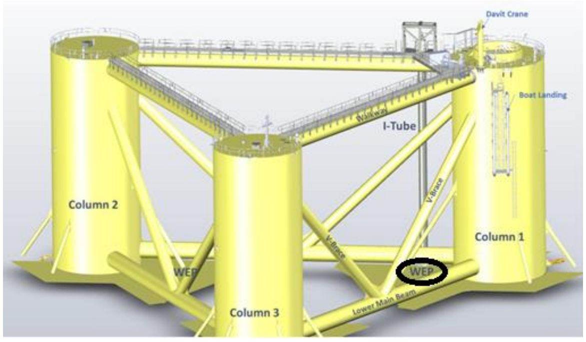


Figure 2.22: Semi-submersible floater. [2]

Figure 2.23: Hull assembly in Portugal (left) vs assembly in Spain (right). [2]

2.4.3 Installation of a Barge type Wind turbine

The hull can be built either in a dry-dock or in a quay, in the case of *FloatGen*, a barge was used to build the concrete foundation on top of it, once finished, was tugged to a dry-dock, and disengaged from the barge, then the substructure was towed out to the crane area, where the turbine components were assembled one by one. The tower, the nacelle, the hub and the 3 blades were installed at quayside. Once this procedure was done, the whole turbine tugged to its final destination. See figure 2.24. [38][39]

Figure 2.24: Barge-type offshore wind turbine floater. [39]

2.4.4 Installation of a TLP Wind turbine

The Tension Leg Platform concept is ideally suited for water depths of moderate depth. The depth ranges between 70 meters, the approximate maximal depth for fixed wind turbines (in terms of costs), and 200 meters, which is the depth beyond which spar-buoy floaters are deemed the most cost-effective option. Even though the industry has seen some TLP Wind Turbine (*TLPWT*) prototypes developed, it is not a commercially attractive concept yet. Some of the deployments were held in 2008 and 2014 for example, where the methods of installation were slightly different. In 2008, Blue H technologies installed their first TLP Floating Wind Turbine. Installing first the tendons while constructing the floater on shore, once this step was completed the floater was tugged on site and subsequently ballasted and then located above the tendons, once the mating was done between the tendons and the floater, the structure was deballasted (with the intention of achieving the desired tension of the tendons) and secured. Whereas in 2014 the *GICON TLP* installation process was held differently, the TLPWT was attached to a *floating slab* (a floating structure that can be ballasted) and then towed on site, then the slab was ballasted and the TLP submerged to its required final draught. As shown in figure 2.25 the processes were different, but the result was the same, attaining certain draught with the structure. [40]

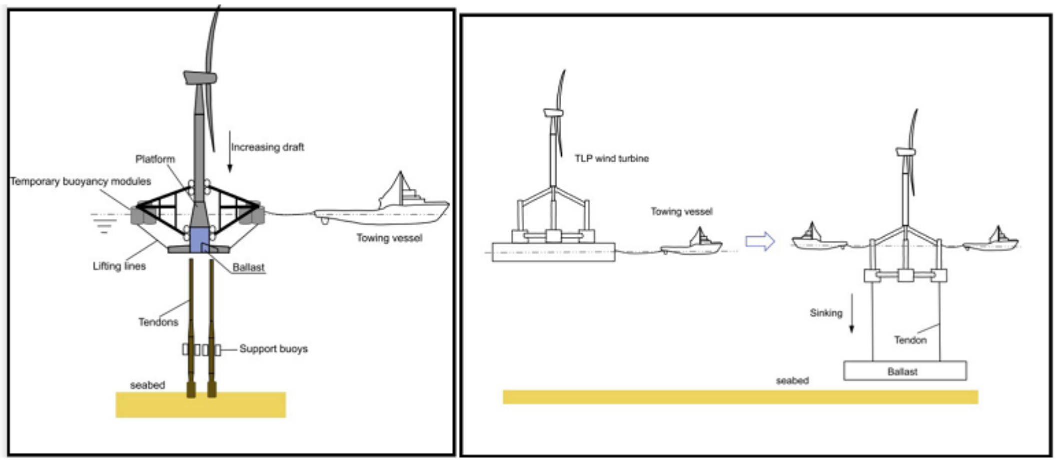


Figure 2.25: Installation methods of TLPs, left side 2008, right side 2014. [40]

2.5 Problems associated when installing floating wind turbines.

Based on a SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) for the three main categories of offshore floaters (*Spar, Semi-submersible* and *TLP)* by [41] the main problems associated to installation are:

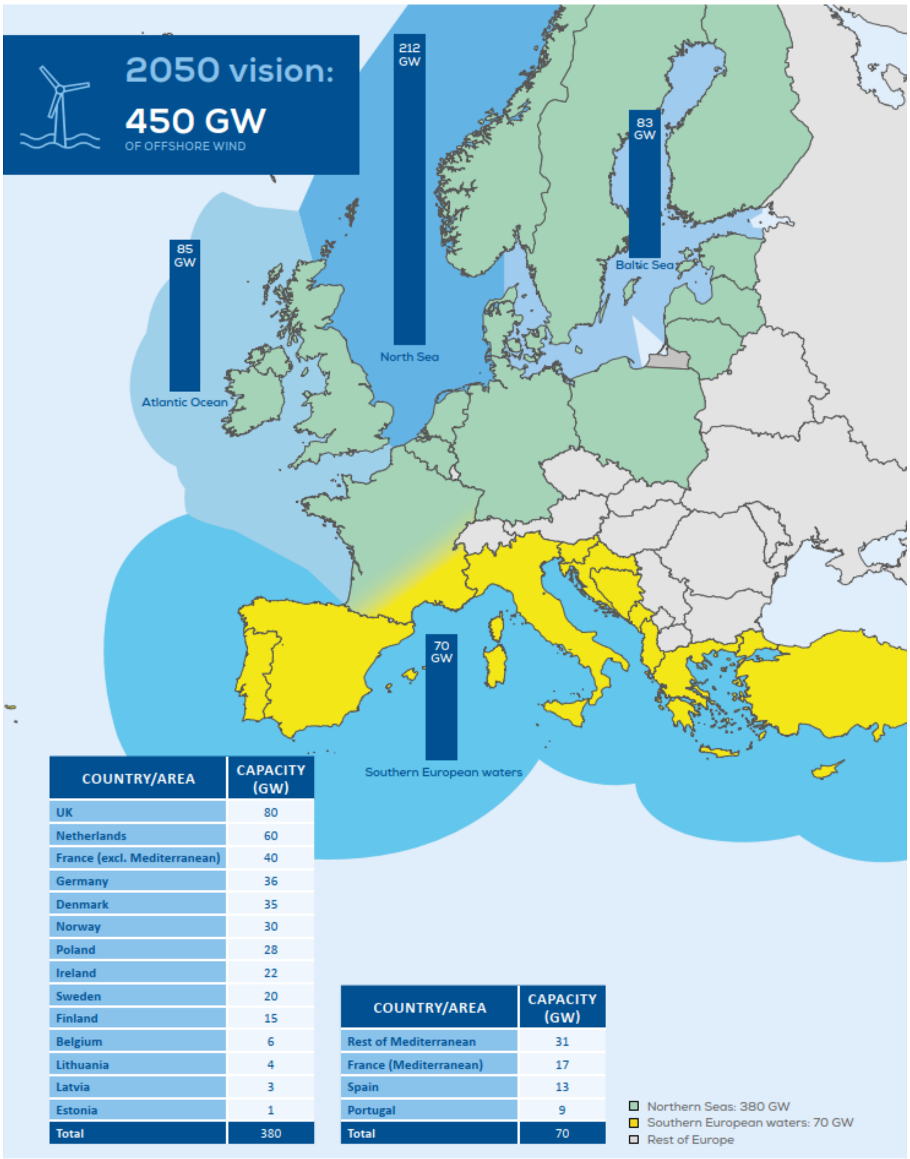
- Need to assemble in sheltered areas.
- Long mooring lines.
- Large structures (when towing).
- If active ballast is used (semi-submersible), it is costly and more complex than non-active.
- Special purpose installation ships needed (Anchor Handling Vessels, among others).
- Port facilities.

3. Offshore Wind expectations for future years and latest progress.

According to one of the reports of *Wind Europe organization*, offshore wind energy production is a key element in achieving Europe’s carbon-neutral milestone. According to the IEA (International Energy Agency), it could become Europe's primary power source approximately by 2042. The EU Commission settled a goal of 230 to 450 GW of OW energy production by 2050, making it a fundamental part of the mix between onshore wind and OW. This report also lights the spotlight on the North Seas, where the greatest number of installations are projected to happen, and points out the necessity for more grid, and supply chain development for offshore wind. The report concludes that it is viable to deploy 450 GW of OW by 2050 and identifies the most effective locations for this capacity. [3]

3.1 Where to place Offshore Wind farms?

Based on the same report of the Wind Europe organization, 85% of the anticipated OW capacity of 450 GW by 2050 is expected to be installed in the North Seas, with 380 GW in the Atlantic, North, Irish, and Baltic Sea. While 70 GW are expected to be developed in Southern waters in the European region. The required area for the 380 GW in the North Seas takes approximately 76,000 km2, which is equivalent to 2.8% of the total area of the North Seas, disregarding exclusion zones. An exclusion zone is understood as an area dedicated either to shipping, fishing or military and these ones can delimitate the available surface used for OW purposes. Figure 3.1 illustrates how the distribution of the 450GW is projected for 2050, 212 GW in the North Sea region, 83 GW in the Baltic Sea, 85 GW in the Atlantic Ocean (Irelands’ side) and 70 GW in the Southern European Waters. [3]



COUNTRY/AREA	CAPACITY (GW)
UK	80
Netherlands	60
France (excl. Mediterranean)	40
Germany	36
Denmark	35
Norway	30
Poland	28
Ireland	22
Sweden	20
Finland	15
Belgium	6
Lithuania	4
Latvia	3
Estonia	1
Total	380

COUNTRY/AREA	CAPACITY (GW)
Rest of Mediterranean	31
France (Mediterranean)	17
Spain	13
Portugal	9
Total	70

Figure 3.1: Expected Offshore Wind installation by 2050 based on wind profile resources. [3]

3.2 Ongoing European Offshore projects

Some of the ongoing projects in the Offshore Wind industry will be explained in this section including countries such as, Norway, United Kingdom, Ireland, and Denmark as for the offshore North Sea investing countries, Spain and France as the Southern European countries investing into offshore in the Atlantic Ocean, and Mediterranean Sea and Poland as a country with offshore wind projects in the Baltic Sea.

3.2.1 Norway

Norway has a growing need for more renewable energy, and OW power can play a major role in meeting this demand. In addition, this presents an opportunity for the expansion and development of the Norwegian supplier industry. The Norwegian Water Resources and Energy Directorate (NVE) has identified potential new areas for offshore renewable energy production. The government's objective is to set aside a region for 30,000 MW (30 GW) of OW power by 2040, which is nearly equal to the current output of Norwegian hydropower. The

NVE works in identifying these new areas as an essential part of the government's efforts to increase offshore renewable energy production, but before any new areas are confirmed, a strategic impact assessment will be conducted (a proposal for an impact assessment program, which will be available for public consultation until 12 June 2023). The government will discuss with stakeholders the NVE's proposals. [1]

Also, a report shows the potential that Norway can potentially install 10 times more wind energy than the national governments target by 2040 (30GW). This report was carried out by Equinor, Hafslund, Deep Wind Offshore and Source Galileo, and shows the areas where Norway could build around 241 – 338 GW of wind energy in their territory in certain areas without much level of conflict. [44]

As seen in figure 3.2, there are two color shaded zones, a green one denoting Offshore Bottom-fixed Wind farms and a blue one denoting Offshore Floating Wind farms. Table 3-1 contains the details about the zones where the floating projects could be executed and table 3-2 contains details the NVE`s early planned wind farms in those permitted areas. In total there will be 28 and 18 areas respectively for each type of concept and the study was carried out taking into consideration aspects such as bird population, fishing industry activities, and environmental issues. [44]

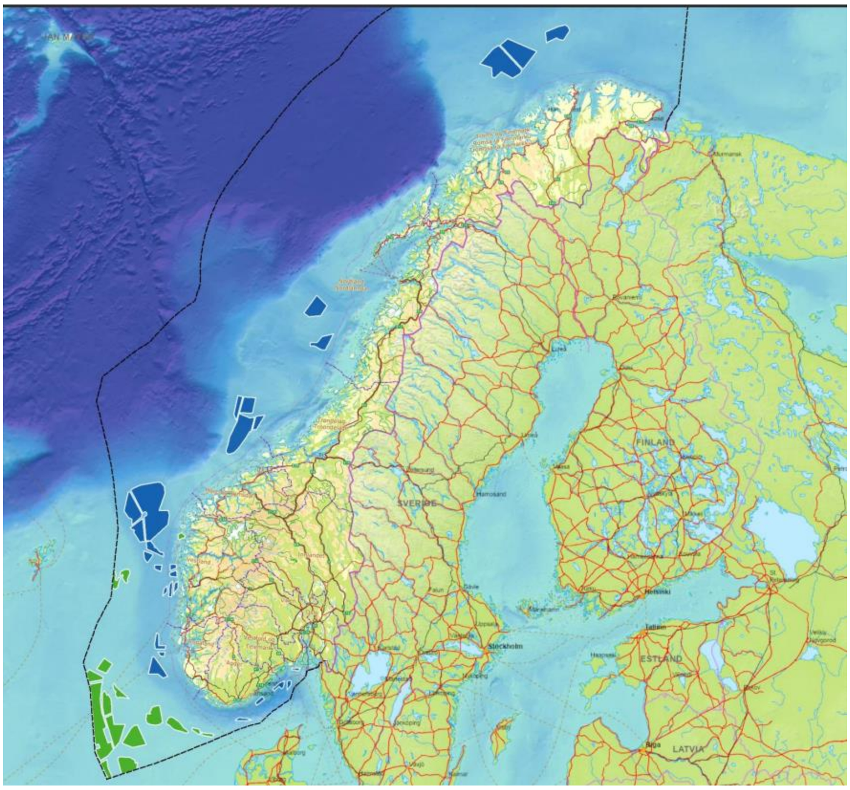


Figure 3.2: Norwegian Offshore Wind Projects. Green related to fixed and Blue to Floating. [44]

Table 3-1: Offshore Floating Wind Projects [44]

Name of the development & Region	Zone Tag (numbering for each zone)	Distance to shore (Km)	Assumed Capacity (MW)	Depth (m) (mean sea level is 0)	Estimated Power (GW)
Skagerrak (Telemark og Agder)	**F1**	10	453 – 635	-205 – -40	4 – 6
	F2	35	780 – 1110	-658 – -376	
	F3	25	1380 – 1930	-650 – -385	
	F4	20	920 – 300	-481 – -370	
	F5	40	910 – 1280	-480 – -280	
Nordsjøen (Rogaland)	**F6**	45	5 580 – 7 820	-295 – -244	8 – 12
	F7	50	660 – 930	-269 – -240	
	F8	35	2170 – 3030	-282 – -258	
Nordsjøen (Hordaland)	**F9**	10	960 – 1350	-371 – -149	5,8 – 8
	F10	20	1230 – 1720	-330 – -269	
	F11	35	630 – 880	-295 – -282	
	F12	5	1020 - 1430	-385 – -127	
	F13	15	900 - 1270	-404 – -158	
	F14	50	1040 - 1460	-331 – -304	
Norskehavet (Sogn og Fjordane)	**F15**	85	1 900 – 2 660	-375 – -322	56 – 78
	F16	40	2 979 – 4 170	-379 – -340	
	F17	105	5 470 – 7 670	-393 – -331	
	F18	50	36490 – 51080	-421 – -230	
	F19	125	8790 – 12310	-395 – -364	
Norskehavet (Nordmøre og Trøndelag)	**F20**	55	16280 – 22790	-354 – -204	27 – 38
	F21	65	2450 – 3440	-335 – -230	
	F22	100	5520 – 7740	-368 – -220	
	F23	110	2700 – 3780	-398 – -307	
Norskehavet (Nordland)	**F24**	85	4980 – 6970	-357 – -290	13 – 18
	F25	110	8060 – 11290	-411 – -251	
Norskehavet (Finnmark)	**F26**	85	19960 – 27940	-410 – -287	42 – 59
	F27	90	14700 – 20590	-402 – -294	
	F28	110	7460 – 10450	-281 – -244	
				Sum	155.8 – 219

The power difference between each tag is due to the surface area of each zone, i.e., variations in size will allow more wind turbines and therefore more power production respectively, regarding the depth ranges, it is important to keep into account the fact that the seabed is mostly irregular and therefore depth will vary. See the size reference as shown in figure 3.3. [44]

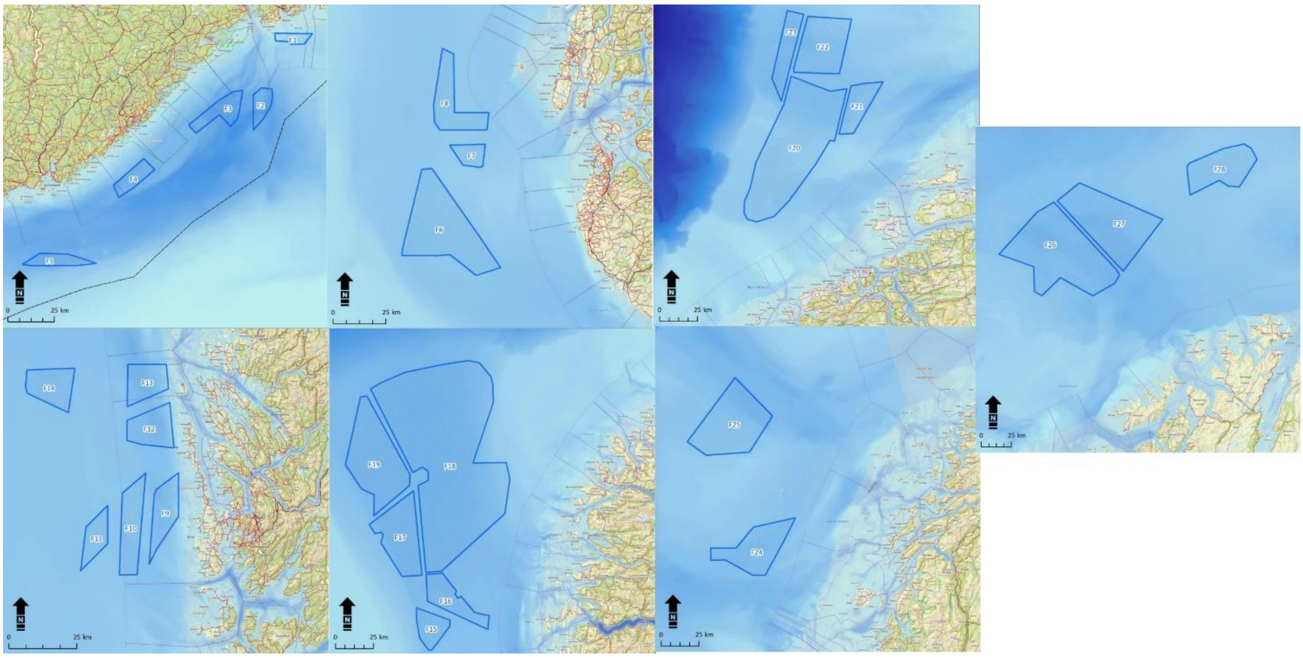


Figure 3.3: Different zones sizes for floating offshore in Norway. [44]

What was shown in table 3-1 corresponds to the potential for OW in Norway, which provides an idea of how productive Norway will be in OW matters, but, according to the NVE`s *identification for offshore wind areas,* the offshore floating projects conceived in those permitted areas can be seen below, in table 3-2.

Table 3-2: Details about early planned projects in Norway. [120]

Name of the development	Substructure	Total capacity (MW)
Northwind A	Floating	1000
Northwind B	Floating	1000
Northwind C	Floating	1000
Northwind D	Floating	1000
Northwest A	Floating	1000
Northwest B	Floating	1000
Northwest C	Floating	1000
West Wind A	Floating	1000
West Wind B	Floating	1000
West Wind C	Floating	1000
West Wind D	Floating	1000
West Wind E	Floating	1000
West Wind F	Floating	1000 (500 from Utsira)
Total		13000

3.2.2 United Kingdom

Electricity System Operator (ESO) which is Great Britain’s system operator, has published a report named *Future Energy Scenarios* (FES) aiming to examine potential changes that could occur in the energy system from now until 2050. These changes include technological innovations, behavioral adjustments, infrastructure improvements, and different decarbonization choices. The implications of these changes are explored to see how they could impact society and the energy system. To demonstrate the credible range of possibilities for the future of energy, FES 2022 presents four scenarios. The first axis is the "*Societal Change*," which combines engagement, innovation, and mandatory change. This axis remains consistent since FES 2020. The two scenarios presented along the Societal Change axis *are Consumer Transformation* and *System Transformation*. Consumer Transformation focuses on changing the way energy is used to achieve Net Zero by 2050, while System Transformation concentrates on changing the way energy is generated and supplied. The other two scenarios are *Falling Short* and *Leading the Way*. Falling Short has slowest decarbonization rate considered to be plausible, and it falls short of achieving Net Zero by 2050, but according to FES 2021 this scenario has accelerated. Leading the Way represents the fastest believable decarbonization rate, attained through a combination of consumer engagement, world-leading technology and policies, and investment, resulting in Great Britain’s reaching Net Zero before 2050. [45]

As seen in figure 3.4, there is a sketch of how each scenario is close to achieving net zero by 2050.

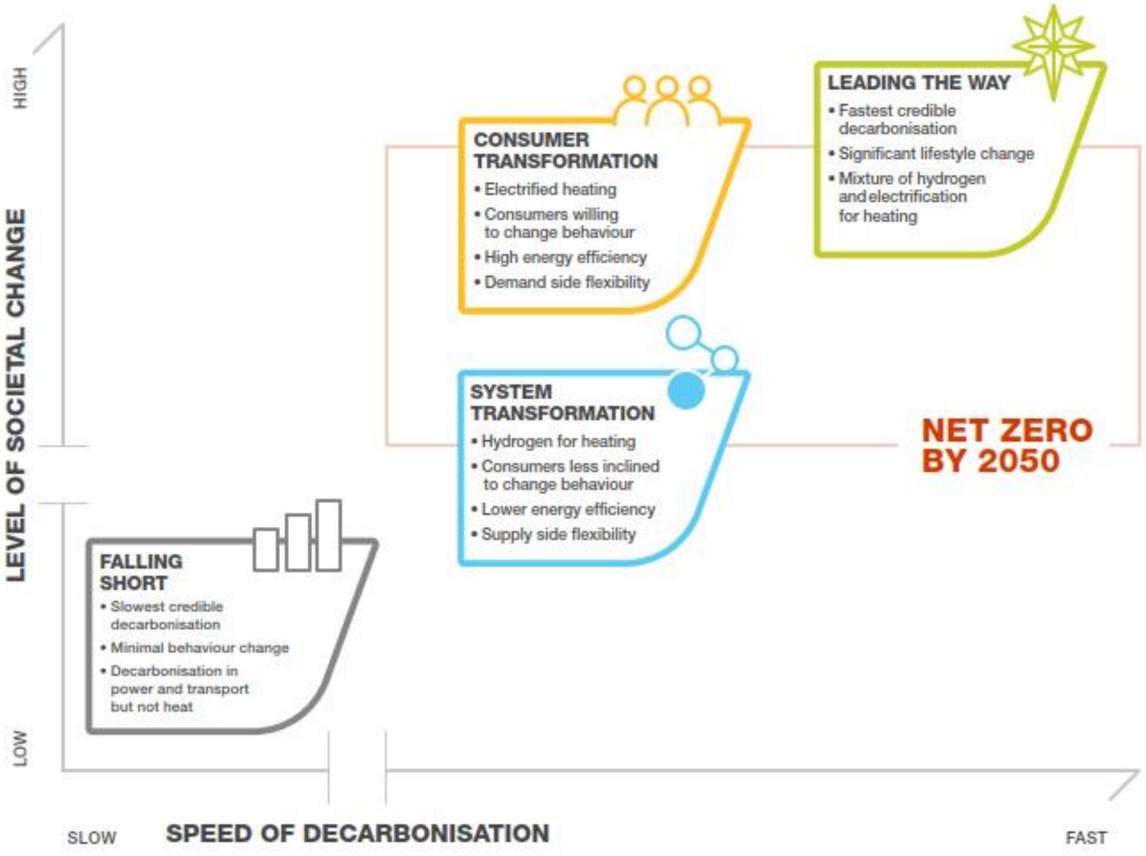


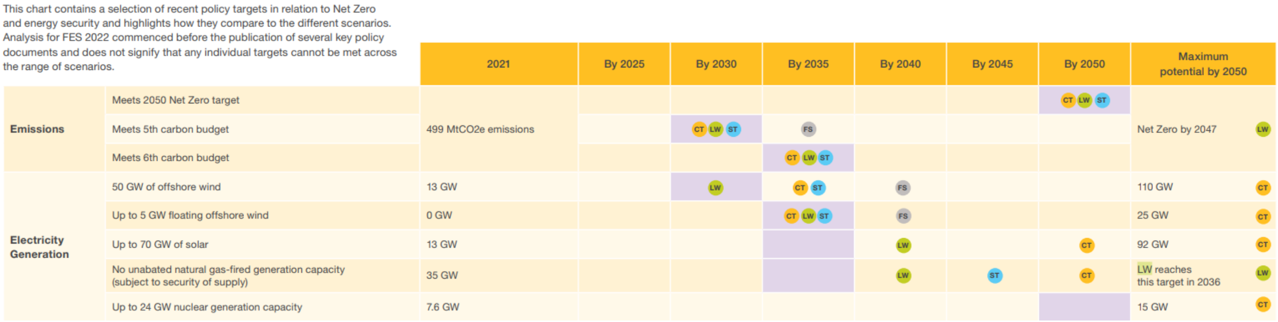
Figure 3.4: Location of each scenario in the decarbonization milestone. [45]

3.2.2.1 Wind Industry in the United Kingdom

The UK is making significant progress in the growth of wind capacity in all scenarios, with OW driving much of the increase. By 2030 and continuing into 2050, as seen in figure 3.5. The UK is well-positioned to take advantage of its vast potential for wind generation, but integrating this supply into the energy system requires improved flexibility and efficient generation sitting. The UK's target of achieving 25 GW of OW by 2050 in the Leading the Way scenario is very likely to be achieved, and the other Net Zero scenarios are not far behind. [45]

Even in the slowest decarbonizing scenario, Falling Short, a rapid and significant increase in wind capacity has been anticipated, which necessitates substantial network investment. Offshore generation requires infrastructure to bring power onshore and move it from coastal landing points to demand centers and one of the main challenges to overcome is the physical limitations, such as, for example, capacities of ports and installation fleet. The recent maximum number of installations nowadays is 4 turbines per day, but to achieve the United Kingdom's target 6 units are needed. The settled goal with all the scenarios can be seen in figure 3.6. [45]

The UK accounts for 45% of the total European OW developments and 24% of the total global OW development, with a stunning amount of 13.7 GW already commissioned and feeding the grids. The OW areas are spread across the whole territory and the distribution can be appreciated as seen in figure 3.13. and this figure includes future and operational developments. [49]



This chart contains a selection of recent policy targets in relation to Net Zero and energy security and highlights how they compare to the different scenarios. Analysis for FES 2022 commenced before the publication of several key policy documents and does not signify that any individual targets cannot be met across the range of scenarios.

		2021	By 2025	By 2030	By 2035	By 2040	By 2045	By 2050	Maximum potential by 2050
Emissions	Meets 2050 Net Zero target	499 MtCO2e emissions						CT LW ST	Net Zero by 2047 LW
	Meets 5th carbon budget			CT LW ST	FS				
	Meets 6th carbon budget				CT LW ST				
Electricity Generation	50 GW of offshore wind	13 GW		LW	CT ST	FS			110 GW CT
	Up to 5 GW floating offshore wind	0 GW			CT LW ST	FS			25 GW CT
	Up to 70 GW of solar	13 GW				LW		CT	92 GW CT
	No unabated natural gas-fired generation capacity (subject to security of supply)	35 GW				LW	ST	CT	LW reaches this target in 2036 LW
	Up to 24 GW nuclear generation capacity	7.6 GW							15 GW CT

Figure 3.5: Offshore Floating Wind Generation expectation by 2050. [45]

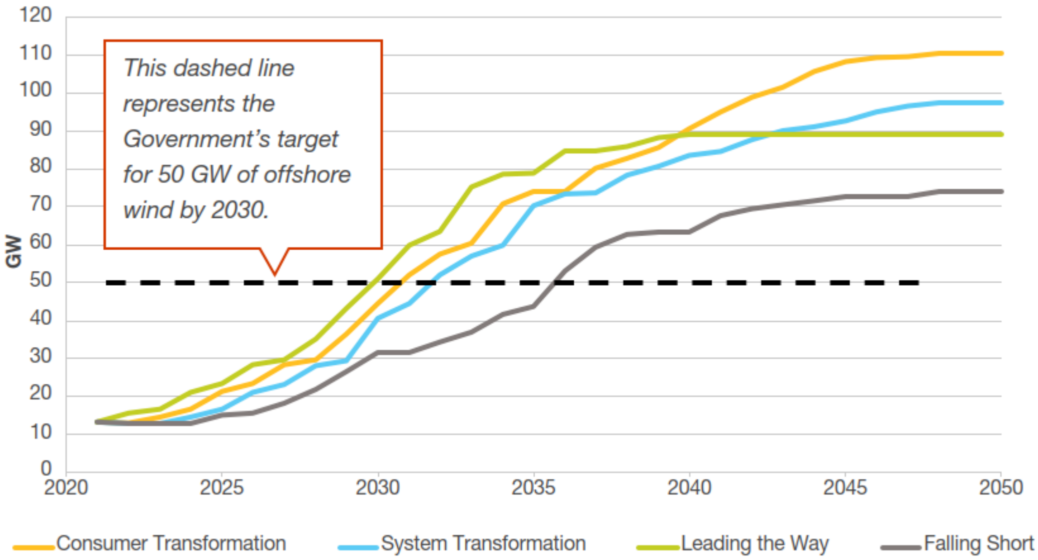


Figure 3.6: UK's Offshore Energy goal. [45]

3.2.3 Scotland

Scotland has significant potential for OW energy generation, and there are opportunities to extract substantial energy resources through it. However, a rise of OW power production in Scottish waters will need the execution of marine spatial planning at a national and local levels in pursuit of identify areas that are appropriate for OW projects. Offshore wind technology, including floating wind, has an opportunity to play a crucial part in the next-generation energy system of Scotland. Floating wind technology, which can be developed in deeper water, has the ability to contribute to the increasingly affordable OW energy supply. This technology is ideally adapted for Scotland's deeper waters and the vicinity of oil and gas infrastructure. [47]

Scotland has a potential of approximately 34 GW when taking into consideration latest leasing rounds, operational wind farms, under construction projects and recently awarded zones. The latest awarded sites conceived in *ScotWind* project, can be seen in table 3-3, this table contains some details about the future development in the awarded sites (originally 17 and the 3 latest added zones). A spatial planning of the other 13 zones applied in the latest leasing round *INTOG* (Innovation and Targeted Oil and gas), seen in figure 3.7. The blue striped zones describe the areas where projects targeting decarbonization from oil and gas projects will be considered, whereas the grey ones are not relevant. [46][49]

Table 3-3: ScotWind awarded sites characteristics and power capacities. [46]

Map reference	Name of the development	Substructure	Total capacity (MW)
1	**Morven**	Fixed	2,907
2	**Ossian**	Floating	2,610
3	**Bellrock**	Floating	1,200
4	**Campion Wind**	Floating	2,000
5	**Muir Mhor**	Floating	798
6	**Bowdun**	Fixed	1,008
7	**Ayre**	Floating	1,008
8	**Stomar**	Floating	1,000
9	**Caledonia**	Fixed	1,000
10	**Broadshore**	Floating	500
11	**Marram Wind**	Floating	3,000
12	**Buchan**	Floating	960
13	**West of Orkney**	Fixed	2,000
14	**Havbredey**	Floating	1,500
15	**Talisk**	Mixed	495
16	**Spiroad and Mara**	Fixed	840
17	**Machair Wind**	Fixed	2000
18	**Arven**	Floating	1800
19	**ScotWind**	Floating	500
	Total		27126

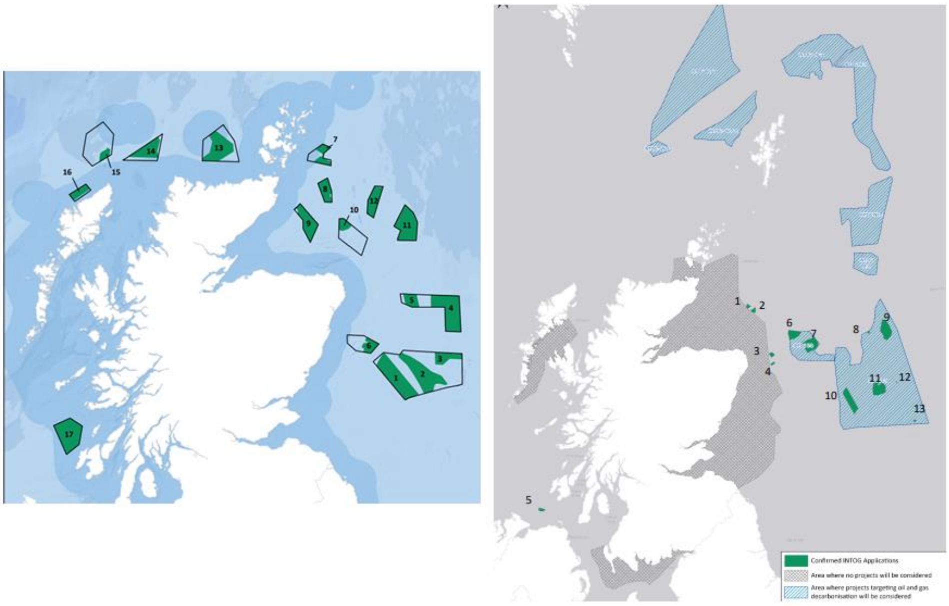


Figure 3.7: ScotWind awarded sites without the latest 3 zones (left), INTOG applications (right). [45][46]

Table A-1 in the Annex section shows other projects in Scotland in different statuses, either operational, under construction or consented, with a total energy production capacity of almost 6 GW. [47]

3.2.4 Wales

By end of 2017, Wales had a total of almost 70 power generation projects connected to the grid, along with roughly 60,000 decentralized sources, largely comprised of residential solar installations. The installed capacity in Wales was 13.2 GW, with the majority (95%) being generated by just 16 power plants that had a capacity of 50 MW or more. The majority (73%) of electricity generated in Wales comes from large fossil fuel plants, such as coal and gas, which account for almost two-thirds of installed capacity. In contrast, renewable generation is more widely dispersed, consisting of nearly 23% of installed capacity and 20% of overall generation. To achieve its goal of generating 70% of its electricity from renewable sources by 2030, Wales will need to generate between 10.1 - 10.6 TWh, based on an estimated electricity demand of 14.4 - 15.1 TWh by 2030. Offshore wind power is a highly scalable renewable energy technology that could be instrumental in helping Wales meet this goal, as modern wind farms can exceed 1 GW of installed capacity. Assuming a higher load factor of 45-50% in modern offshore wind farms, the capacity gap could be reduced to 1.1-1.2 GW from 1.6 -1.8 GW extra power generation needed after decommissioning some renewable projects by 2030 due to the end of the useful life of those assets. As seen in table 3-4 the power generation expectation by 2030 for Wales comes mostly by wind power, first onshore and then offshore. [50]

Table 3-4: Power production in Wales by 2030 [50]

Source	**Operational in 2017**	**Decommissioned by 2030**	**Operational by 2030**
	Capacity (GW)	**Capacity (GW)**	**Capacity (GW)**
Biomass	0.11	-	0.11
Hydro	0.18	-	0.18
Offshore Wind	0.73	0.06	0.67
Onshore Wind	1.00	0.14	0.86
Solar	0.97	-	0.97

In the years preceding 2050, the current fleet of power generation assets will reach the end of their useful lives, demanding the installation of new capacity via repowering, lifecycle extension, and new plants. Although decentralized generation is anticipated to increase, large facilities connected to the transmission network will continue to play a significant role in the generation of electricity. To meet this demand, renewable energy sources that are scalable, especially OW power, will be essential. As seen in figure 3.8 and table 3-5, at present, there are three operating wind farms in Wales, North Hoyle, Rhyl Flats, and Gwynt-y-Môr, all of which are situated in the Irish Sea off North Wales and contribute around 10 percent of the United Kingdom's OW capacity, approximately 726MW of installed capacity as seen in table A-2 in the annex section. However, the relative proportion of OW in Wales is anticipated to decline in future years, as the vast majority of the United Kingdom's current development initiatives take place outside of Wales. This may hinder Wales of the economic, social, and environmental benefits that OW can bring to the United Kingdom.[50]

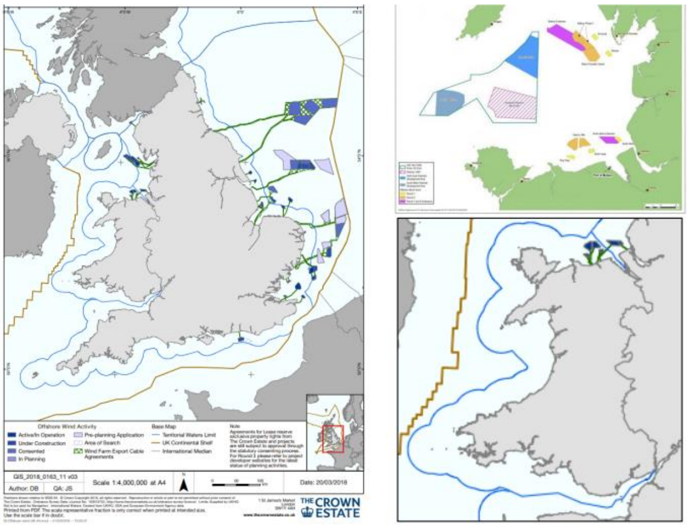


Figure 3.8: Offshore wind in the UK and Wales. [50]

For the future of offshore wind in Wales waters, the Crown Estate put out a call in February 2017 for developers to expand existing operational wind farms in UK waters, limiting additional capacity to the currently installed capacity of each wind farm. Eight UK wind farms, including the Gwynt-y-Môr wind farm off North Wales, submitted applications for a total of 3.4 GW of capacity by the May 2018 deadline, meeting The Crown Estate's application criteria. The proposed extension projects have now been accepted and will undergo a Habitats Regulations Assessment at the plan level to determine any potential impacts on relevant nature conservation sites. To utilize Wales's offshore wind opportunity, it will be essential to set up floating foundations in deep water areas. Wales possesses significant wind resources in the deep waters of Pembrokeshire and in some pockets of deep water in the northwest region. However, the present technology for deep water concept utilizing floating foundations is not sufficiently developed or cost-effective to be included in the upcoming Crown Estate licensing rounds. Future leasing cycles, however, might require the use of floating technologies with the aim of establish a pipeline able to reach the UK industry's 50 GW by 2050 target after 2030. In figure 3.9 it is possible to see the water depths favoring floating concepts. [50]

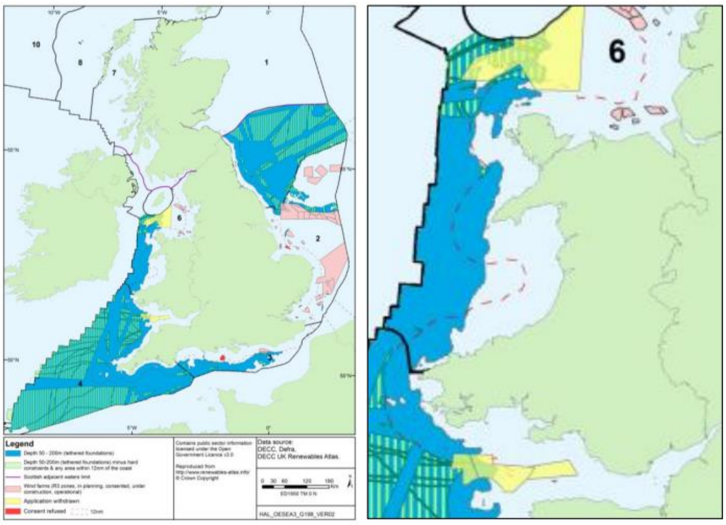


Figure 3.9: Blue color denotes depths of 50-200m, showing availability for OFWT [50]

The latest project to submit a consent application was the Awel y Môr wind farm. This project consists of a wind park estimated to produce approximately 1100MW using fixed substructure wind turbines. The park will be located 10.5 Km off from the North Wales coast, closely located between Gwynt-y-Môr and Rhyl Flats wind farms, as seen in figure 3.10. [48] [83]

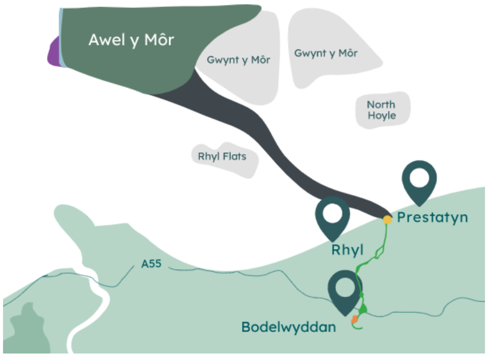


Figure 3.10: Awel y Môr Wind farm location [83]

Whereas in the Celtic Sea region, South of Wales, the Crown State has designated 4GW of FOWT by 2035, in 5 areas. The process of defining these areas goes as follows, every time a new zone is announced to be exploited with FOWT farms it is necessary to *refine* them to avoid conflict with other users of the sea, as for example, fisheries, defense and military, navigation and in some cases even civil aviation. Which means that at the beginning an *Area of search* (which is the area that represents potential for FOW development) will be discussed with representatives of the other organizations to redefine a convenient delimitation of the zone for every user. As seen in figure 3.11, the result of the refining process is the grey area, contained in the colored zone, where areas (a) and (c) are located within Welsh territorial sea and are expected to be floating wind farms. The rest of the areas belong to English waters and will be listed in the English section. [84] [85]

See Table 3-5 as a reference for future projects in planning phase or under HRA (*Habitats Regulations Assessments)* condition in Wales.

Table 3-5: Future projects in Wales [48] [49] [84]

Project Name	Power Capacity (MW)	Substructure	Status
Llŷr 1	100	Floating	HRA
Llŷr 2	100	Floating	HRA
White Cross	100	Floating	HRA
Gwynt Glas	1000	Floating	Concept Early Planning
Petroc	300	Floating	Concept Early Planning
Llywelyn	300	Floating	Concept Early Planning
Valorous	300	Floating	Concept Early Planning
Awel y Môr	300-1100	Fixed	Concept Early Planning
Celtic Sea A	1000	Floating	Development Zone
Celtic Sea C	1000	Floating	Development Zone
Total	Approx. 4500 MW		

Figure 3.11: Celtic Sea spatial planning. [84]

3.2.5 England

Various OW farms development initiatives are currently in the Agreement for Lease (AfL) phase. This gives developers an option on a seabed geographical region for offshore wind growth and development. Prior to the start of construction and lease entry, developers complete essential tasks such as ensuring grid connections, performing environmental and technical research, obtaining consents, and acquiring contracts with the supply chain as well as financing during the AfL phase. In 2022 and 2023, despite a competitive supply chain and an uncertain economic situation, developers worked tirelessly to meet government project completion deadlines. Consent issues, including compensation measures within the Habitats Regulations, must be addressed through collaborative and proactive strategies between industry and government. Six Round 4 offshore wind farms projects were added to AfL at the beginning of 2023. Six Round 3 projects continue in AfL, with three receiving a Contract for Difference (CfD): Hornsea 3, Norfolk Boreas, and East Anglia THREE. The Secretary of State issued a Development Consent Order to Norfolk Vanguard, while legal challenges filed on the Development Consent Orders of East Anglia ONE North and East Anglia TWO. In the case of England, up until December 2022 this country had in its territorial waters approximately 41 wind farms all along its coast from which there is almost 11 GW of already installed or under construction projects, see table A-3. As seen in figure 3.12, 41 wind projects were in either operational stage or under construction. Except for the case of 4 offshore wind projects such as *Wave Hub, East Anglia Three, Norfolk Boreas and Hornsea 3* which offers were supported by the government, meaning that a CfD or *Contract for Difference* was secured. Table 3-6 contains details about future projects for England CfD awarded projects.[49]

Table 3-6: England Offshore with CfD granted. [49]

Area Tag	Project Name	Power Capacity (MW)	Status
51	**East Anglia THREE**	1480	CfD Secured
53	**Hornsea 3**	3000	CfD Secured
56	**Norfolk Boreas**	1800	CfD Secured
57	**Wave Hub**	30	CfD Secured

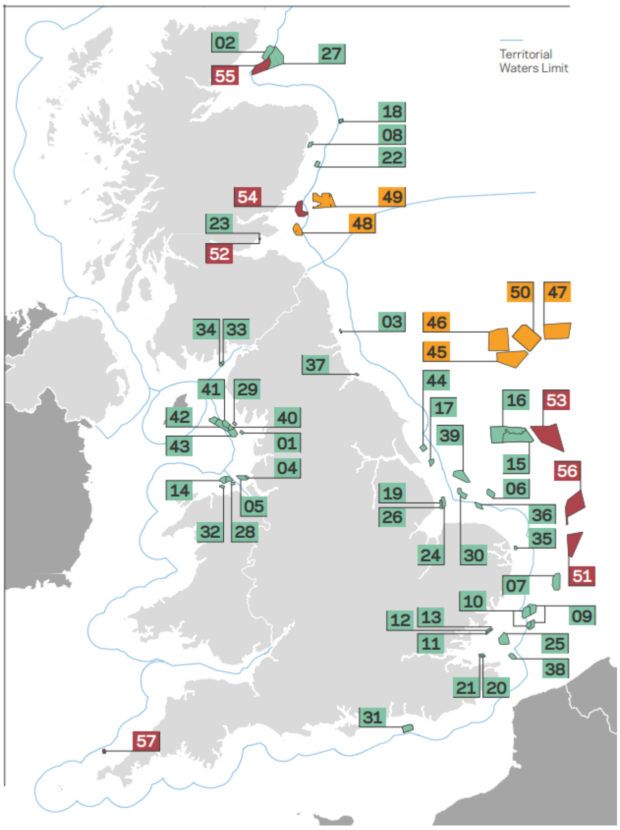


Figure 3.12: Current Offshore Wind Projects as for 31/12/2022. [49]

As for future developments, almost 20 new wind projects are expected to be developed in English waters only, with approximately 18 GW capacity. There are almost 50 new projects across the whole United Kingdom for a total of 50.5 GW extra from the already existent wind power production, excluding projects from north Ireland that will be explained in the next section. See figure table 3-7. The *Consented* status correspond to those projects in that have received consent from the government but do not have yet a CfD, the *In Planning status* corresponds to those projects where the consent application has been sent, and the *Pre-planning* status comprises all those wind farms where the consent application has not been submitted yet. [49]

Table 3-7: England's Future offshore wind projects. [49] [84]

Area Tag	Project Name	Power Capacity (MW)	Substructure	Status
02	**East Anglia ONE North**	950	Fixed	Consented
03	**East Anglia TWO**	980	Fixed	Consented
04	**Norfolk Vanguard East**	900	Fixed	Consented
05	**Norfolk Vanguard West**	900	Fixed	Consented
10	**Dudgeon Extension**	402	Fixed	In planning
12	**Hornsea 4**	2700	Fixed	In planning
14	**Sheringham Shoal Extension**	317	Fixed	In planning
23	**Dogger Bank South (East)**	1500	Fixed	Pre- Planning
24	**Dogger Bank South (West)**	1500	Fixed	Pre- Planning
25	**Five Estuaries**	353	Fixed	Pre- Planning
29	**Mona**	1500	Fixed	Pre- Planning
30	**Morecambe**	480	Fixed	Pre- Planning
31	**Morgan**	1500	Fixed	Pre- Planning
34	**North Falls**	504	Fixed	Pre- Planning
36	**Outer Dowsing**	1500	Fixed	Pre- Planning
37	**Rampion 2 (Rampion Extension)**	400	Fixed	Pre- Planning
38	**Rampion 2**	800	Fixed	Pre-Planning
	Total	17186 MW		

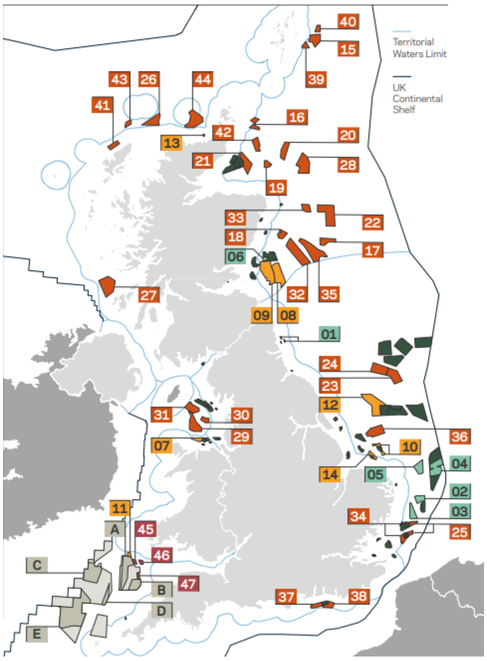


Figure 3.13: 2022 Situation of Offshore Wind in the UK. [49]

3.2.6 Northern Ireland

Northern Ireland has been making major progress in generating energy from renewable sources, especially wind, which accounts for 45 % of its total electricity consumption. However, the remainder, or 55%, continues to be obtained from fossil fuels, which dominate the heating and transportation sectors of the energy system. Northern Ireland wants to develop the installation and utilization of a variety of low-carbon technologies over the next ten years with the intention of addressing this situation. Northern Ireland anticipates that some technologies, such as electrolyzers, floating OW, and carbon capture and storage, will become advanced and affordable over the coming years, despite the uncertainty related to the future equilibrium of existing and coming energy sources and technologies. To diversify its blend of renewable technologies, Northern Ireland plans to prioritize marine technologies, notably offshore wind. The objective is to attract potential investors in offshore and marine ventures in Northern Irish waters by enabling pre-commercial tests and demonstration venues in the 2020s. While doing so, Northern Ireland intends to attain commercialization by or before the beginning of the 2030s. [51]

Northern Ireland has conceived 4 wind farms as seen in figure 3.14, all currently in early planning stage, three different developers participate in the offshore wind pipeline in this region of the North Channel and the Irish Sea. In 2022 the company SBG (*Simply Blue Group)*, an Irish developer specializing in floating offshore wind, wave power, and minimally disruptive aquaculture has announced a second offshore wind project over Northern Ireland. *Olympic Offshore* (d) will have a sister project, *Nomadic Offshore Wind* (a), that was announced previously in the year. Along the coast of Northern Ireland, the Olympic Offshore and the project will have a power output of up to 1.3 GW, whereas Nomadic Offshore Wind will have 0.5 GW. The project is intended to be developed in phases using a concept that SBG has already implemented in other projects. In addition, the initiative will provide opportunities for Northern Ireland's regional supply chain to develop and plan for commercial scale offshore possibilities. Nomadic project starts in 2021 and it is expected to be operational in 2030. [48] [52] [54]

The other 2 wind farms belong to the North Channel Wind venture, which is being developed together by SBM Offshore and NMK Renewables. SBM Offshore is a market leader in floating offshore solutions, including a TLP foundation used in floating offshore wind. Meanwhile, NMK Renewables is a specialist project development firm focused on bringing OFW projects to reality in the United Kingdom and Ireland. One of them is called *North Channel Wind 1* (b) and the other one *North Channel Wind 2* (c) both are in the early planning stage which helps to characterize and optimize the whole layout of both offshore floating projects. Projects are expected to be operational by 2030, according to figure 3.15. Table 3-8 contains details about the projects in Northern Ireland Pipeline. [53] [55]

Table 3-8: Specifications of Northern Ireland Offshore Wind projects. [52] [53] [56]

Name of the development	Distance to shore (Km)	Capacity (MW)	Depth (m) (mean sea level is 0)	Status
North Channel Wind 1	9	1000	-315 − -422	Early Planning
North Channel Wind 2	15	420	-387 − -406	Early Planning
Olympic Offshore	-	1300	-83− -118	Early Planning

Nomadic Offshore	35	500	-164 − 220	Early Planning

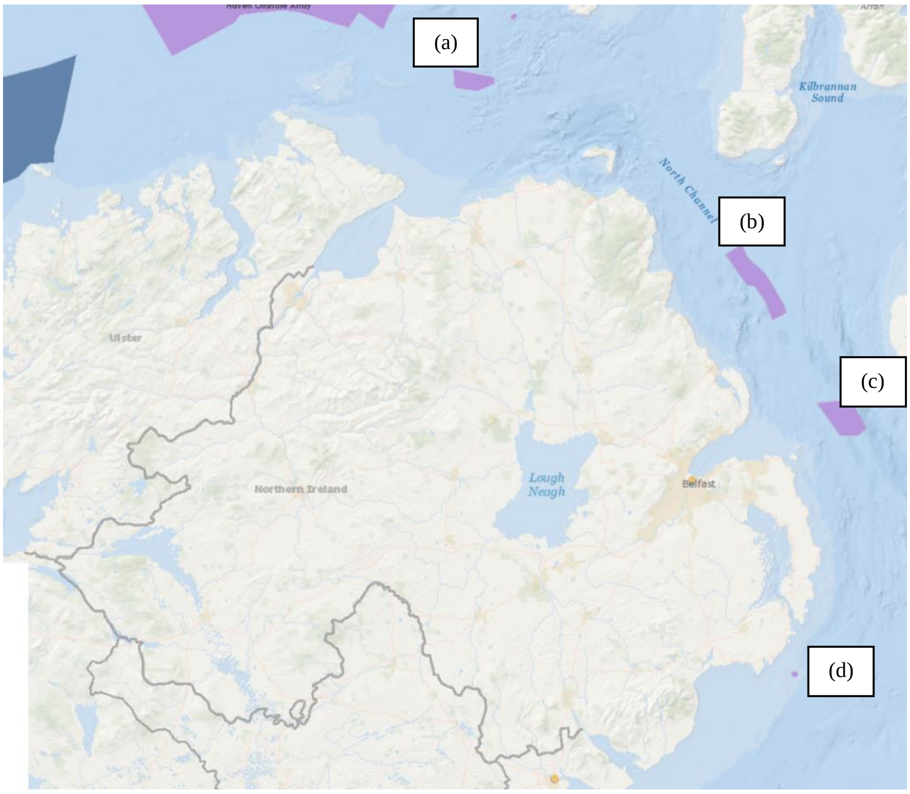


Figure 3.14: Northern Ireland Offshore Wind Projects. [48]

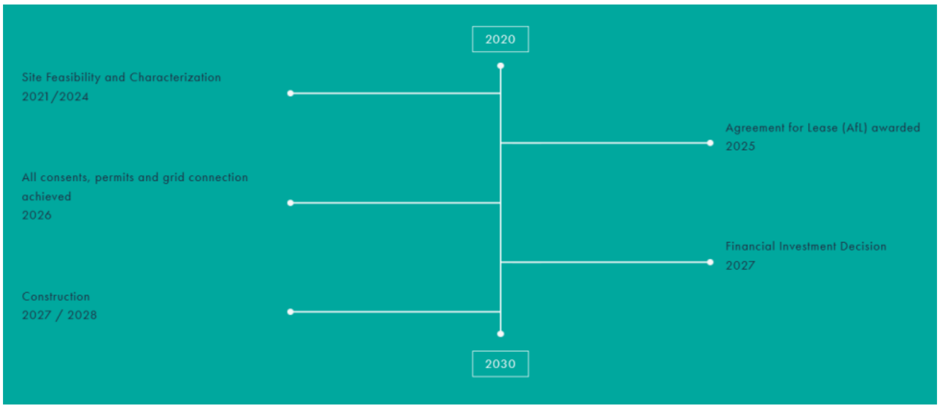
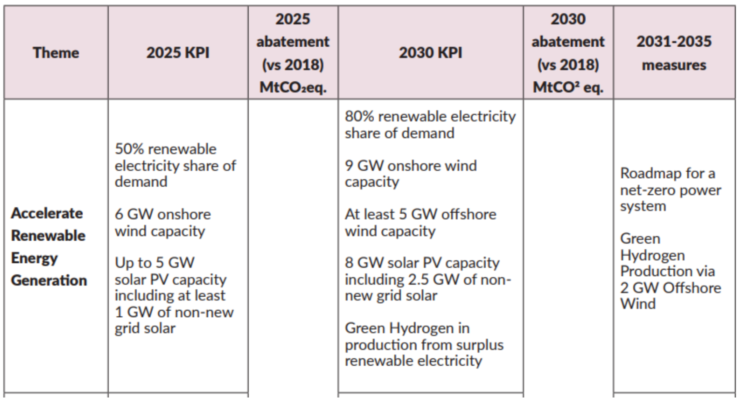


Figure 3.15: Timeline of North Channel Wind, construction expected in 2027. [55]

3.2.7 Ireland

Ireland has a duty under the Climate Action and Low Carbon Development (Amendment) Act 2021 to attain a climate-neutral, ecologically sustainable, and ecosystems-rich economy by the year 2050. Furthermore, the Act requires Ireland to reduce its emissions of greenhouse gases (GHG) by 51% by 2030, compared to 2018 levels, in accordance with Ireland's Paris Agreement commitments and the European Union's goal of decreasing GHG emissions by as much as 55% by 2030, based on the levels of 1990, and attaining climate neutrality by the year 2050. The National Development Plan (NDP) for the period 2021-2030 establishes investment priorities totaling around €165 billion, with the goal of matching the Government's climate targets and serving as the cornerstone for the National Planning Framework. To fulfill the sectoral emissions targets, a considerable shift in climate action is required, which will need rapid implementation of upcoming technologies and fuels, as well as a shift in consumer attitudes. It is predicted that 22 GW of renewable energy capacity would be required by 2030 to satisfy the emissions route compatible with the sectoral emissions limitations. The goal is to raise onshore wind to 9 GW, solar energy production to 8 GW, and offshore wind to at least 7 GW (2 GW particularly dedicated to green hydrogen generation). Figure 3.16 explains Ireland's government expectations up to 2035. [57]

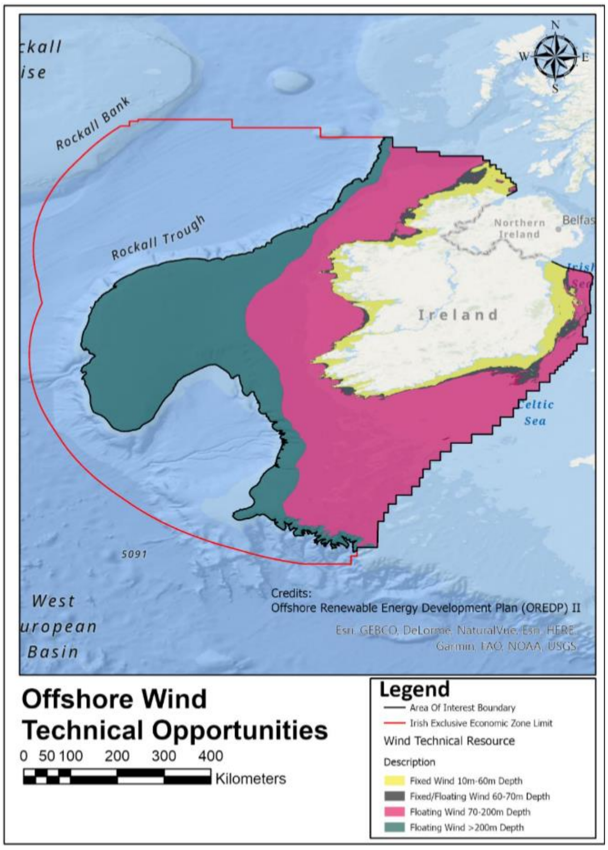
And by 2050 it is expected to install at least 37 GW of OW considering fix and floating substructures. [105]



Theme	2025 KPI	2025 abatement (vs 2018) $MtCO_2eq.$	2030 KPI	2030 abatement (vs 2018) $MtCO^2$ eq.	2031-2035 measures
Accelerate Renewable Energy Generation	50% renewable electricity share of demand 6 GW onshore wind capacity Up to 5 GW solar PV capacity including at least 1 GW of non-new grid solar		80% renewable electricity share of demand 9 GW onshore wind capacity At least 5 GW offshore wind capacity 8 GW solar PV capacity including 2.5 GW of non-new grid solar Green Hydrogen in production from surplus renewable electricity		Roadmap for a net-zero power system Green Hydrogen Production via 2 GW Offshore Wind

Figure 3.16: Ireland's Key Performance Indicators from 2025 to 2035. [57]

Ireland has enormous potential for both offshore wind developments, either fixed or floating, The OREDP II (*Offshore Renewable Energy Development Plan II)* draft report estimates that in the Ireland`s territorial waters, (see figure 3.17) Offshore Wind for fixed substructures can be developed up to 62 GW along Irelands coasts whereas offshore can attain an amazing amount of 579 GW (assuming 15 MW wind turbines according to this study). The reason of this huge increase in predicted power output is because the first report for offshore wind forecast, the OREDP I, accounted for 5 MW wind turbines only, and when the size of the wind turbines increases up to 15 MW so does the wind speed, because the nacelle can be located a higher point. Table 3-9 contains OREDP II estimations. [58]



Credits:
Offshore Renewable Energy Development Plan (OREDP) II
Esri, GEBCO, DeLorme, NaturalVue, Esri, HERE, Garmin, FAO, NOAA, USGS

Figure 3.17: OREDP II Offshore Wind Estimation for future developments. [58]

Table 3-9: Technical Wind Potential [58]

	Water Depth (m)	Gross technical Capacity (GW)	Energy potential (TWh/year)
Bottom Fixed	10 – 60	42	170
	60 – 70	20	83
Total		62	253
Floating Wind	60 – 70	20	83
	70 – 200	331	1334
	200 – 1000	246	1065
Total		579	2482

This Initiative already has an application in real offshore development zones as seen in figure 3.18. and some of the wind farms already conceived in concept planning phase can be seen in table 3-10.

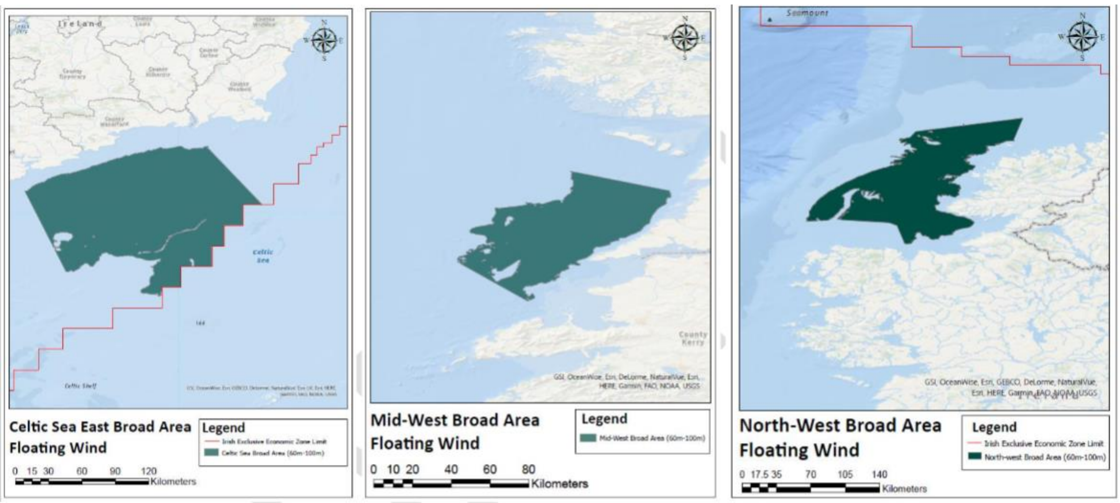


Figure 3.18: Ireland's Broad areas of interest. [58]

Table 3-10: Some Offshore Wind Projects in Early planning phase. [48] [59] [60] [61]

Name	Capacity (MW)	Foundation type	Status
Blackwater	1500	Floating	Early Planning
Celtic Horizon	700	Floating	Early Planning
Dylan	300	Floating	Early Planning
Dylan Extension	1000	Floating	Early Planning
Wexford	2500	Fixed	Early Planning
East Celtic	900	Fixed	Early Planning
Helvick Head	800	Fixed	Early Planning
Péarla Offshore Wind Farm	1680	Floating	Early Planning
Inis Ealga Marine Energy Park	1000	Floating	Early Planning
Voyage Offshore Array	2900	Floating	Early Planning
Emerald	1300	Floating	Early Planning
Kinsale	1000	Not specified	Early Planning
Bore Array OWF	500	Not specified	Early Planning
Tulca Offshore Array (Phase 1)	1650	Floating	Early Planning
Cork Offshore Wind	1000	Floating	Early Planning
Valentia	920	Floating	Early Planning
Valentia (Phase 2)	620	Floating	Early Planning
Rian Offshore Array (Phase 1)	2500	Floating	Early Planning
Clarus	1000	Floating	Early Planning
Western Star Floating	1350	Floating	Early Planning
Inis Offshore Wind Kerry	1000	Fixed	Early Planning
Munster Sea Wind	1000	Floating	Early Planning
Sceirde (Skerd) Rocks	450	Fixed	Early Planning
ANIAR Offshore Array - phase 1	500	Mixed	Early Planning
ANIAR Offshore Array (Phase 2)	500	Mixed	Early Planning
Arranmore Wind	1000	Floating	Early Planning
Total	30720 MW	(20420 MW for Floating concepts)	

Nevertheless, there are also other projects in early planning phase not only granted in those areas. As seen in figure 3.19, to the west of the country, in the Irish Sea, there are also projects in Early Planning phase. Due to the proximity to the coast and water depths, most of them are fixed OWT, hence, not relevant for this study.

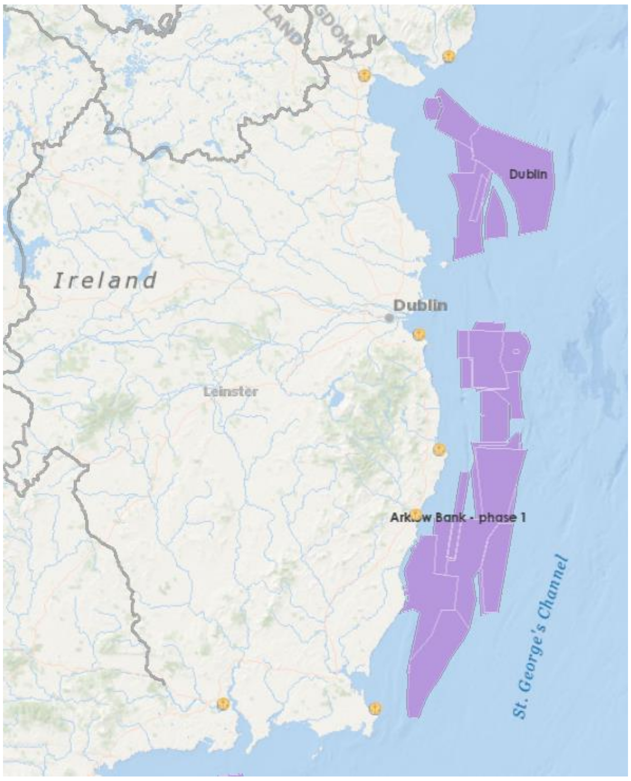


Figure 3.19: Ireland’s West coast Offshore Wind Projects. [48]

3.2.8 Denmark

Denmark was the first nation in the world to establish an offshore wind farm, the *Vindeby OFW farm*, consisting of 11 x 450 kW turbines, in 1991. The major goal of the wind farm was to show the possibility of building turbines in the more difficult offshore environment, as well as to demonstrate their financial viability in terms of electricity generation. The wind farm was successfully operational for 25 years until its decommissioning in 2017. Following the success of Vindeby, project developers were encouraged to launch more small-scale demonstration projects and ended up forming associations nowadays known as *energy cooperatives*. In 1998, the Danish government reached a settlement with the two main power providers to carry out large-scale offshore wind demonstration operations. The goal was to investigate the financial, technological, and environmental implications of offshore development and to hasten its progress. This effort resulted in the development and building of two of the biggest OW farms at the time; the Horns Rev I in 2002 with a capacity of 160 MW, and Nysted, in 2003 with a capacity of 165.6 MW. These activities also prepared the groundwork for MSP (Maritime Spatial Planning) for offshore wind in Danish seas, as well as research into its impact on marine life. [62]

According to a study carried out by the Danish Energy Agency in 2022 states that Denmark could grow into an important net exporter of offshore wind energy by 2050 once that 10-15% of the total North Sea build-out takes place in designated renewable energy development areas. This equates to 25-35 GW of added capacity, including current offshore wind farms, and would be cost-effective. The research is based on estimates of the technical feasibility and expected costs of the construction and operation of offshore wind farms, which consider factors such as water depths, distances to places where power can be transported onshore, and local wind speeds. As seen in figure 3.20. Denmark accounts for ideal conditions for offshore wind developments (mostly bottom fixed) considering wind speeds and *LCoE* (*Levelized Costs of Electricity*).[63]

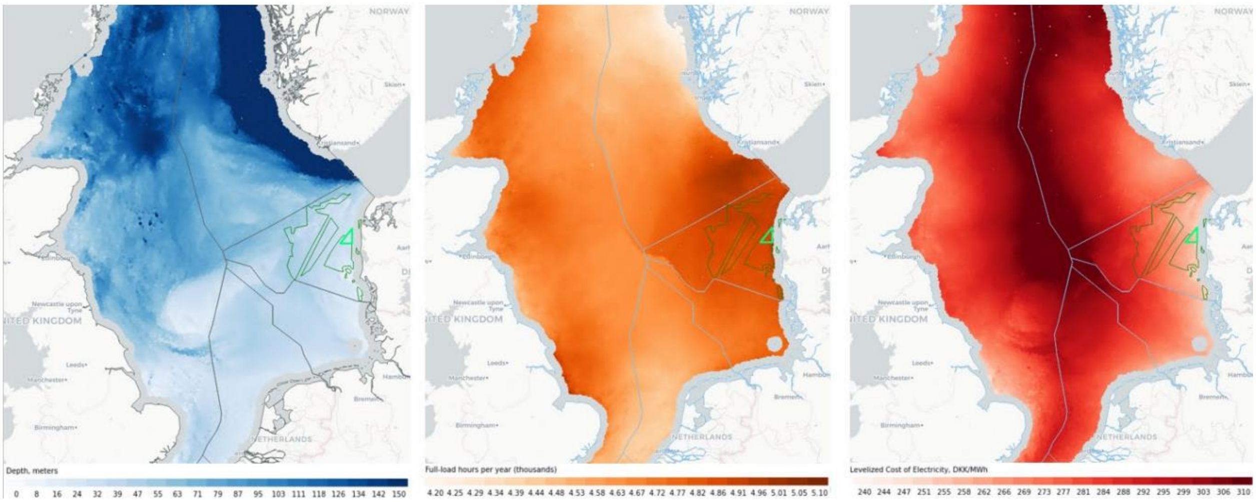


Figure 3.20: Water depth, Full load hours per year, and LCoE in Denmark's waters. [63]

In figure 3.21 is possible to appreciate the delimitation where Denmark's government estimates to develop offshore wind project farms while table 3-11 contains the details of some of the windfarms in planning phase (since most of them are bottom fixed and non-relevant for this study), refer to table A-4 to see fully commissioned/ Under construction projects with a total installed capacity of 2652.8 MW. [62]

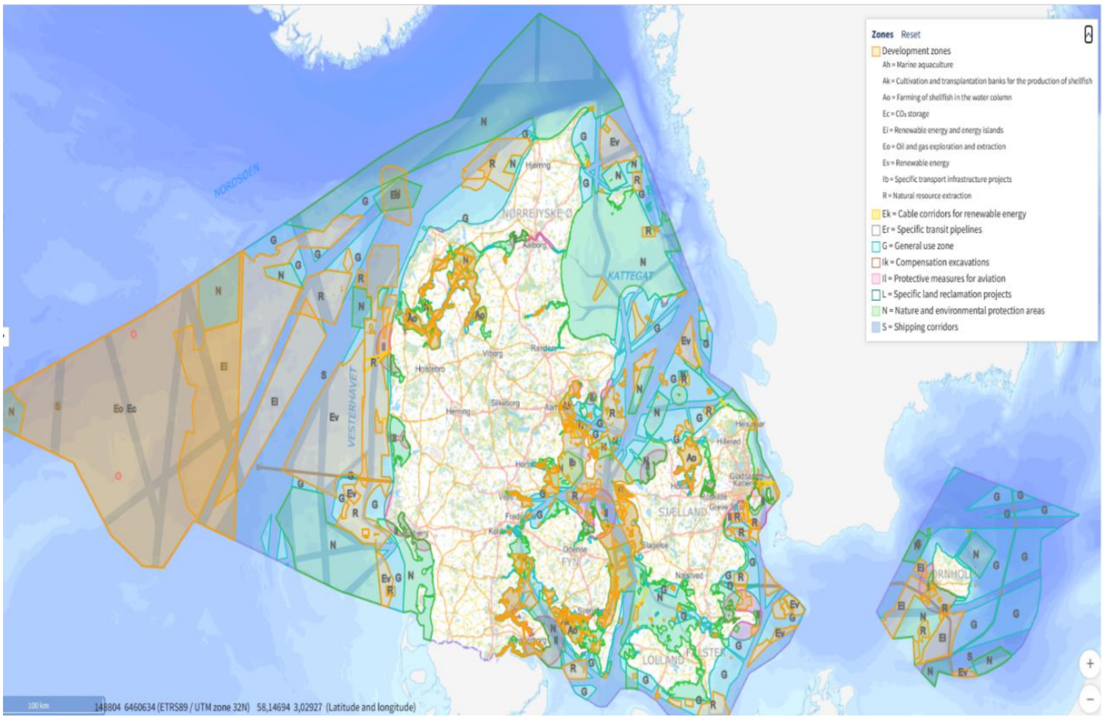


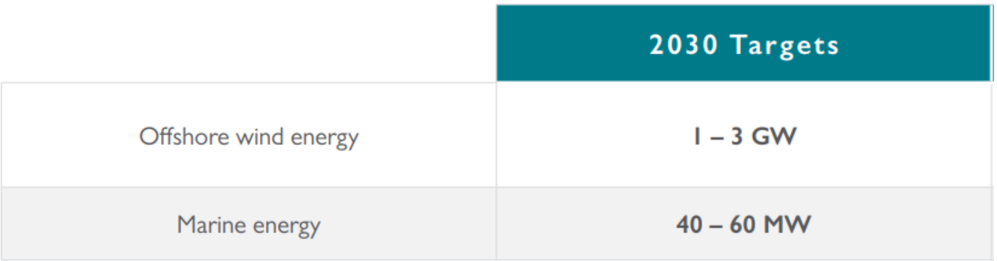
Figure 3.21: Denmark's maritime plan [64]

Table 3-11: Some of Denmark's Offshore Wind farms, in planning phase. [48]

Name	Capacity (MW)	Substructure	Status
Vindeby	4.95	Fixed	Development Zone
Bornholm I Nord	950	Fixed	Development Zone
Bornholm II	1900	Fixed	Development Zone
Hesselø	1200	Fixed	Development Zone
Kattegat II	495	Fixed	Development Zone
Danish Kriegers Flak II	1005	Fixed	Development Zone
Nordsøen	3015	Fixed	Development Zone
KadetBanke	500	Fixed	Early Planning
Paludan Flak	280	Fixed	Early Planning
Bornholm	100	Fixed	Early Planning
Bornholm I Syd	950	Fixed	Development Zone
Hesselø Nedskaleret	1005	Fixed	Development Zone
Lolland Syd	260	Fixed	Early Planning
Vikinge Banke	1140	Fixed	Early Planning
Odin	2250	Fixed	Early Planning
Thybo	4000	Fixed	Early Planning
Freya	1500	Fixed	Early Planning
Jyske Banke Nord	1040	Fixed	Early Planning
Thybo II	1760	Fixed	Early Planning
Hanstholm Syd	500	Fixed	Early Planning
Bøchers Banke	1102.5	Not specified	Early Planning
Læsø	540	Fixed	Early Planning
Gjerrild Bugt	400	Fixed	Early Planning
Norddjurs	650	Fixed	Early Planning
Thor	1000	Fixed	Early Planning
Stokkebro	210	Fixed	Early Planning
Gilleleje	210	Fixed	Early Planning
Bornholm Bassin Øst	1500	Floating	Early Planning
Bornholm Bassin Syd	1500	Not specified	Early Planning
Frederikshavn Nord	500	Fixed	Early Planning
Grenå	315	Fixed	Early Planning
Lysegrund	550	Fixed	Early Planning
Stevns Nord	350	Fixed	Early Planning
Guldborgsund	500	Fixed	Early Planning
Rømø	500	Fixed	Early Planning
Klintebjerg	585	Fixed	Early Planning
Sønderbjerg	285	Not specified	Early Planning

3.2.9 Spain

The *INECP* (*Integrated National Energy and Climate Plan*) 2021-2030, or *PNIEC* in Spanish, aims to attain an average of 42% renewable energy consumption and up to 74% in the power sector. The plan contains objectives for energy efficiency objectives and intends to generate about 59 GW of extra renewable power over the next decade. The plan explicitly calls for an expansion in wind power capacity of 25.7 GW (current wind power capacity) and 80 MW in other technologies, e.g., marine energy. In the case of offshore wind power, it should be emphasized that the reduction of its generation costs already indicates a significant potential in Spain with floating technology in the 2030 horizon, implying that the mechanisms to encourage it should be tailored to its increasing levels of competitiveness. The total floating offshore contribution by 2030 is expected to range between 1 GW – 3 GW by 2030 as seen in figure 3.22. [65]



	2030 Targets
Offshore wind energy	**1 – 3 GW**
Marine energy	**40 – 60 MW**

Figure 3.22: Spain’s FOW farms contribution by 2030. [65]

By 2050, according to a report made by the Eolic Business Association, (*EAA* in Spanish) Spain will have a potential to develop up to 17GW of Offshore Wind, as a result of the consolidation of this market in terms of competitiveness, being a considerable source to boost the Spanish economy. [86]

In terms of synergies with other important industries such as naval construction, civil engineering, and the maritime-port industry, offshore wind energy in Spain represents a potential market for these sectors in terms of diversification, many Spanish enterprises have played an important part in developing offshore wind farms around Europe, and they are at the vanguard of delivering the continent's first floating wind turbine arrays. Currently, Spain is the leading provider of floating foundations. Spain's geographical location, extensive shoreline, different maritime regimes, and significant technological position make it suitable for developing, testing, and demonstrating innovative offshore wind prototypes and technological solutions, notably floating technology. Table 3-12 contains floating projects mostly around Canary Islands due to its water depths characteristics as seen in figure 3.23. [65]

Table 3-12: Spain Projects in Canary Islands. [48][67][68][69][70][71][72][73]

Name	Capacity (MW)	Foundation Type	Status
PLOCAN Hybrid Floating Wind Platform	2	Floating	Early Planning
Nordes Phase 1	525	Floating	Early Planning
Nordes Phase 2	10	Floating	Early Planning
Medfloat Pilot Parc	50	Floating	Early Planning
Granadilla	50	Floating	Early Planning
Nautilus Demonstration	2	Floating	Early Planning
Floating Power Plant - PLOCAN	8	Floating	Early Planning
Parc Tramuntana	500	Floating	Early Planning
Floating Offshore Wind Canarias (FOWCA)	225	Floating	Early Planning
Mar De Agata	300	Floating	Early Planning
GOFIO	50	Floating	Early Planning
DUNAS	50	Floating	Early Planning
MOJO	50	Floating	Early Planning
Pe San Agustin I	50	Floating	Early Planning
Salinas I	50	Floating	Early Planning
Canarray II	132	Floating	Early Planning
Gran Canaria Este	144	Floating	Early Planning
Canawind	250	Floating	Early Planning
Tarahal	225	Floating	Early Planning
Maresía	254	Floating	Early Planning
FOWCA	225	Floating	Early Planning
Canawind I	250	Floating	Early Planning
CARDON	50	Floating	Early Planning
Mencei	150	Floating	Early Planning
GUANCHE	50	Floating	Early Planning
Total	3652 MW		

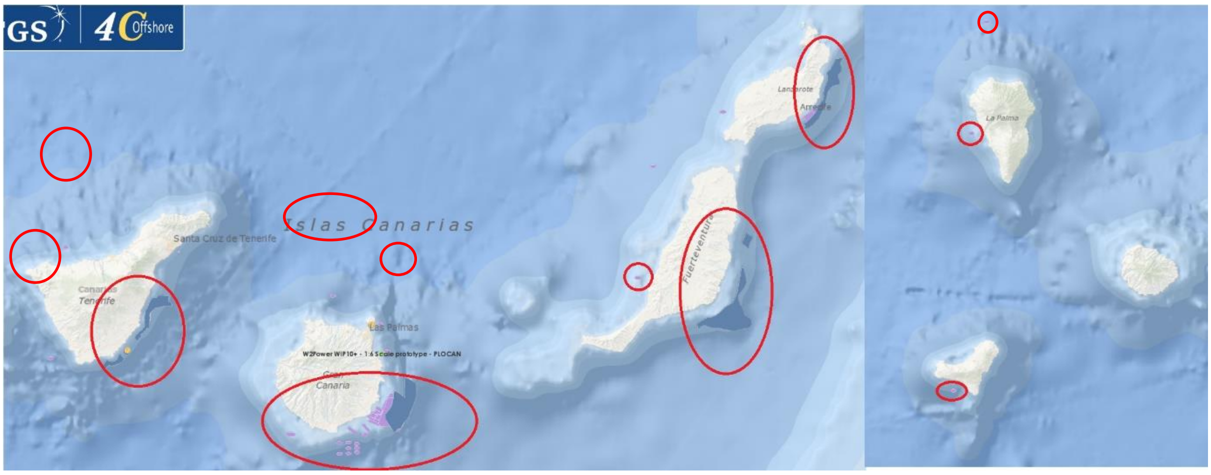


Figure 3.23: Offshore wind farms display in Canary Islands. [48]

Spain is one of the richest countries in the EU in terms of marine biodiversity, and it has made tremendous gains in increasing its understanding. Spain aspires to be a leader in ocean preservation and conservation, with over 11,000 species and a considerable presence of maritime ecosystems of Community interest. This goal has been demonstrated in its involvement in the Global Ocean Alliance and High Ambition Coalition, both of which advocate for the protection of 30% of the world's sea surface, which is why Spain has several areas dedicated to the protection of the marine environment within relatively close zones to shore as seen in figure 3.24 and 3.25, where the red zones imply forbidden areas to any kind of development, the yellow zone refers to restricted areas, the blue ones are designated areas dedicated to offshore wind developments and the vertical stripes indicate which areas are destined to the preservation of marine wildlife. [65] [66]

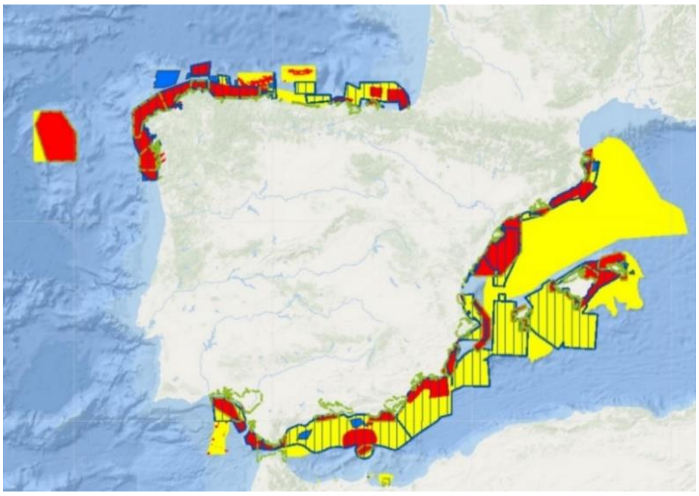


Figure 3.24: Spatial Planning in Spain. [66]

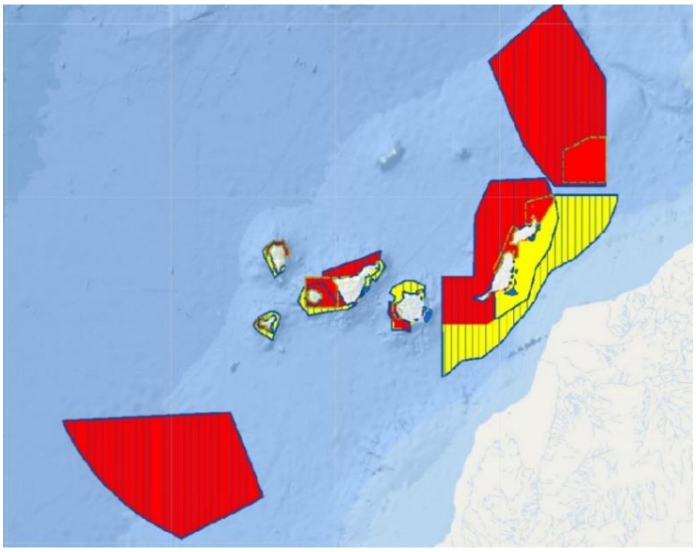


Figure 3.25: Canary Islands Spatial Planning. [66]

From picture 3.24, it is possible to appreciate the zones delimited for other projects in the Atlantic Ocean region, at the north of Spain (blue colored zones). Projects such as *Celta I*, *San Cibrao* and *San Brandan* of almost 500 MW each, *Ventus* of 600 MW and *Breogán* of 510 MW are floating projects in early planning phase. [48] [66]

3.2.10 France

France planning for the distribution of its energies in the future years is specified in France’s multiannual energy programming (*PPE*), which is modified every five years to determine the nation’s energy trajectory and meet the energy transition law's goals. The PPE for 2019-2023 describes the offshore wind project sites and capacity required to meet these goals, nevertheless, the Energy Transition Act passed in 2015, established a target of 40% energy from renewable sources by 2030, which offshore wind farms are likely to help to achieve. The energy and climate legislation, officially known as Legislation No. 2019-1147, amended this aim and set a target of 33% consumption from renewable sources for all energy industries by 2030, with a minimum of 40% for electricity generation. Offshore wind is critical to achieving these objectives. The target is to have 2.4 GW of fixed and floating offshore wind power built by 2023, and about 5 GW by 2028. [74]

The government`s plan for the offshore wind industry is to increase the auctioning for 2 GW each year from 2025 and from now the auctions for the concession will allow 1 GW per year, expecting to reach a built capacity of 20 GW by 2030 and 40 GW by 2050. By now out of the 3.5 GW of offshore wind installed capacity, only 500 MW are floating and expected to be expanded by 1.5 GW by 2030.[92]

As seen in figure 3.26, the French government has estimated that (at least for now) the floating projects will be placed in the Mediterranean Sea while the rest of the offshore projects located in the North and South Atlantic Ocean and the North Sea are fixed foundations. [75]

The floating projects consists mostly of 2 wind farms in early planning phase of 250MW each that are expected to be in service by 2030 and expanded progressively through the years up to 750MW each wind farm, to feed the grids of communities such as *Narbonnaise* (1), *Gulf of Fos* (2), and *Rousillon (3*) (see figure 3.27). The rest of the areas are covered by “pilot farms” (nowadays under construction) used to feed small communities all around the French Mediterranean region with a produced amount of energy equivalent to 80MW as seen in figure 3.28. where (a) is the zone for the wind farm *Golf du Lion*¸ (b) for the zone belonging to *EOLMED* project and (c) for *Faraman* project. [75][76][77][78]

Figure 3.26: French territorial waters spatial planning for 2030. [75]

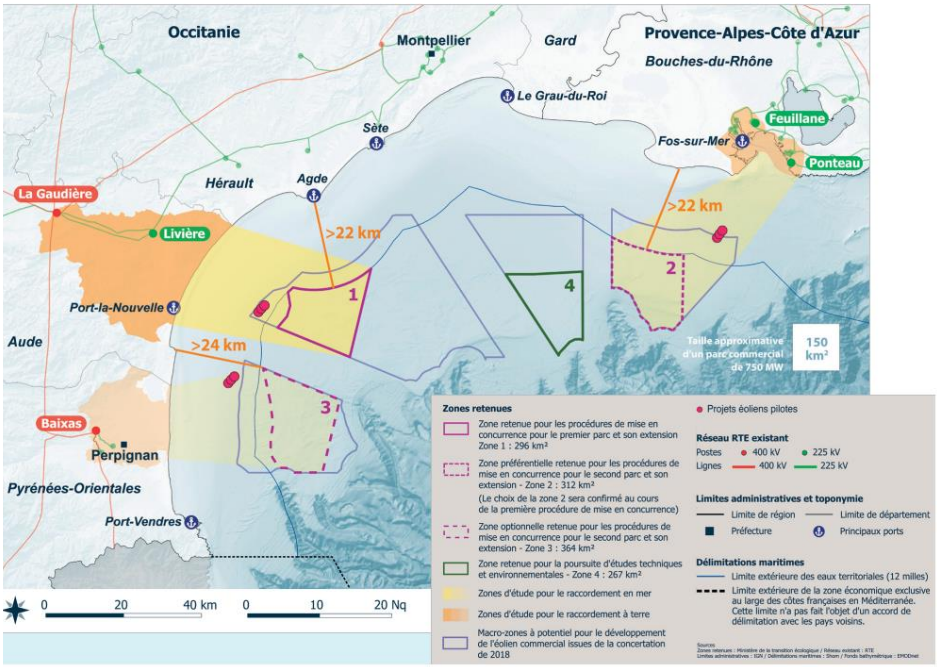


Figure 3.27: Latest concession for Floating Offshore wind development in southern France. [76]

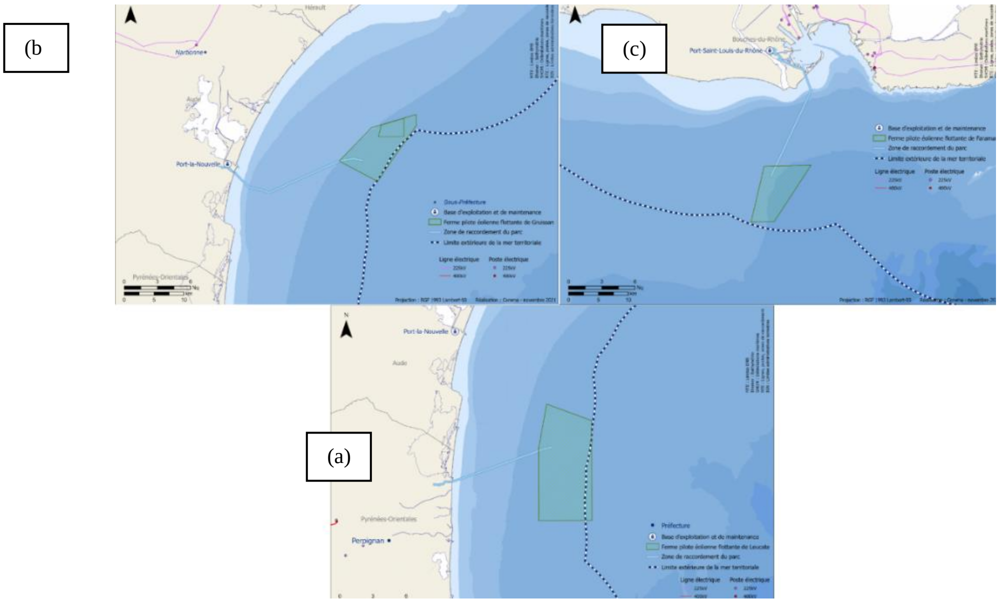
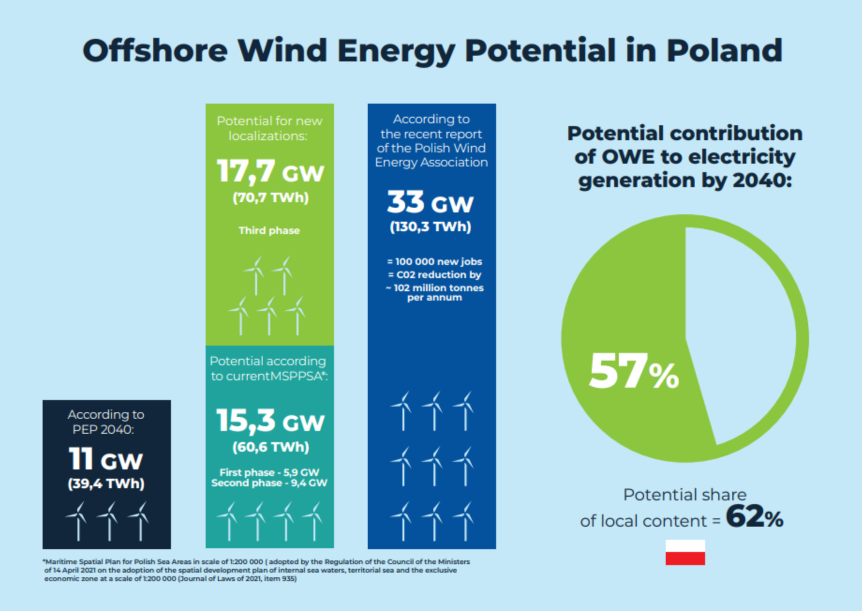


Figure 3.28: Zones used for pilot operating offshore floating wind farms. [75]

3.2.11 Poland

Offshore wind turbines in Poland have the potential to produce up to 33GW of sustainable energy (as seen in figure 3.29). The first OFW farm in the Baltic Sea is planned to start producing power in 2026. Previously, the growth of renewable technologies in Poland was not as active. Currently, preparations for constructing the first wind farms in the Polish section of the Baltic Sea are underway as are administrative processes to issue further project licenses for Phase II development. The increased interest in this sector suggests offshore wind energy has the potential to play a critical role in securing Poland's power supply and autonomy. Furthermore, the growth of OW power would benefit the Polish economy by establishing a modern and stable supply chain. The *PWEA* (*Polish Wind Energy Association*) conducted a study titled "Offshore Wind Energy Potential in Poland" in 2022. The report analyzes investment prospects in the Polish portion of the Baltic Sea as well as other possible OW energy sites. The publication offers fresh insights into the potential of offshore wind energy and may serve as a guide for investors and administrations interested in exploring the considerable opportunities in the renewable energy industry. [80]

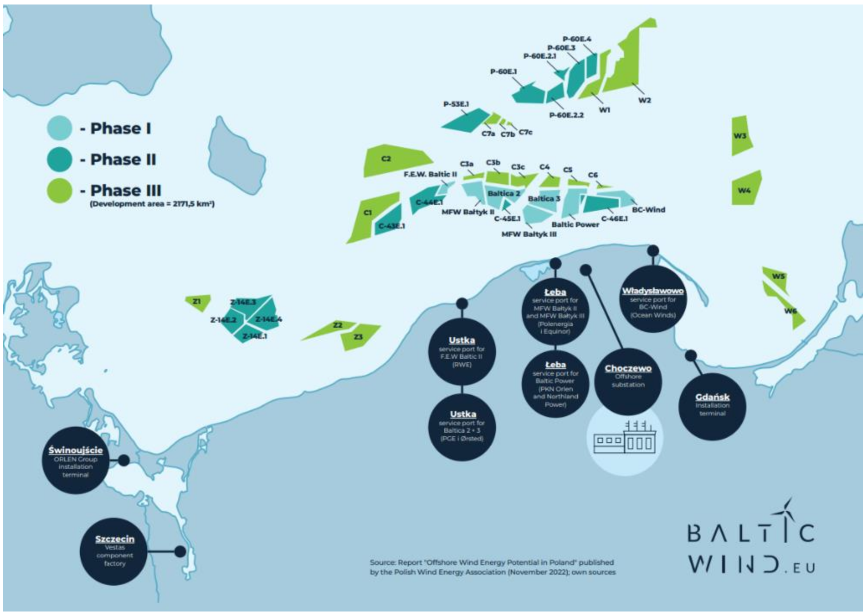
Polish offshore regions are now continuously developing projects with an overall capacity of around 8.4 GW. 5.9 GW from Phase I projects and 2.5 GW from Phase II projects. Based on a comprehensive review of the variables impacting the potential of the installed capacity and generation of energy in Poland, it is anticipated that OWT farms may achieve a total capacity of 33 GW while producing an annual energy output of 130 TWh. The analysis found 20 additional locations totaling 2171.5 km^2 with the capacity to generate 17.7 GW as well as produce 70.7 TWh of energy.[80]



*Maritime Spatial Plan for Polish Sea Areas in scale of 1:200 000 (adopted by the Regulation of the Council of the Ministers of 14 April 2021 on the adoption of the spatial development plan of internal sea waters, territorial sea and the exclusive economic zone at a scale of 1:200 000 (Journal of Laws of 2021, item 935)

Figure 3.29: Potential of Wind energy in Poland. [80]

The first estimation given was that by 2030 at least 3.8 GW would be installed and by the year 2050 the amount will increase to 28 GW, but with the identification of the new areas that number increased to 33 GW that are expected to be delivered in a 3-phase plan. See figure 3.30. [80] [81]



Source: Report "Offshore Wind Energy Potential in Poland" published by the Polish Wind Energy Association (November 2022); own sources

Figure 3.30: Planning to accomplish 33GW OWT power in Poland [80]

3.2.12 Sweden

Sweden's position as Europe's greatest net power exporter is partly due to its abundance of onshore wind energy. It now ranks fifth among European nations in terms of onshore wind power. Nevertheless, due to the electrification of the economy and green steel manufacturing programs utilizing hydrogen from renewable sources, the country's power consumption is predicted to double by 2045. This demands the inclusion of additional renewable energy sources, among which offshore wind is a possible candidate. In comparison to its neighbors Norway and Finland, Sweden remains comparatively slow-moving towards offshore wind technology. Sweden currently has 192 MW of offshore wind power fully commissioned as seen in table A-5, with no additional projects finished in early 2010`s. In the past, Sweden has prioritized onshore wind as a less expensive choice, and no bids or governmental financial assistance for offshore wind projects have been given. Nonetheless, recent big announcements suggest that Sweden's offshore wind industry has the potential for considerable expansion in the latter half of the 2020s. [87]

The Swedish government is currently working on a centralized system with a view to simplify the development process for OW (*Offshore Wind*) ventures. They have identified three sites in northern Sweden that are appropriate for OW development: the Gulf of Bothnia, The Kattegat marine area, and the Baltic Sea. The Ministry of Environment assigned the SEA (*Swedish Energy Agency*) and some other key stakeholders with finding regions capable of producing an extra 90 TWh of power production to promote the spread of OW. To plan for all of this, the Swedish Spatial Plan will be updated by 2024 to include designated OW regions. This program intends to provide a clear framework for future offshore wind project deployment and administration in Sweden. [87]

Sweden has an opportunity to become a major European OW market. The wind sector is well-prepared, with an extensive pipeline of projects, with roughly 15 GW of capacity now in the permitting process. These projects, if permitted, might be fully commissioned, and contributing to the power grids by 2030. In addition to regular OW initiatives, there is significant interest for installing FOWT in Swedish seas. Freja Offshore, a partnership between Aker Offshore and Hexicon, is pushing forward with proposals for floating offshore wind projects in Sweden. They have a potential pipeline of four projects with a total capacity of 8 GW around Southern Swedish waters. Furthermore, numerous different companies, including Simply Blue, Deep Wind Offshore, Njordr Offshore Wind, and RWE, are developing major OFW projects in Sweden. [87]

As seen in figure 3.31, The zones where these floating projects are intended to be developed, is in the Baltic Sea region, at approximately 100 Km from the city of Stockholm. 3 wind farms, *Skidbladner, Herkules I* and *Herkules II* will be installed there, with a combined capacity of 4.75 GW. Another project considered very interesting is the *Freja Offshore*, the latter consists of 4 different wind farms located as seen in figure 3.32. Three of them are located in the Baltic Sea region: *Dyning, Kultje*, and *Cirrus*. The last one is called *Mareld*, and will be installed in the North Sea, approximately at 40 Km West to the island of Orust. See table 3-13 as reference of the OFWT projects in early planning phase in Swedish waters (All of these projects must be completed as per Swedish planning, net zero emissions by 2045). [88] [89]

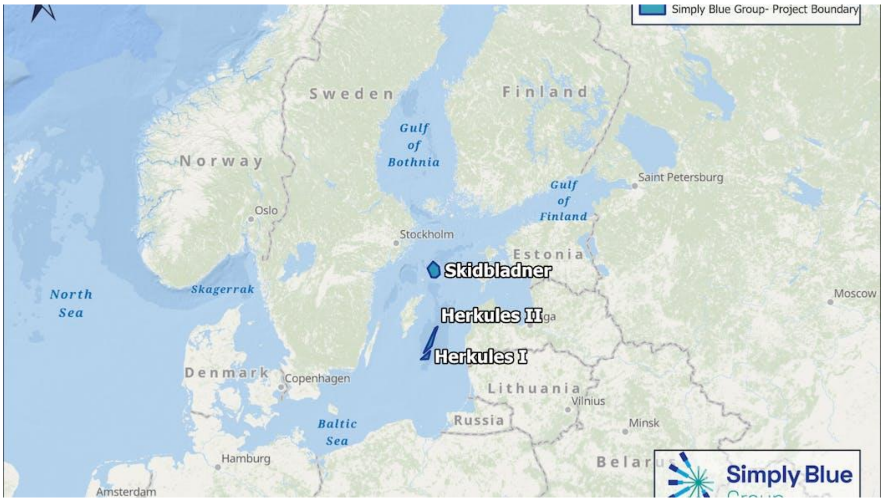


Figure 3.31: Simply Blue 4.75 GW FOWT projects. [88]

Figure 3.32: Freja Offshore with all its FOWT projects. [89]

Table 3-13: Swedish Offshore Floating Wind Turbine projects in early planning phase. [48] [88]

Name	Capacity (MW)	Foundation Type	Status
Skidblander	2000	Floating	Early Planning
Herkules I	1000	Floating	Early Planning
Herkules II	1750	Floating	Early Planning
Dyning	2000	Floating	Early Planning
Kultje	2150	Floating	Early Planning
Cirrus	2550	Floating	Early Planning
Mareld	2500	Floating	Early Planning
Total	13950 MW		

4. High and Low scenarios for 2030 and Beyond

In the previous section, an extensive exploration of future developments in the energy sector was presented, specifically the offshore wind field. With the intention of capturing the energetic goals set by governments, in terms of *Offshore Wind Capacity Installed* for the future decades (2030, 2040, 2050). More specifically, for all those projects in early planning stage that make use of floating technologies. To make the simulation more conservative table 4-4, 4-5 and 4-6, describe how the cases will be set into the simulation tool. This is relevant to each one of the countries designated as a *Hub Port*, while considering also assumptions explained in section 4.1.

4.1 Assumptions

It is important to acknowledge that this master thesis focuses on the analysis of the installation process of floating wind farms. Since there are uncertainties related to any future process prediction, some assumptions will be made and explained further. This makes possible to frame the study into more realistic objectives considering aspects such as:

- Offshore Wind Hub Port's location.
- Component's location.
- Special vessels availability and configuration.
- Ports and Power Grid investment.
- Crane availability and lifting capacity.
- Turbine specifications.
- Maximum installation per year.
- Countries Low and High Scenarios.

4.1.1 Offshore Wind Hub Port's location

Hub ports assumption is made based on different criteria, one of the criteria is the expertise the country has in wind technology, secondly the distribution potential, for instance, as UK has several OW projects pipelines, therefore, it is convenient to set up a base here. And finally, as per Wind Europe`s report, it is expected to cover the energetic quota in North Sea, the Baltic Sea, Atlantic Ocean and Southern European waters with OFWT farms (see figure 3.1). Therefore, having hub ports in the below-mentioned areas is essential and the distribution of such bases follows table 4-1 locations.

Table 4-1: Hub Ports location In Europe.

Hub port location per Country
Scotland and Wales
Norway
Ireland
Spain
France
Sweden

4.1.2 Component's Location

All the components are assumed to be already available and stored at Hub Ports, ready to be installed.

4.1.3 Special vessels availability and configuration

According to a report made by the GWEC (*Global Wind Energy Council*), Europe might face a shortage of special vessels used during the installation of wind farms by the end of this decade, unless investments are made. [90] Assumption consists of having enough availability of vessels related to OFWT installation process and defining the number of vessels to be employed.

As per a previous master thesis based on the optimization process of the installation of a wind farm process, the set up used will be the most optimal combination of assets found in this master thesis. [92]

The details about day rates, fuel consumption rates and vessel speeds can be found on tables B-1 to B-3 While details about the assets applied to all simulations in this master thesis can be found on table 4-2. Further subsections contain a short explanation of each asset/vessel specific function.

Table 4-2: Combination of assets/vessels used. [92]

Vessel	Amount
Anchor Handling Vessel (AHV)	1
Crew transfer vessels	2
Tugs	2
Floater assembly crane (semisub only)	2
WTG Integration Crane (limiting criteria)	1
Quayside Crane	1

4.1.3.1 Anchor handling vessel (AHV)

Floating structures imply mooring lines, these ones are elements used to prevent the floating structure from drifting freely on the sea i.e., to hold the structures in position. Mooring lines are often made of chains, wires or synthetic ropes that are attached in one end, to the structure, and in the other to an anchor. The positioning or deploying of the anchor into the seabed comes from an operation called anchor handling operation (AHO), which is normally done by a dedicated vessel called anchor handling vessel, (AHV) also used to tug structures to the sea. See figure 4.1. [95]

Figure 4.1: Skandi Skolten AHV vessel. [94]

4.1.3.2 SWATH trimaran

Fore crew transportation purpose, a multihull concept allows small vessels to behave in a very satisfactory way when sailing in non-favorable weather conditions, instead of the old concept of large monohulls, the SWATH concept (stands for *Small Water plane Twin Area Hull*) has a good design option, this kind of concept is well known for its seakeeping and almost non perturbed responses while sailing at high speeds of around 20 Knot. See figure 4.2. [96]

Figure 4.2: Trimaran SWATH vessel. [97]

4.1.3.3 Tug

A tug vessel is a ship used to tow/tug another vessel/structure, in offshore industry is mostly used to tow out and place structures in a determined location for posterior hook up and commission. [98]

For this master thesis, a set of two tugs or AHTS (*Anchor Handling Tug and Supply)* will initially be employed when towing out the WTG and to support the AHV while *hooking-up* the mooring lines to the substructure. Progressively this number will be increased to see the impact it has on the project completion time.

4.1.4 Ports and Power Grid Investment

For these projects to be successfully coupled to the power network, onshore electrical grids and offshore substations must be adapted for the purpose of being able to receive all of the converted energy, therefore it is assumed that each country`s plan has been progressively followed, not only at installation level, but also preparation for distribution. Regarding the ports' investment, it is assumed that all the future development of ports has been carried out and will allow the assembly process to be performed normally.

To determine the locations of the ports, research was conducted by relevant governments as OW development ports. The findings can be seen in section 5, specifically Table 5-1.

4.1.5 Cranes availability and lifting capacity

The presence of a crane is critical at an Offshore Wind Port since it performs the key task of assembling wind turbines, (specially the most critical lifting operation, the nacelle assembly) while other activities are carried out, such as the installation of anchors and mooring lines on-site. Offshore floating wind turbines (OFWT) of the floater type can normally be stored and towed out to their intended location after the turbine-floater mating is completed (*integration*). Once on-site, it can be coupled with the anchoring system. [102] Consequently, any delays in the wind turbine assembly can lead to project time extensions making emphasis on the importance of timely completion.

The size and weight of offshore wind turbines have increased significantly in recent years. Turbines have become much taller and heavier over the last decade, surpassing a capacity of 15 MW, with nacelles reaching approximately 1,000t. Furthermore, the use of bigger foundations to support these turbines has had a significant influence on onshore logistics. Because of these advancements, the management of organizing ports for both foundations and WTG now calls for more robust technology, and one example of the need for growth or adaptation is cranes. [91] [103]

Companies as Mammoet, Liebherr, Huisman and Tadano own cranes capable of lifting towers (in one piece) and nacelles for 15MW WTG (one of the limiting criteria regarding assembling process) which means that the number of cranes is limited worldwide. Which is why the assumptions made regarding the crane utilization goes as follows: at first, all the hub ports stated in table 4-1 will have one crane each for the WTG integration (assembly of the WTG and mating with the floater), once the limitations and behavior of the installation process is defined from the base case other cases can be settled.

4.1.6 Turbine specifications

For this master thesis two different Wind turbines will be considered for the installation process of the wind farms, one with 15MW production capacity and another one of 20 MW. Wind Turbines installed from 2023 to 2030 will be 15 MW OFWT and from 2031 and beyond (2050) 20 MW will be used (Table 4-3 contains the main features of both types of wind turbines).

Since the characteristics of the Hub port will influence the floater concept, [102] the assumption made in this master thesis concerning the floating substructure consists in allocating Spar type floater to Norway, the reason is that because of its deep waters and sheltered areas because of the presence of Fjords [103] makes it ideal for assembly this type of floater.

For the rest of the countries a semisubmersible concept will be used.

Table 4-3: Properties of a 15MW and a 20MW wind turbine. [100] [101]

Item	Type/Value		Units
Name	15MW	20MW	-
Rated Power	15	20	MW
Rated Wind speed	10.6	10.7	m/s
Cut-in Wind speed	3	3	m/s
Cut-out Wind speed	25	25	m/s
Rotor Diameter	240	276	m
Hub Height	150	160.2	m
Tower Weight	860	2070	t
Rotor and Nacelle's mass	1017	1975	T
Mooring Lines	3	3	Units

4.1.7 Project`s starting dates

With the intention of being able to do a comparative study from each country the starting date of the projects it is assumed to be on the 01/03/2023 and the installation of the mooring system one year before, despite the fact that projects have different starting dates due to permitting processes.

4.1.8 Countries Low and High scenarios

This subsection is intended to capture a conservative amount of installed OW capacity for each country, considering the amount set by their respective governments. The objective is to present a more realistic approach since there will always be uncertainty towards the future installation process, either because of supply chain variations, long licensing process, and many other possibilities that may influence the completion of the proposed projects.

Table 4-4: floating offshore wind low and high scenarios for countries with 2030 and 2050 energetic goals. [45] [58] [62] [65] [76] [86] [92]

	Low Scenarios Installation cap. (GW)		**High Scenarios Installation cap. (GW)**	
Country	**2030**	**2050**	**2030**	**2050**
UK		25		50
France	1.8	10	15	20
Spain	1	10	3	15
Ireland	5	20	10	25

As stated in previous section, in the case of France, out of the 2.4 GW capacity expected to be installed by 2023, only 500MW are floating, which means that almost 21% will be OFWT. There is a very optimistic approach of 20 GW by 2030 and 40 by 2050 for Offshore Wind [92], but a more conservative approach will be the one given by [72] which is around 5 GW by 2028. Giving an installation ratio of around 500 MW per year from 2023, hence 6 GW by 2030 of the total offshore wind installed it is assumed that at least 30% of those 6 GW to be floating, the result is 1.8 GW expected to be installed by 2030.

Table 4-5: Low and high scenarios floating offshore wind for Norway. [44]

	Norway`s scenarios installation cap. (GW) by 2040	
Country	**Low**	**High**
Norway	20	30

Even though there is a report identifying a huge potential for the country with regards to OFWT farms (115.8 -219 GW), it is not realistic to account for the total installation of these available zones, it would require a massive amount of investment from the government not only to adapt the power grids, but also logistics, production, and other aspects. As a result, for the purposes of this master thesis, the number considered as a high scenario will be the one specified by the government, i.e., 30 GW. As a result, 20 GW is considered as a more cautious strategy.

Table 4-6: Low and high scenarios floating offshore wind for Sweden. [87] [88] [89]

	Sweden`s scenarios installation cap. (GW) by 2045	
Country	**Low**	**High**
Sweden	10	15

5. Simulation and Shoreline

5.1 Shoreline

Shoreline Design™ is a web-based application developed by Ph.D. Ole-Erik Vestøl while working on his degree in offshore technology at University of Stavanger. One of its functionalities is to simulate the whole process of installation, commissioning, testing and completion for wind turbine projects, while delivering a financial (cost-related) and strategy (related to hours of service and waiting for weather windows) report that helps to understand how much a project will cost and how long will it take while using certain assets (vessels as tugs, Heavy lift vessels, Anchor handling, among others) under certain weather conditions and allowing to set up a variety of possibilities to foresee possible outcomes. [106] [107]

5.2 Bases and Hub Ports

The base cases were located in the countries described in the previous section, "*Assumptions*". As seen in table 5-1, the port distribution goes as follows. Table 5-2 contains an extra base in reference to the UK cases, since Scotland will be installing North Ireland`s projects. Each one of the cases will have a Hub port defined as a *Base*, in Shoreline. All the components that are already assumed to be onsite will be assembled for posterior installation.

The inputs used in Shoreline can be seen in table C-1 in Annex C.

Table 5-1: Base case Port Locations.

Hub port location	Port Location	Coordinates	Reference
Scotland	Cromarty Firth	57.6866; -4.1701	[110]
Wales	Port Talbot	51.6115; -3.8455	[115]
Norway	Wergeland Group	60.8470; 5.0772	[109]
Ireland	Shannon Foynes	52.6129; -9.1076	[112]
Spain	Puerto de Granadilla	28.0789; -16.4916	[114]
France	Port-La Nouvelle	43.0207; 3.0616	[111]
Sweden	Port of Trelleborg	55.3708; 13.1403	[109]

Table 5-2: Extra Hub port.

Hub port location	Port Location	Coordinates	Reference
North Ireland	Belfast Harbor	54.6177; -5.906	[117]

5.3 Met Ocean Data

The weather conditions used for the simulation purposes come integrated into the simulation tool, provided by *ERA 5*, the 5th generation of the ECMWF's reanalysis of the previous eight decades' worth of global climate and weather. Data is accessible starting in 1940. For a vast range of oceanic, atmospheric, and surface parameters, ERA5 gives hourly estimates and uncertainty estimates are sampled every three hours. These estimates are directly tied to the informational value of the existing observational system, which has changed significantly over time. The daily updates to ERA5 have a lag of around 5 days. This data may change from the final release two to three months later if significant problems are found in this early version (referred to as ERA5T). If this happens, users are informed. [121]

5.4 Assets Cycles

This section refers to the operational order of tasks that assets perform during the installation process. Each asset has its own and will be explained further.

5.4.1 Mooring System Campaign

This campaign consists of the installation of anchoring and mooring system of the floater. This activity is assumed to start earlier (previous year) so as to save time and move forward with the installation process. The cycle of the vessel (AHV) that performs this task goes as follows:

1. Mobilization
    a. The vessel Loads the anchors and mooring lines relevant to one floating structure, using the quayside crane.
2. Installation of the components
    a. As-found survey of the mooring/anchor and FWT locations.
    b. Installation of anchor: lowered to the seabed by the lower chain segment (LCS) connected.
    c. Deployment of the lower chain section (LCS).
    d. Pull-in / proof load of anchor.
    e. Connect LCS and HCS (heavy chain section) and deploy.
    f. Deploy chain to seabed and return to base.
3. Demobilization at 15 Knots

5.4.2 Floater assembly Campaign (semi-submersible)

This campaign is carried out in the starting year of the project and at a certain point, it will be carried out in parallel with the mooring campaign. When it comes to the floater assembly for the semi-sub the process described by the cranes:

1. Mobilization
    a. Crawler type or rail type cranes used (2) first must be positioned into the hub port.
2. Assembly
    a. Installation of center column on the supports.

   b. Installation of the three trusses on to the center column.
   c. Installation of the three outer columns on to the trusses.
   d. Installation of tendons lower
   e. Installation of tendons upper.
   f. Tensioning of tendons.
   g. Floater outfitting, testing and completion.
3. Demobilization

5.4.3 WTG Integration crane (semi-submersible)

This crane will integrate (assemble) the wind turbine and the floater together. The process goes as follows:

1. Mobilization
   a. Initialization and start up.
2. Assembly
   a. Loadout of the floater
   b. Assembly the Tower
   c. Assembly of the Nacelle
   d. Assembly of the blades
3. Demobilization

5.4.4 WTG Integration crane (Spar)

Same as for the semi-submersible floater, will occur at the starting date of the project, and this one differs from the semisubmersible since it will be only used in Norway for depth reasons. The process goes as follows:

1. Mobilization
   a. Initialization and start up.
2. Assembly
   a. Assembly of tower bottom section.
   b. Assembly tower section.
   c. Assembly of the Nacelle.
   d. Assembly of the blades.
   e. Assembly finalization.
   f. Connects mooring line and anchors for the AHV.
   g. Loads AHV with connected Mooring lines.
3. Demobilization

5.4.5 Tug AHTS

Tugs are used to tow out the already assembled integrated wind turbine-floater structure and provide support in an effort to connect the floater with its already deployed mooring system. A set of tugs comprises 2 vessels and the operational tasks are defined as:

1. Mobilization
   a. While the tug is not connected to the floater the transit speed is 15 Knots, whereas while tugging is 3 Knots.
2. Loadout towing out
3. Install component on site
   a. Connect the WTG with the mooring line.

4. Demobilization and return to base

5.4.6 Crew transfer vessel (CTV)

These vessels transport technicians to perform completion, commissioning, snagging and testing activities once the WTG is already on site and connected to its mooring system.

1. Mobilization
    a. Carrying personnel.
    b. Waits for fulfillment of tasks.
2. Demobilization

5.5 Case Study

In this section all the assets described in previous sections are combined and studied with a view to obtain the most appropriate combination of vessels to avoid bottlenecks and long waiting times. As long as the amount of integration cranes (the one that assembles the tower and nacelle with the floater) since this is the most critical asset due to the lack of worldwide units.

The starting date of the projects is assumed to be all for the same, although this may not be the case owing to variances in the length of permission procedures across various nations, it is assumed that all projects begin on the same day to enable comparisons. These variances may lead to either longer or shorter processing durations, which would modify the projects' actual commencement dates.

5.5.1 First Case, Semi-submersible optimization

This case was held in Ireland and will help to determine the optimal number of assets that can be used to have a fully operational hub port when installing Semi-submersible floater type while also considering all the assumptions listed in section 4.

100 WTGs will be installed and progressively add more infrastructure assets to reduce bottle necks. Description of this case can be seen in the table below, 5-3.

5.5.2 Second case, Spar-buoy optimization

This case was performed in Norway. The objective of this base case is to minimize bottlenecks while installing Spar type substructures. 300 WTGs to be installed and modified assembly process for the integration crane. Description of the case can be found in table 5-4.

5.5.3 Third case, 7 cranes 7 hub ports up to 2030

This case is ideal since the presence of 7 integration cranes working all at the same time seems unlikely, since the worldwide amount of these units is limited. Therefore, this case will provide the most optimistic result achievable in the region up to 2030, to obtain a distribution and study the annual installed capacity of each country up to 2030 and also how the weather downtime (time where the operations are ceased due to weather conditions) affects the hub ports installing the same floater type. Figure 5.1 describes the positioning of the hub ports and cranes. Table 5-5 contains the wind farms used with the aim of determining the annual installed capacity. The wind farm arrays can be seen in Annex D, *Arrays.*

Table 5-3: Base case description, Assets used.

Ireland`s Base case (Shannon Foynes`s Port)			
WTGs to be installed	100 Units		
Vessels used in Logistics			
AHV	1 Unit		
Integration Crane	1 Unit		
Floater Crane	1 Unit		
CTV	2 Units		
Tug	1 Unit	Towing speed	3 Kn

Table 5-4: Second Base Case description.

Norway`s Base case (Wergeland`s Base Port)			
WTGs to be installed	300 Units		
Vessels used in Logistics			
AHV	2 Unit		
Integration Crane	1 Unit		
CTV	2 Units		
Tug	2 Unit	Towing speed	3 Kn

.

Figure 5.1: 7 cranes located at 7 Hub ports. [56]

5.5.4 Fourth case, Scenarios achievements

All the hub ports will have a designated integration crane and the objective of this case is to estimate when each country can fulfill its Offshore Floating wind energetic quota, considering a fully operational condition where there are only delays due to weather conditions based on its low and high installation scenarios.

- Ireland (2030 and 2050 Low and High scenarios)
- UK, composed mostly of Scotland, North Ireland, and Wales (2050 Low and High Scenarios when installing North Ireland projects from Scotland)
- Spain (2030 and 2050 Low and High Scenarios)
- France (2030 and 2050 Low and High Scenarios)
- Norway (2040 Low and High Scenarios)
- Sweden (2045 Low and High Scenarios)

Using the most optimal infrastructure obtained in first and second case, where the second case is only applicable to Norway since it is the only hub port installing Spar-type floaters due to its geographical features (Water depth).

5.5.5 Fifth Case, Sensitivity study for crane transfer

This case will be conducted between Norway and Sweden and the objective is to analyze what is the best outcome when transferring the crane from one hub port to another in terms of annual installed capacity. Four different proposals will be studied, three based on time and another one based on installed capacity.

- 24 months
- 36 months
- 48 months
- 2 GW installed capacity

Once one of the hub ports fulfills the given condition the crane will be transferred and allow the commencement of the other hub port's activities. The time elapsed for the totality of the crane transfer was taken from a consultation tool developed by *MAERSK* (Logistics Sea freight company) called *Twill* [119] while the assembly and disassembly time was taken from one of Mammoet`s previous project, using its containerized crane Mammoet PTC 200-DS that equals 12 weeks in average. [118]

5.5.6 Sixth Case, Crane transfer Ireland - Wales

This case will take into account the most effective period from the previous case with the intention to perform the integration crane transfer between Ireland and Wales hub ports using *Twill* and the same Assembly/disassembly time given by Mammoet.

5.5.7 Seventh Case, Crane transfer Spain France

This case will study serves for the same purpose as the previous one (Sixth case) but, will be carried out between Spain`s and France`s hub ports, based on the results obtained in the fifth case.

5.5.8 Eight to Eleventh case, Situational analysis

These cases will display how the fact of transferring the crane from one location to another affects each country's achievable date of their own Offshore Floating Wind milestones.

- Eighth case: 7 hub ports, 7 integration cranes. First a map will show how much each country (with its own crane) installed from 2023 – 2050.
- Nineth case: 7 hub ports, 6 integration cranes: one case of crane transfer will be applied to make it 6 cranes and 7 hub ports.
- Tenth case: 7 Hub ports, 5 integration cranes: Another crane transfer case will be applied to make it 5 cranes and 7 hub ports.
- Eleventh case: 7 Hub ports, 4 integration cranes: Lastly, an extra crane transfer case will be added to see how it affects the assembly rates.

Table 5-5: Wind farms to be installed using 7 Integration Cranes at 7 Hub ports.

Hub port location	Port Location	Desired Capacity in GW	Wind farms
Scotland	Cromarty Firth	5.8 GW	Ossian Bellrock Campion Wind
Wales	Port Talbot	4.2 GW	Llŷr 1 Llŷr 2 White Cross Gwynt Glas Petroc Llywelyn Valorous Celtic Sea A Celtic Sea
Norway	Wergeland Group	4.5 GW	West Wind A West Wind B West Wind C West Wind D West Wind F
Ireland	Shannon Foynes	5.2 GW	Blackwater Celtic Horizon, Dylan, Dylan Extension, Péarla Offshore Wind farm
Spain	Puerto de Granadilla	3.6 GW	Refer to table 3-12
France	Port-La Nouvelle	1.8 GW	Refer to table 4-4
Sweden	Port of Trelleborg	4.7 GW	Skidblander Herkules I Herkules II

6. Results and Discussion

Results obtained from the cases previously stated will be discussed in this section.

6.1 Results First case, Semi-submersible optimization

From this case the objective was to set up an amount of assets used in the installation process that will allow a smoother installation of a determined wind farm (1.5 GW in this case) and more specifically, reduce bottlenecks and waiting times of the assets involved (tugs and cranes). From figure 6.1 it is possible to appreciate that the combination of one floater crane (since the limiting criteria for this Master`s thesis is the integration crane, cannot be employed more than one) and one set of tugs, completed the installation of the wind farm in approximately 5.25 years or 1919 days. A progressive increase of such assets was done to obtain a reasonable number of cranes and sets of tugs. The result obtained points that 2 floater cranes and 2 sets of tugs will reduce the completion of the wind farm by a significant amount of time. See figure 6.2. The installation was completed in 2.5 years or 913 days. representing a reduction of almost 52% of the total installation time, giving a reasonable approach to apply this configuration for the rest of the semi-submersible installation hub ports.

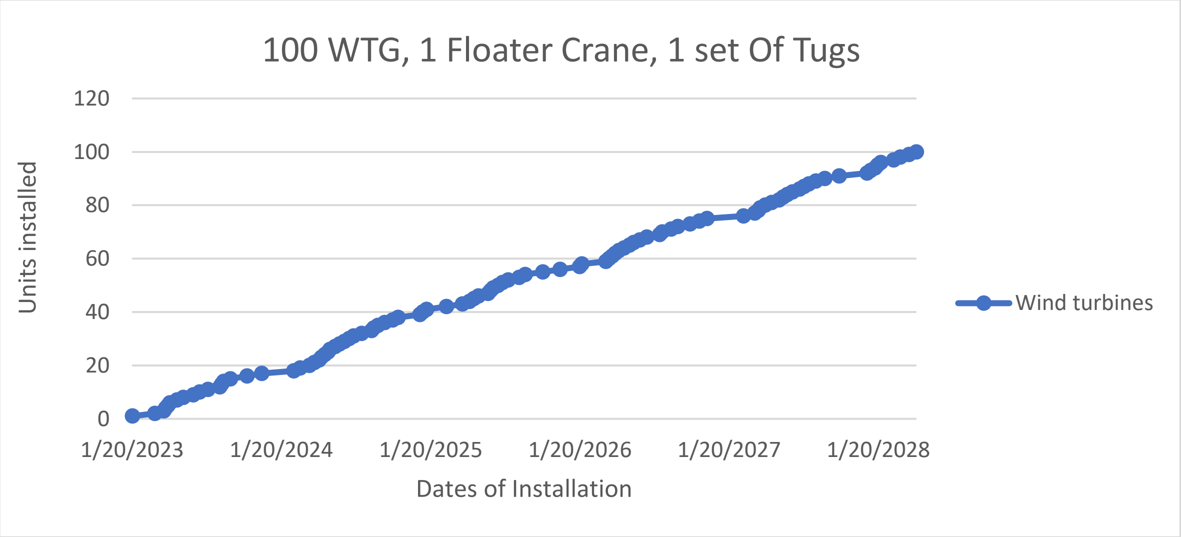


Figure 6.1: First approach to install a 1.5 GW wind farm.

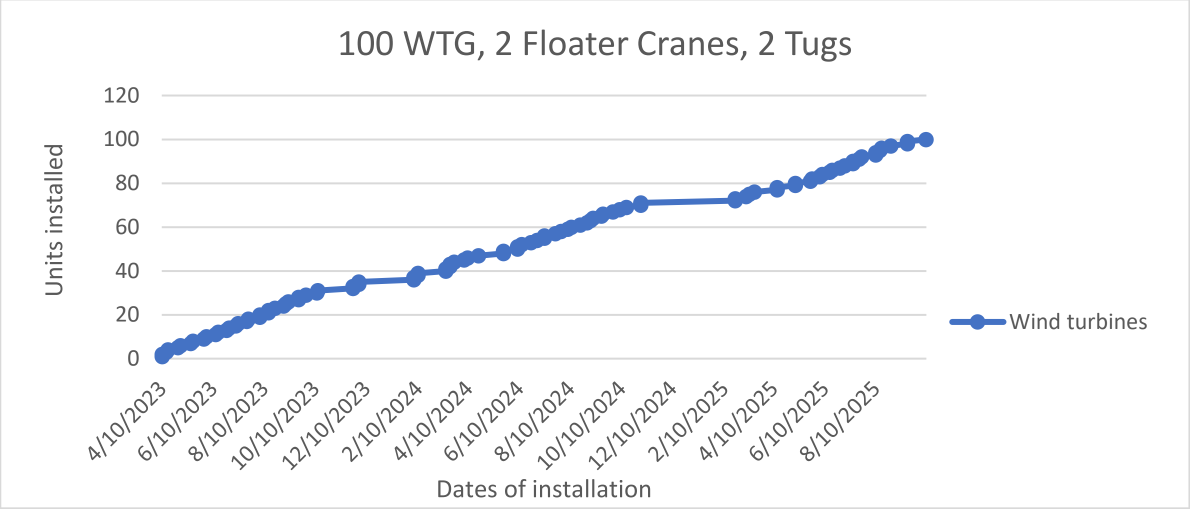


Figure 6.2: Optimized configuration of assets to install a 1.5 GW wind farm.

6.2 Results Second case, Spar buoy optimization

With the same purpose of the first case, this instance was settled in an effort to obtain an optimized configuration of infrastructure used in the installation of a wind farm from Norway. Using a different floating concept implies a different assembly process and therefore, completion times. This case was set to install a 4.5 GW wind farm starting with 2 AHV and 2 Sets of tugs. Figure 6.3 provides information regarding the completion rate of the wind farm; a total of approximately 7 years or 2569 days were employed to complete the 4.5 GW project. An extra set of tugs was added with the intention of having a reasonable number of tugs in service since adding tugs marginally increases the project's completion cost. Results of adding an extra set of tugs can be seen in figure 6.4. The result was a significant reduction in completion time since the project was completed in 5 years or 1854 days, which is approximately a reduction of 28% in completion time. Which is why for further simulations in the case of Norway this combination of infrastructure will be considered.

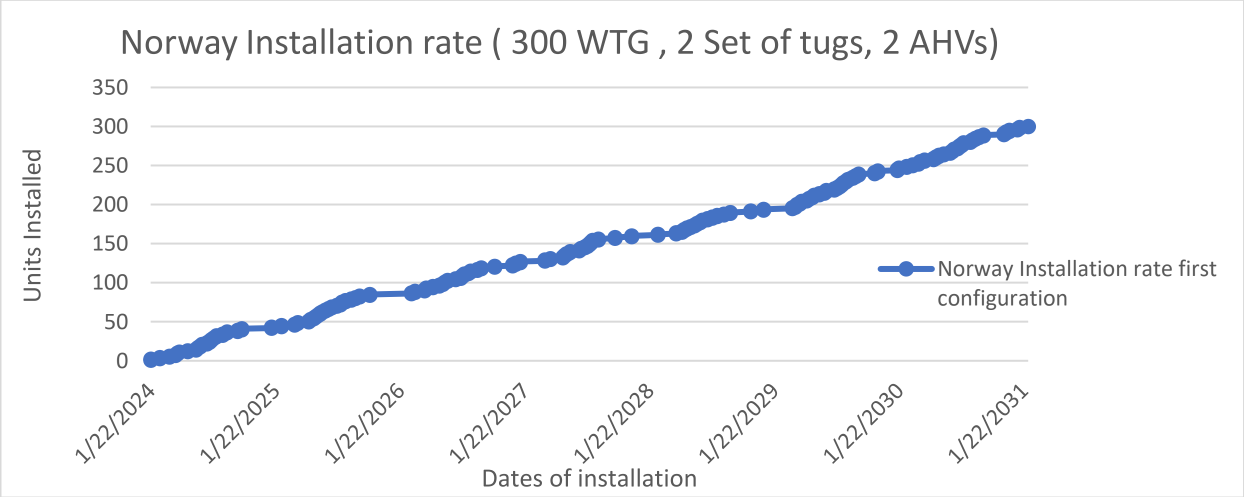


Figure 6.3: First approach to install a 4.5 GW wind farm From Norway.

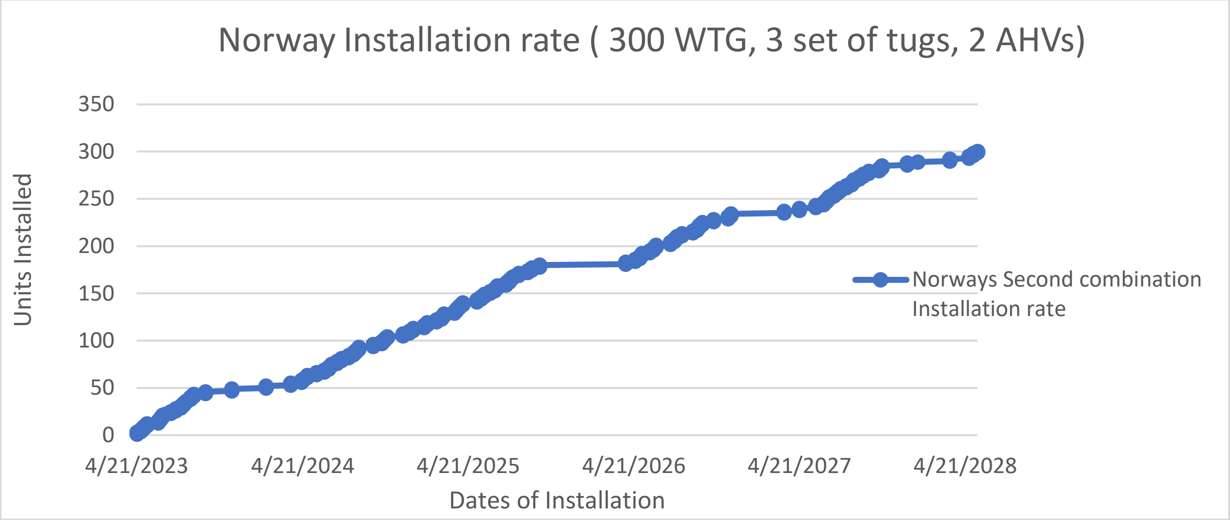


Figure 6.4: Optimized configuration of assets to install a 4.5 GW wind farm.

6.3 Results Third case, 7 Cranes and 7 Hub ports up to 2030

This case serves to provide an estimate of how much each country can install per year, and to analyze how weather conditions and the floater type can influence the completion time of the installation process.

This case is considered very optimistic because of the amount of integration cranes working at the same time in different countries, knowing that the global number of cranes is very limited.

As seen in figure 6.5, Norway has the highest amount of annual installed capacity since the assembly of Spar-buoy type floater takes less time considering the previous assumption, that all the components are located on site and ready to install.

In comparison with the hub ports assembling semi-submersible floaters, in Norway the floater is upended by ballasting (not requiring a crane) and therefore it just depends on the integration process to install a unit on site, whereas for semi-submersible concepts, the substructure must be first assembled and then integrated with the WTG.

Another comparison can be made among semi-submersible assembling hub ports, since they all have the same crane cycles the differences lies mostly in weather conditions. As seen in figure 6.5, the country that installed the most capacity per year is Scotland, while the lowest was France.

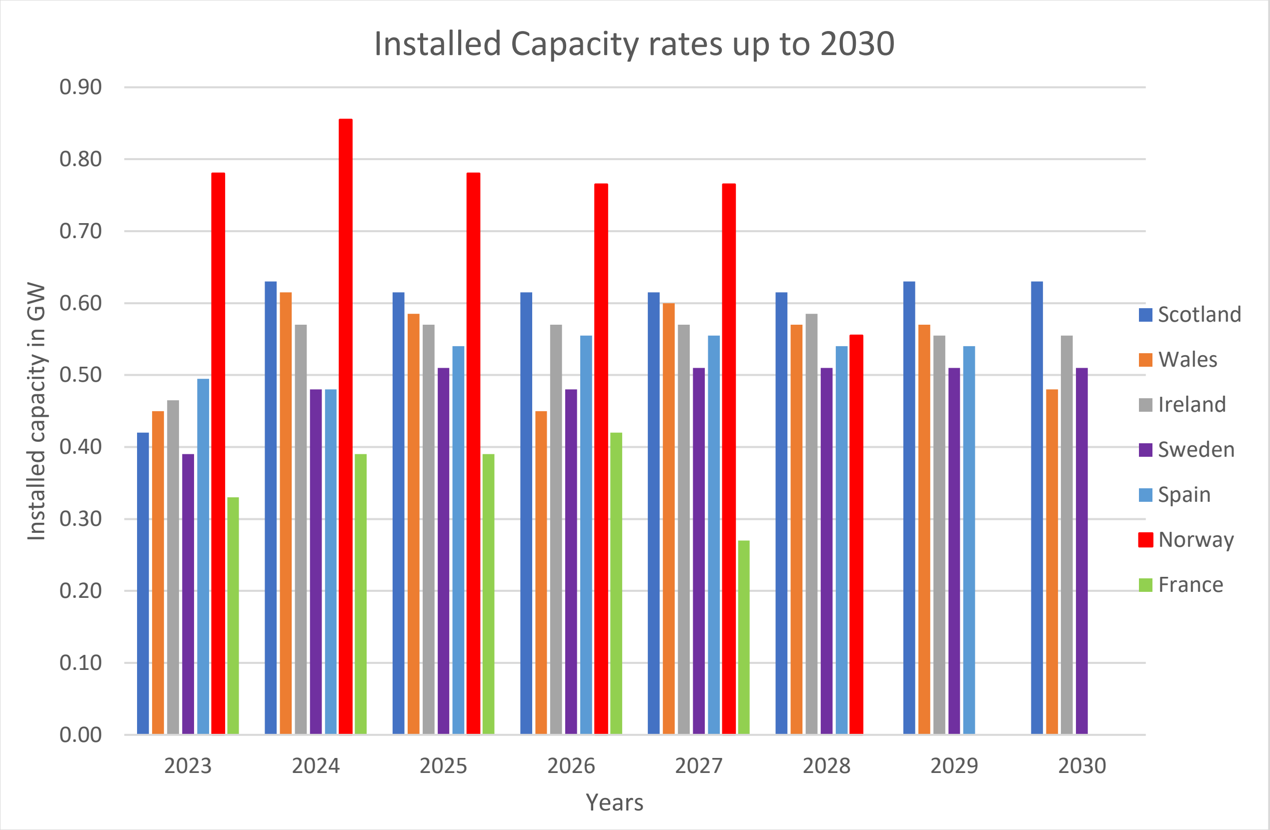


Figure 6.5: Annual installation per year per country 2023 – 2030.

Analyzing the interval 2023-2027 from figure 6.6 and 6.7 the annual downtime in % (closer to 100% means there were no weather windows) indicates that France has a shorter annual installed capacity in comparison with the rest of the countries during this period because of the weather downtimes of its cranes, both for floater assembly and integration crane. Scotland has on average the lowest downtime per year in both cases, which is why its annual installation rate is the highest among semi-submersible hub ports.

Sweden has a higher weather downtime for the integration crane, but significantly lower values of annual downtime for floater assembly cranes in comparison to France, which indicates that for semi-submersible hub ports, floater assembly cranes are more prone to decrease the annual installation rate.

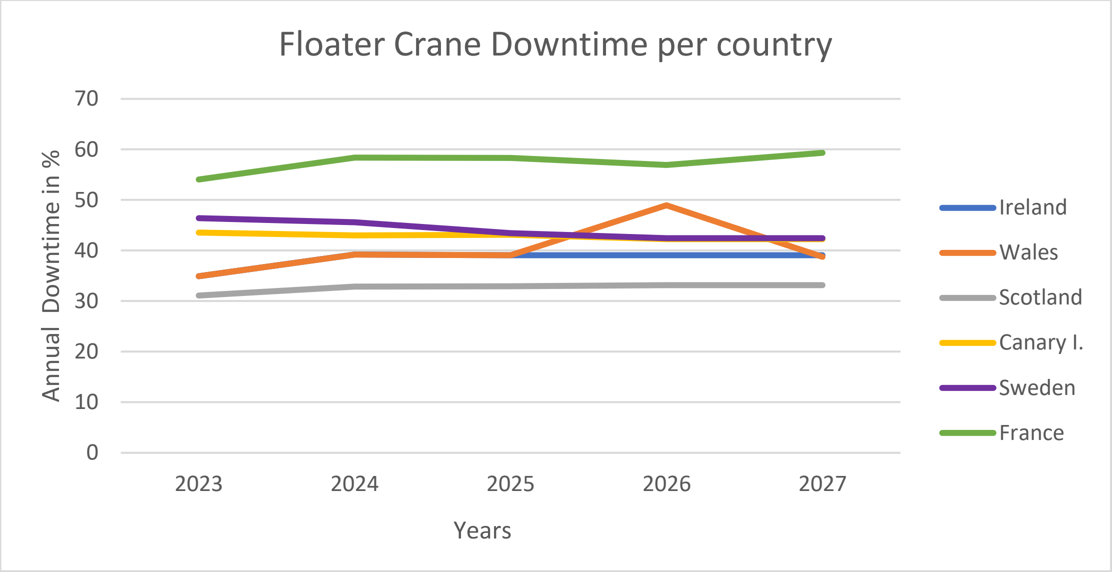


Figure 6.6: Floater Crane downtime per country.

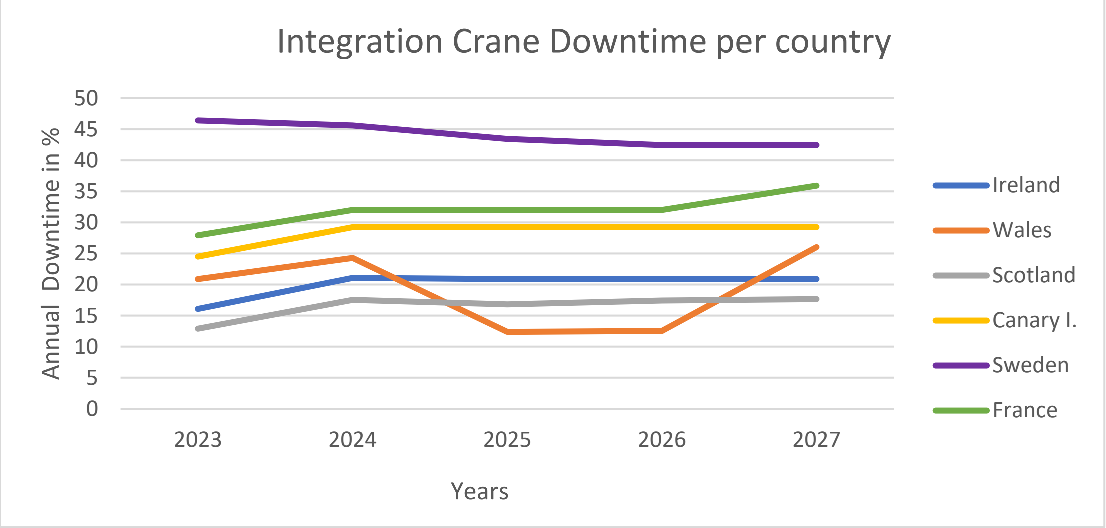


Figure 6.7: Integration Crane downtime per country.

Finally, figure 6.8 indicates the waiting time of the tugs, Scotland has the highest value since its installation process went more smoothly and therefore the tugs were waiting for the integration process to finish in order to tow out the complete WTG.

It is important to consider the uncertainty about the accuracy of the weather forecast since the use of *ERA5* does not guarantee a 100% accurate prediction, especially over future years.

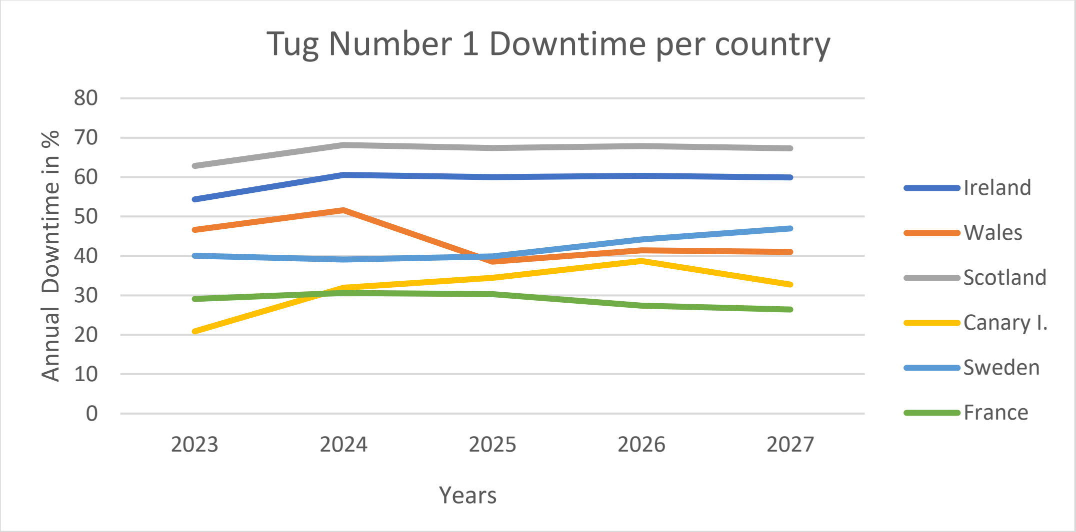


Figure 6.8: Tug downtime per country.

6.4 Results Fourth case, Scenarios achievements

This case was settled with the objective of expressing the feasibility of achieving the scenarios proposed by governments while taking into consideration all the assumptions in chapter 4. Aspects such as commencement dates, presence of the components on site, adaptation of existing electrical networks, and including an integration crane dedicated to assembly WTGs on each designated port without being transferred to any other location.

Ireland

Figure 6.10 indicates Ireland`s total installed capacity from 2023 up to 2050 based on the annual installation distribution from figure 6.9. Such distribution has a shift in capacity from 2031 since it is assumed that the used WTGs have a capacity of 20 MW instead of 15 MW from that year on.

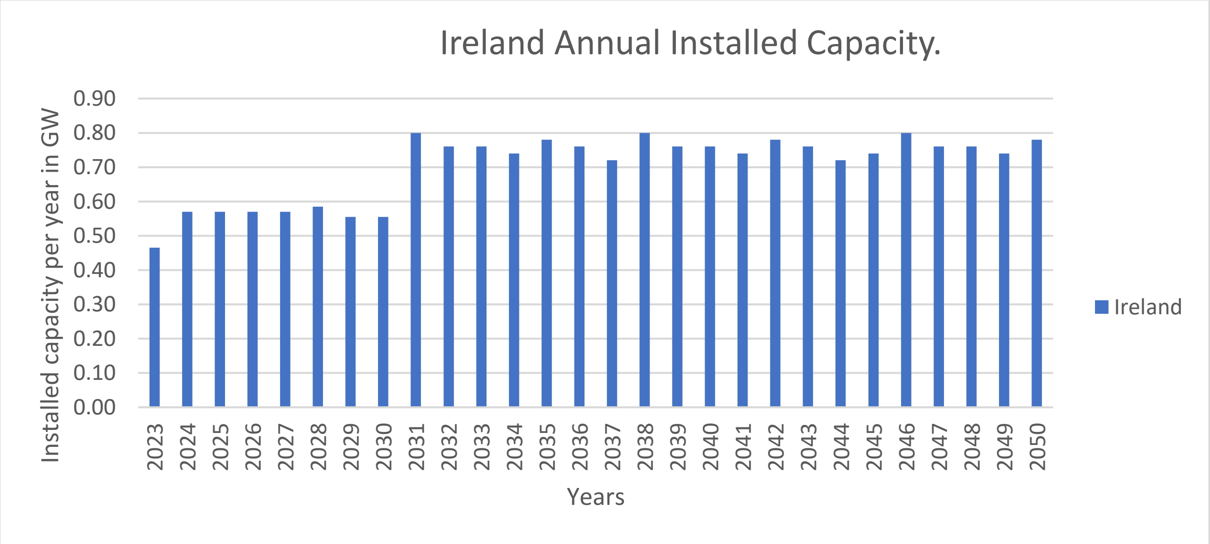


Figure 6.9: Ireland`s annual installed capacity distribution.

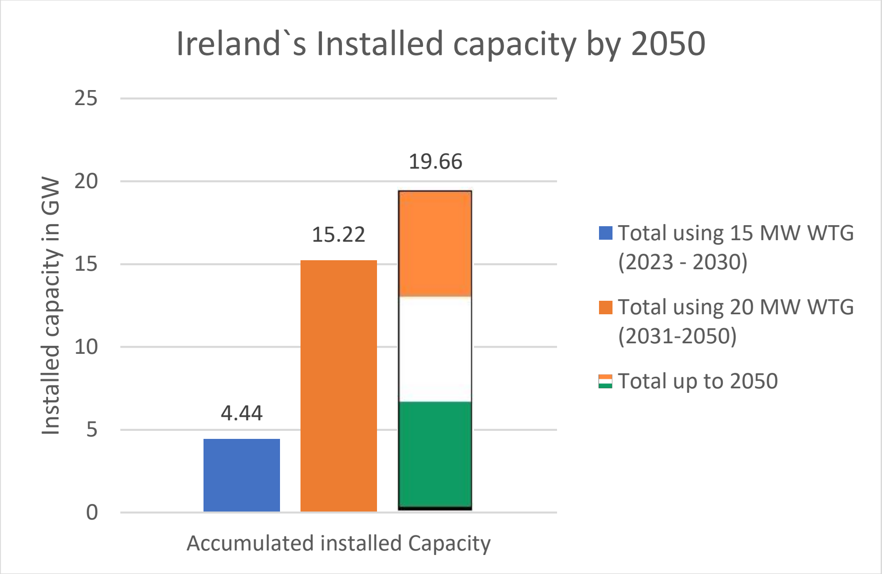


Figure 6.10: Ireland`s total installed capacity from 2023 – 2050.

Table 6-1 contains the reference values previously stated in section 4, that will help to determine the achievement year of Ireland`s energetic goals, based on this table and the distribution in figure 6.9 it is possible to state the following:

- Low 2030 Ireland scenario falls short for 0.56 GW but can be achieved by 2031.
- High 2030 Ireland scenario can be achieved by 2038.
- Low 2050 Ireland scenario can be achieved by 2051.
- High 2050 Ireland scenario can be achieved by 2058 (Assuming the same technology employed).

It was possible to estimate the installed capacity beyond 2050 by extrapolating an average value of the annual installed distribution based on its behavior. Meaning that the Low 2050 scenario is not far to be reached, 1 year after the milestone proposed by Ireland`s government, while also achieving the High cap only 8 years after.

Table 6-1: Ireland`s floating offshore wind energetic goals. [58]

Ireland	Low Scenarios Installation cap.		High Scenarios Installation cap.	
Year	2030	2050	2030	2050
GW	5	20	10	25

UK

In the case of the UK, for simplicity purposes and to keep the initial ratio of 7 hub ports, the projects in North Ireland`s pipeline were installed from Scotland, starting from 2023, as soon as these projects were completed, the Scottish projects were executed. Regarding Wales, there were no changes.

Figure 6.11 shows the annual installation rate distribution of both Scotland and Wales and generates figure 6.12, which summarizes the total installation capacity from 2023 up to

2050 in the UK (represented by Scotland and Wales since England`s projects are mostly located in shallow waters i.e., fixed substructures). Both Hub ports worked simultaneously.

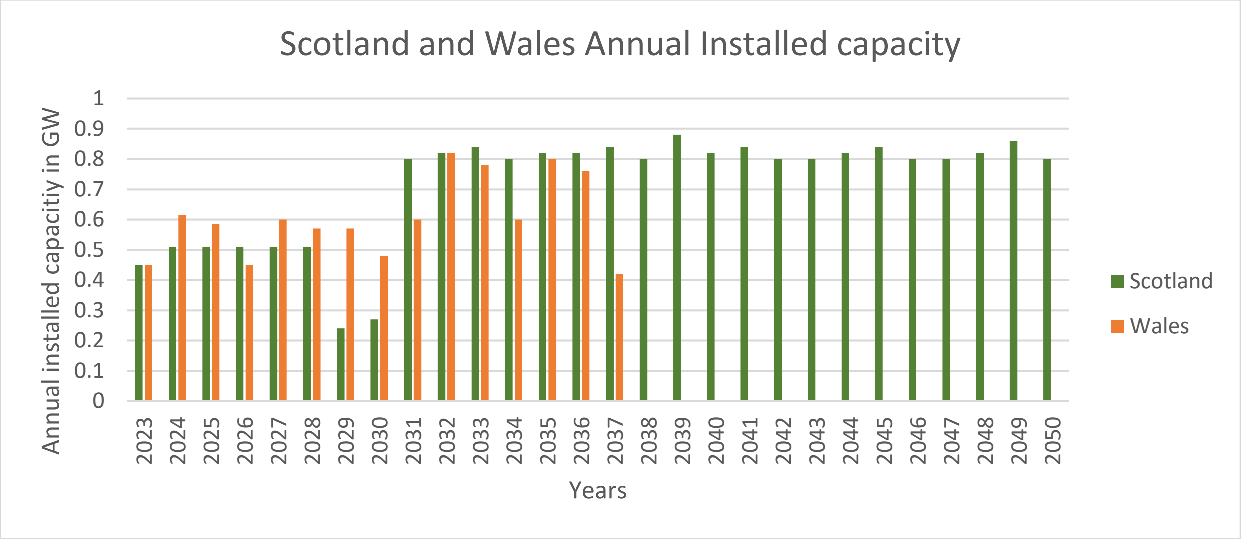


Figure 6.11: Scotland and Wales annual installed capacity distribution.

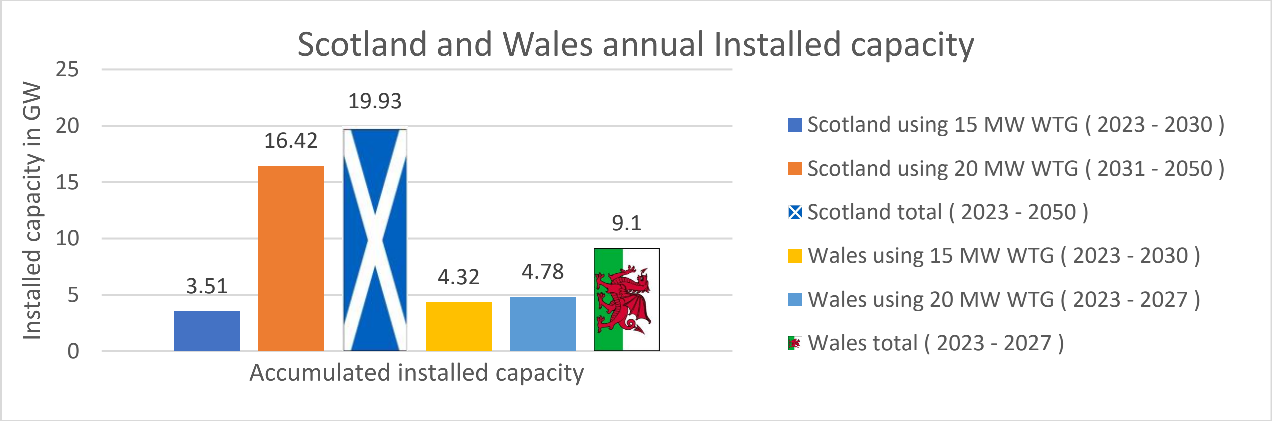


Figure 6.12: UK`s total installed capacity from 2023 – 2050.

When comparing the results obtained in figure 6.12 with table 6-2 the results were split into 3 categories, an overall look of the UK`s goal achievements (combining Scotland installed capacities and Wales`s), followed by Scotland`s and Wales`s own achievements respectively.

- Low 2050 UK Scenario achieved by 2046.
- Low 2050 Scotland Scenario achieved by 2051.
- Low 2050 Wales Scenario achieved by 2032.
- High 2050 UK Scenario by 2074. (Assuming the same technology employed)
- High 2050 Scotland Scenario achieved by 2074. (Assuming the same technology employed)
- High 2050 Wales Scenario achieved by 2037.

Likewise with the case of Ireland, the estimation beyond 2050 it is based on the extrapolation of the annual distribution. Which means that the overall UK offshore wind energetic goal Low scenario can be achieved by 2046, 4 years before the date proposed by the government. On the other hand, the high 2050 scenario, can be achieved 24 years later.

Table 6-2: UK`s floating offshore wind energetic goals. [45]

	Low Scenarios Installation cap.		High Scenarios Installation cap.	
Country	2030	2050	2030	2050
UK		25		50
Scotland		20		40
Wales		4.5		9

Spain

Using the hub port stated in section 5, Spain installation was mostly carried out on Canary Islands. Figure 6.13 contains the annual installed capacity distribution by Spain from 2023 to 2050 and figure 6.14 provides the total installed capacity.

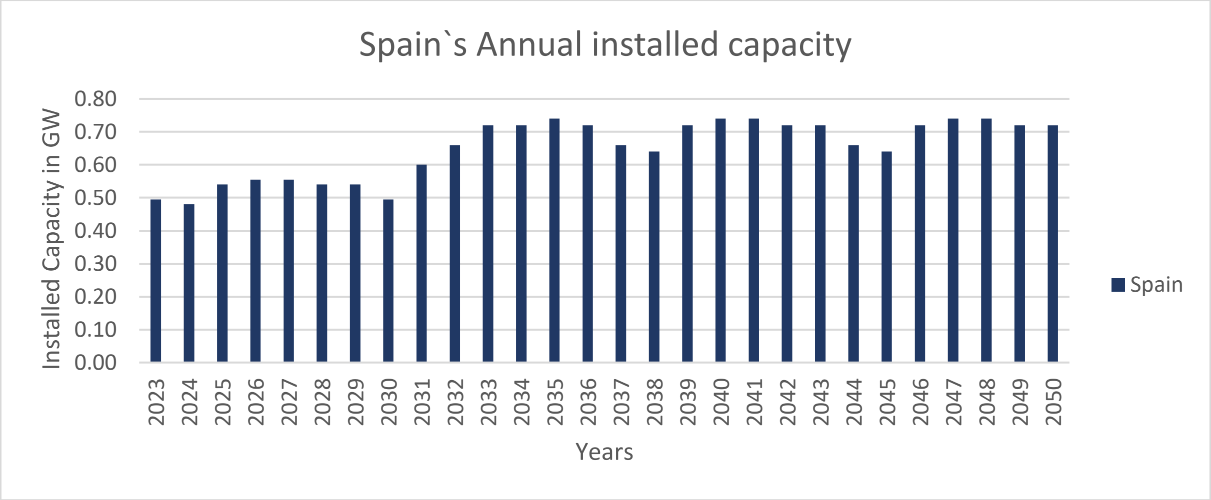


Figure 6.13: Spain`s annual installed capacity distribution.

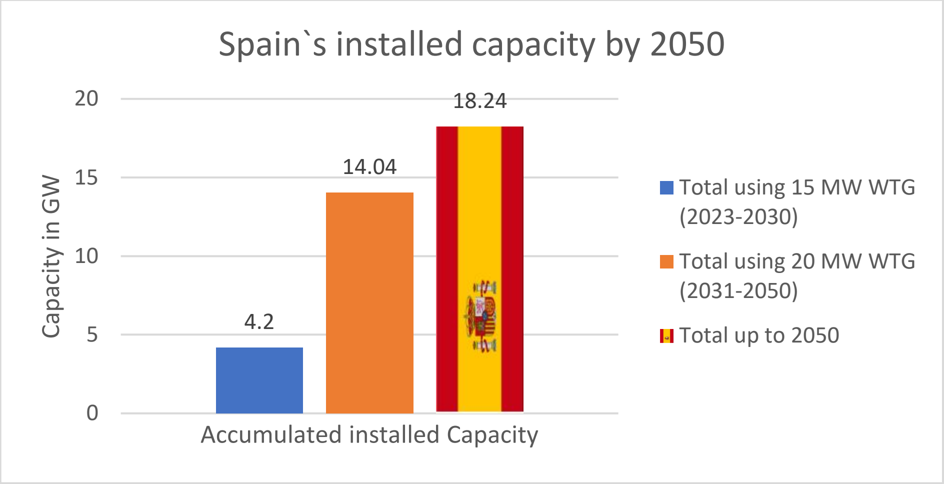


Figure 6.14: Spain`s total installed capacity from 2023 – 2050.

When matching the information contained in figure 6.14 with table 6-3 the results obtained were the following ones, with regards of the expected dates of achievement of Spain`s energetic goals.

- Low 2030 Spain`s scenario can be achieved by 2025.
- Low 2050 Spain`s scenario can be achieved by 2039.
- High 2030 Spain`s Scenario can be achieved by 2028.
- High 2050 Spain`s Scenario can be achieved by 2046.

Meaning that in the case of Spain, both high scenarios can be achieved before 2050.

Table 6-3: Spain`s floating offshore wind energetic goals. [65] [86]

Spain	Low Scenarios Installation cap.		High Scenarios Installation cap.	
Year	2030	2050	2030	2050
GW	1	10	3	15

France

In the case of France figures 6.15 and 6.16 will describe the country`s annual installed capacity distribution and total installed capacity from 2023 – 2050 respectively, this country has the lowest annual installed capacity in comparison with the other hub ports for the reasons exposed in the results of the third case, the distributions can be seen below.

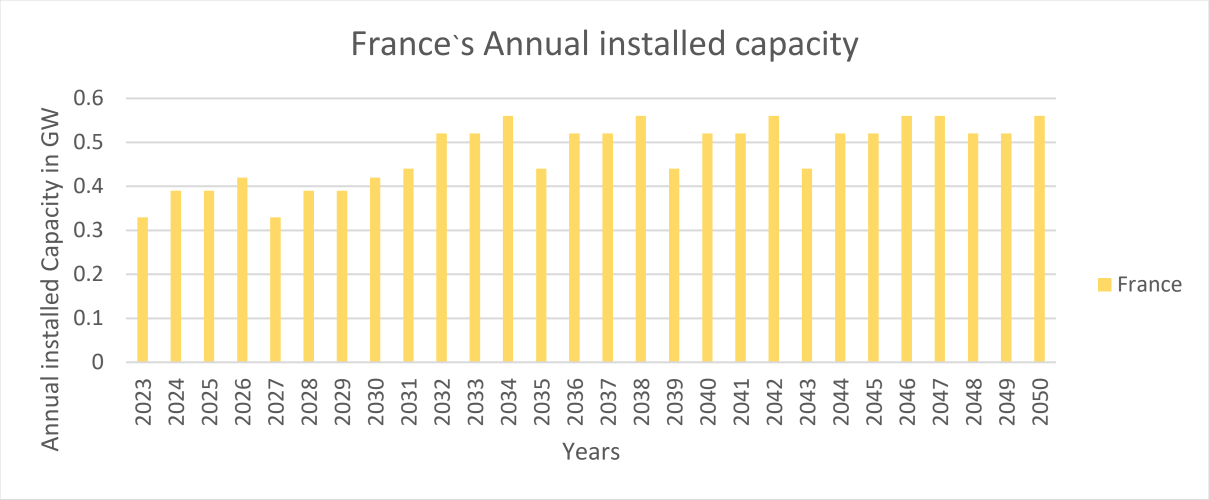


Figure 6.15: France`s annual installed capacity distribution.

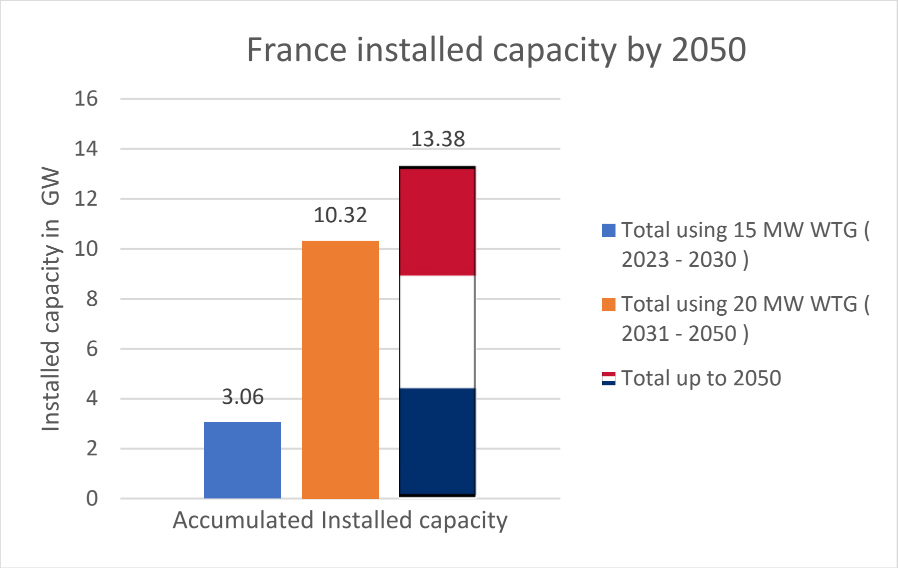


Figure 6.16: France`s total installed capacity from 2023 – 2050.

When comparing the distributions with the expected energetic goals stated in the table 6-4, below, it is possible to state that:

- Low 2030 France`s scenario can be achieved in 2027.
- Low 2050 France`s scenario can be achieved by 2044.
- High 2030 France`s scenario can be achieved by 2054 approximately.
- High 2050 France`s scenario can be achieved by 2064 approximately.

The strategy for estimating France`s achievement of its both High scenarios milestones was performed via extrapolation of figure 6.15 making possible to estimate when the milestone can be achieved, of course, assuming that the same technology is employed beyond 2050. Both Low case scenarios can be achieved before 2050, but both high scenarios go beyond 2050.

Table 6-4: France`s floating offshore wind energetic goals. [76] [92]

France	Low Scenarios Installation cap.		High Scenarios Installation cap.	
Year	2030	2050	2030	2050
GW	1.8	10	15	20

Norway

In contrast with the rest of the countries, Norway has an expectation of fulfilling its energetic expectation by 2040, which is why the annual installed capacity distribution goes from 2023 up to 2040.

Figure 6.17 contains the annual installed capacity distribution of Norway while figure 6.18 contains the total installed capacity from 2023 – 2040. See figures below.

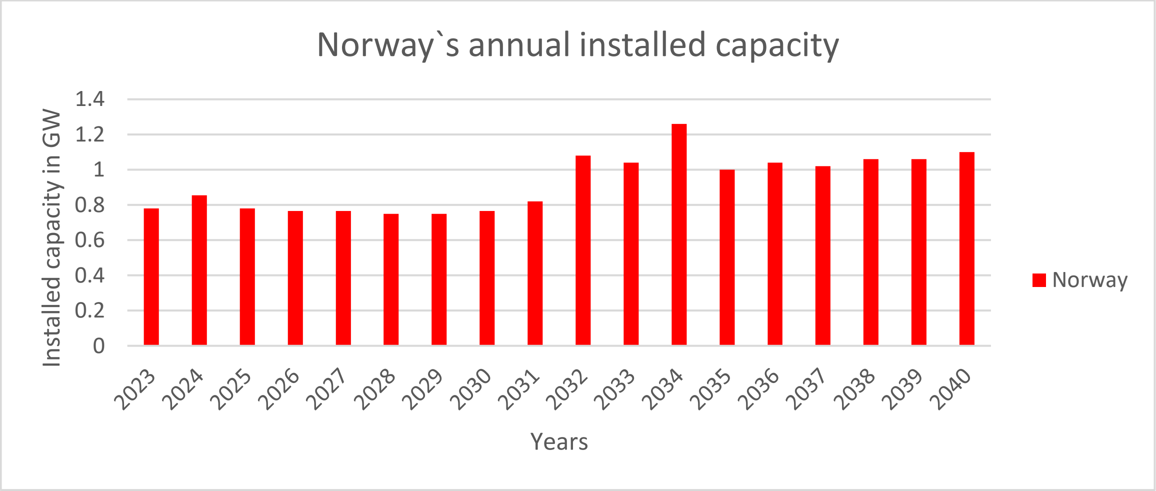


Figure 6.17: Norway`s annual installed capacity distribution.

When matching the distribution from figure 6.17 and 6.18 with table 6-5, the results obtained lead to state that:

- Low 2040 Norway`s scenario falls short by 3.31 GW. but can be achieved by 2043.
- High 2040 Norway`s scenario can be achieved by 2053 approximately.

For both scenarios it was necessary to extrapolate the distribution, in pursuit of obtaining an estimated date of completion. Both Low and High scenarios exceed the date established by the government for 3 years in the Low case and by 13 years for the High case scenario.

Table 6-5: Norway`s floating offshore wind energetic goals. [44]

Norway	Scenarios installation cap. by 2040	
Country	Low	High
GW	20	30

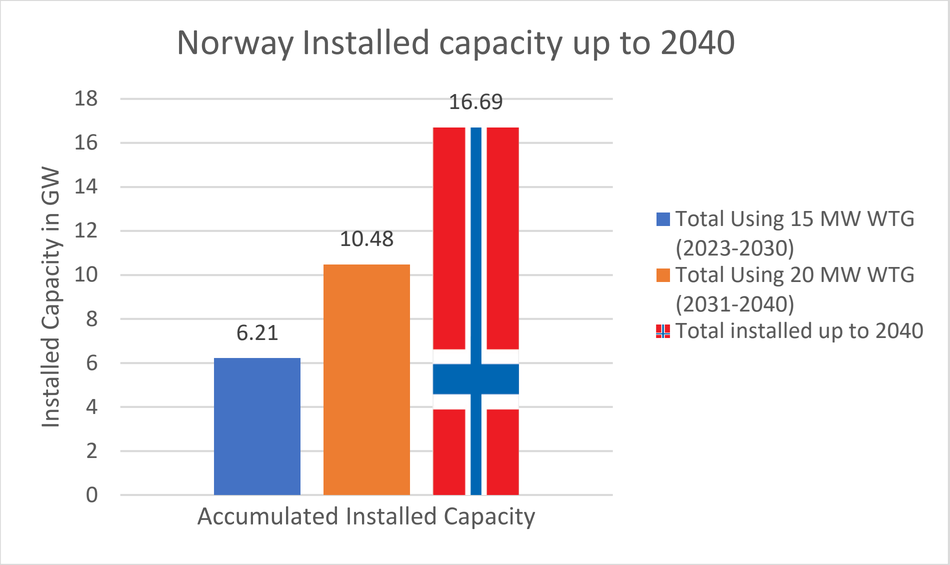


Figure 6.18: Norway`s total installed capacity from 2023 – 2040.

Sweden

Also, a different case than Norway and the rest of the countries since, Sweden’s estimated fulfillment date is in 2045. Therefore, the distribution from figure 6.19 goes from 2023 up to 2045 and also for figure 6.20. See figures below.

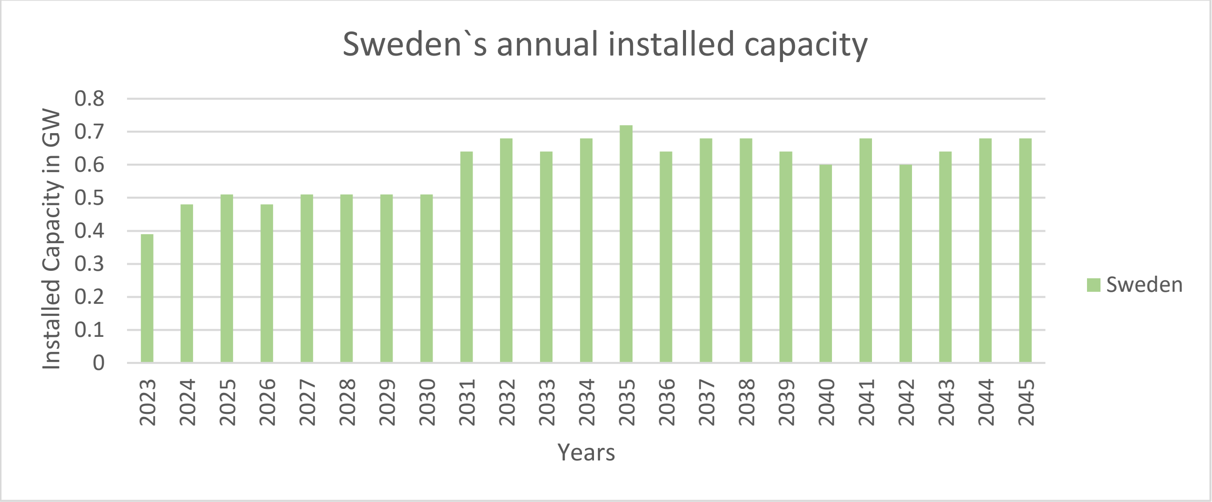


Figure 6.19: Sweden`s annual installed capacity distribution.

When analyzing the distributions from both figures 6.19 and 6.20 and comparing it with table 6-6 the results are the following:

- Low 2045 Sweden`s scenario is achieved by 2039, approximately.
- High 2045 Sweden`s scenario can be achieved by 2048.

To determine the High scenario completion date, it was necessary to extrapolate the distribution from figure 6.19.

The low scenario was achieved 6 years before the established date, whereas the High scenario achievement was reached 3 years later, in 2048.

Table 6-6: Sweden`s floating offshore wind energetic goals. [87] [88] [89]

Sweden	Scenarios installation cap. by 2045	
Year	Low	High
GW	10	15

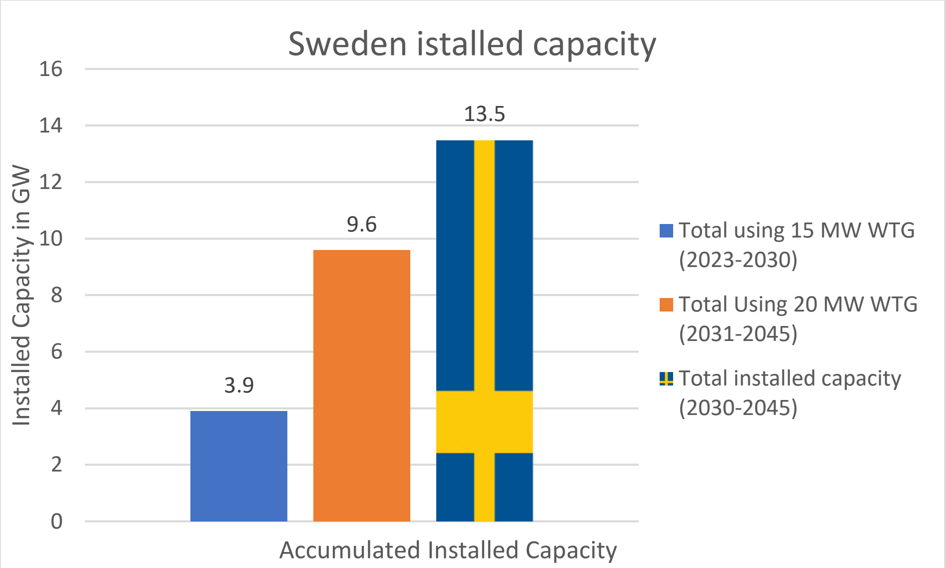


Figure 6.20: Sweden`s total installed capacity from 2023 – 2045.

6.5 Results Fifth case, Sensitivity study for crane transfer

This case was settled with the purpose of seeing the effect that transferring cranes between countries (by proximity criteria) causes on annual installed capacity, in this first case, the transfer operation occurs between Norway and Sweden, and further cases will include other exchanges.

The purpose was to carry out a sensitivity analysis with a view to pick which time period or installed capacity criteria will fit best for both countries, starting with 24 months, then 36 months and finally 48 months as cases where the crane was transferred by time intervals, and only one case where the crane was transferred by installed capacity (every 2 GW the crane was moved to the other country). The methodology goes as follows, once a country completes either the time interval or installed capacity milestone, the crane is supposed to be moved to the other country and therefore, allowing it to start its installation process.

24 Months Case

Figure 6.21 shows the annual distribution of each country while transferring the crane every 24 months. This figure shows that the final year of operations in Norway before the crane transfer also happens to point Sweden`s installation activity. The reason is because it takes approximately 16 weeks to disassemble, transport the crane via container ships and assemble it in Sweden. Since the crane is assembled approximately in June, there are still good weather conditions to perform assembly and integration of the WTGs in Sweden. When Sweden finishes its operations the winter season will already start and therefore Norway must wait till March to commence its assembly operations.

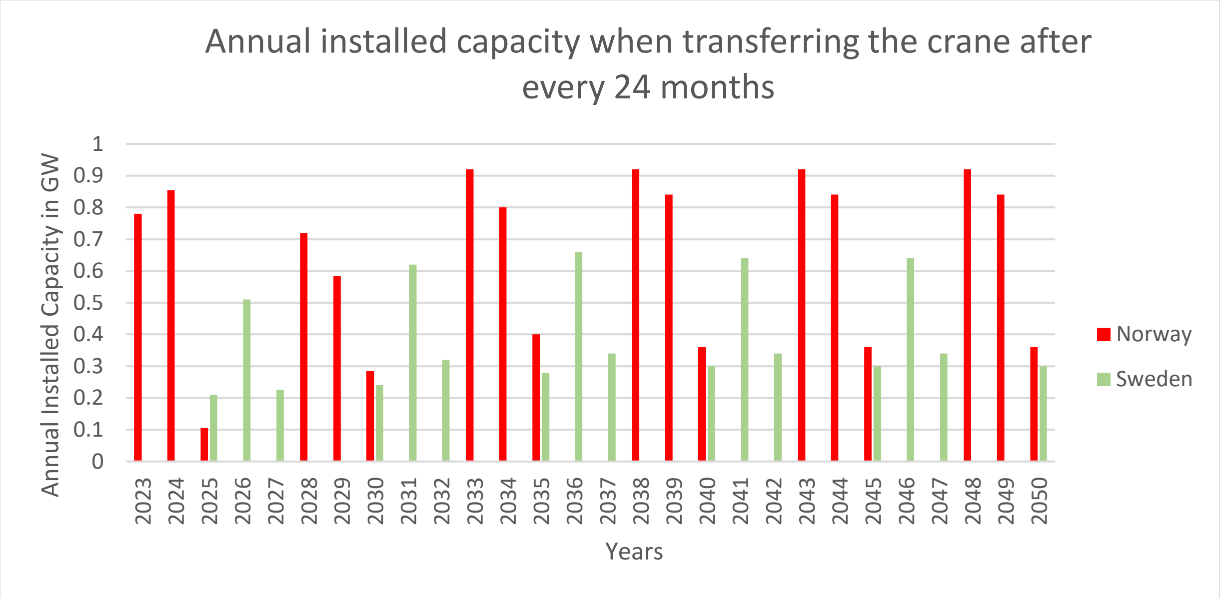


Figure 6.21: 24 months case, Norway`s and Sweden`s annual installed capacity distribution.

When comparing figure 6.21 with table 6-7 the results obtained were the following ones:

- For Sweden to attain its Low scenario value it will be necessary at least to install up to 2066.
- For Norway to reach its Low Scenario, it will be necessary to install up to 2070.

Which clearly exceeds both countries date for achieving their targets, by 21 years in the case of Sweden and 30 years in the case of Norway, assuming of course, same technology over the years. Figure 6.22 shows the total installed capacity from 2030 – 2050 between both countries.

Table 6-7: Norway`s and Sweden`s offshore floating wind scenarios. [44] [87] [88] [89]

	Offshore Floating Wind Scenarios capacity.	
Norway	Low	High
GW	20	30
Sweden	Low	High
GW	10	15

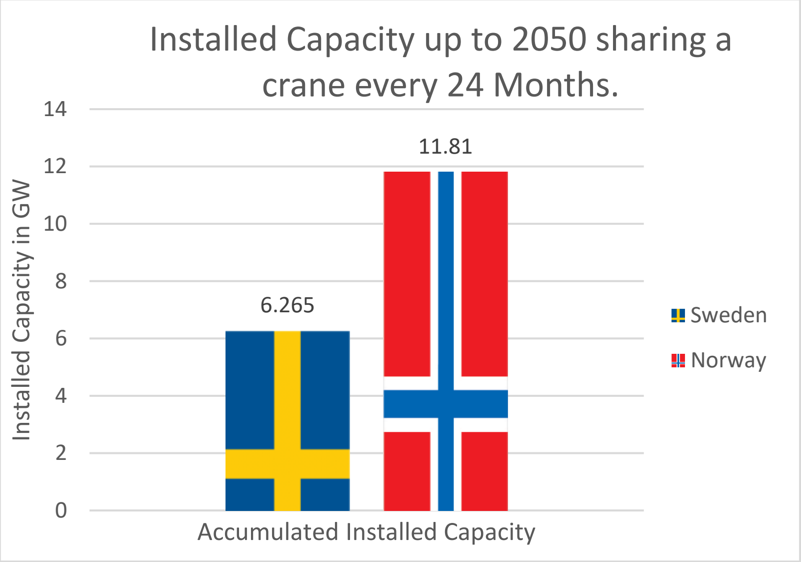


Figure 6.22: 24 months case, Norway`s and Sweden`s total installed capacity from 2023 – 2050.

36 Months Case

Similar to the previous case, but instead 12 more months were added before the crane transfer operation.

Figure 6.23 displays the annual installed capacity distribution of both countries and again, in this case, the final year of operations in Norway shares activities with the first year of operations with Sweden.

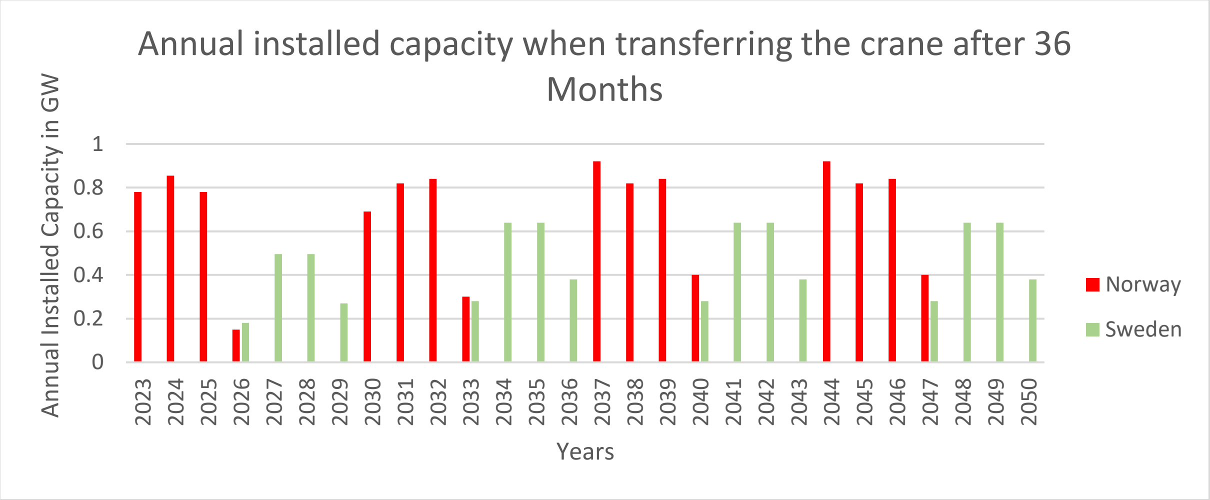


Figure 6.23: 36 months case, Norway`s and Sweden`s annual installed capacity distribution.

When analyzing again table 6-7 with the new distribution from figure 6.23, it is possible to state that:

- For Sweden to attain its Low scenario value it will be necessary at least to install up to 2062.
- Norway to reach its low, it will be necessary to install up to 2068 (assuming the technology remains the same)

Which implies a reduction of 4 years for Sweden to achieve its targets and two years reduction for Norway to achieve its own milestone when comparing it to the first case of 24 months. There is also a marginal decrease in Norway`s total installed capacity (as seen in figure 6.24) of approximately 6% while Sweden has an increase of 16 % of total installed capacity compared to 24 months case.

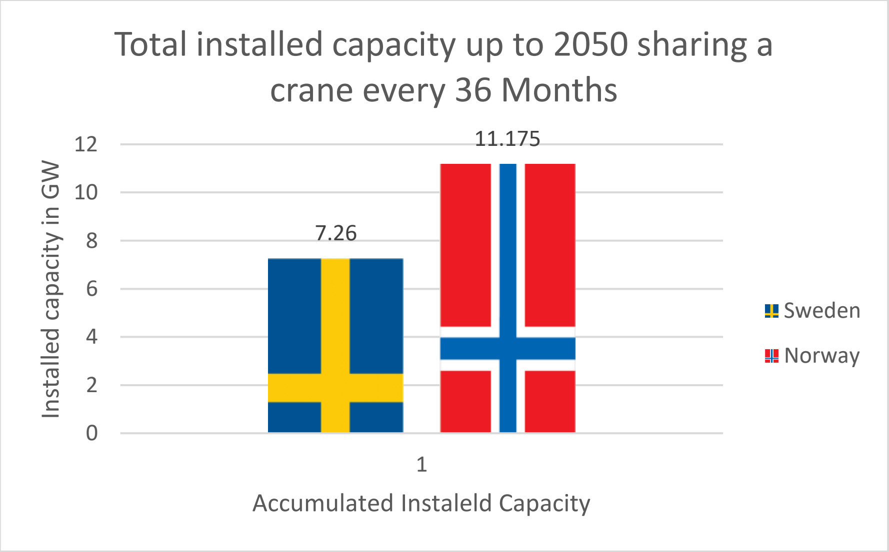


Figure 6.24: 36 months case, Norway`s and Sweden`s total installed capacity from 2023 – 2050.

48 Months Case

Similarly, in previous cases the crane was transferred by time intervals, and in this case, it takes 48 months to carry out the transfer operation. The crane disassembly/assembly plus transportation time still takes 16 weeks on average per operation and it happens the same the final year of operations in Norway and the first year of operations of Sweden, it is possible to assemble the crane in Sweden before the winter season starts.

As seen in figure 6.25, the annual installed distribution for both countries show 3 cycles for each nation from 2023 up to 2050 (excluding the last year where Norway should normally restart its operations) in comparison to 5 cycles in the 24 months case, and 4 cycles each in the 36 months one. To estimate the year of completion for the countries' targets, it will be necessary to recall table 6-7. The results were the following ones:

- For Sweden to attain its Low scenario value it will be necessary at least to install up to 2059.
- Norway to reach its Low scenario, it will be necessary to install up to 2068.

Which means that Sweden reduced its completion date 3 years shorter than the 36 months case and 7 years faster when comparing it to the 24 months case. In the case of Norway, the Low scenario date can be fulfilled in 2068, meaning the same result as the 36 months case.

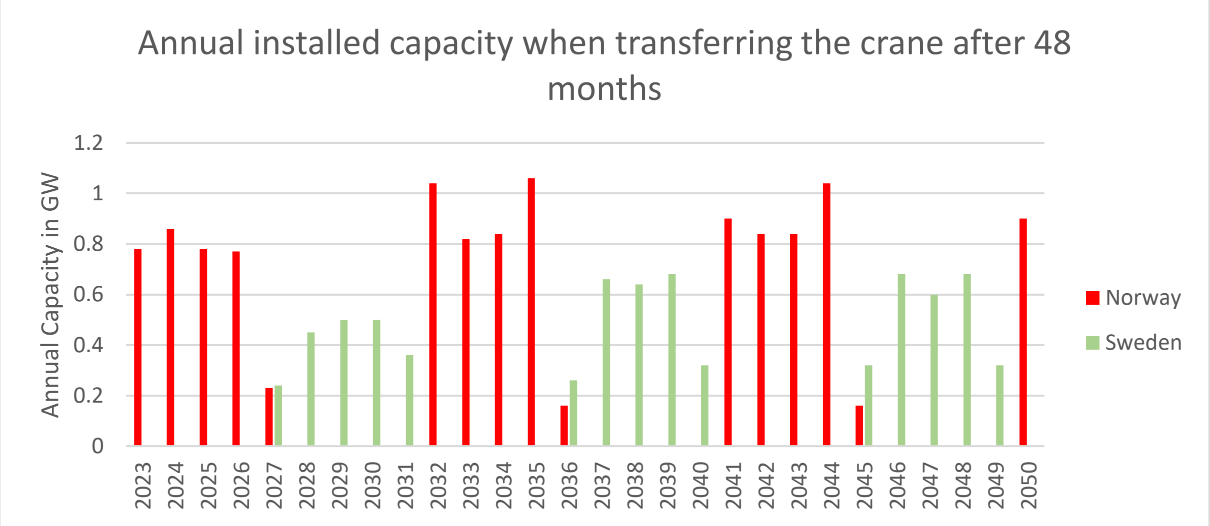


Figure 6.25: 48 months case, Norway`s and Sweden`s annual installed capacity distribution.

According to figure 6.26, there is an increase in Norway's total installed capacity compared to the 24 months case of almost 2% and almost 7.5% compared to the 36 months case. Sweden, on the other hand shows an increase of approximately 14% compared to the 24 months case scenario and a marginal decrease of 0.7% compared to the 36 months case. Since the cycles are longer it is possible for Sweden to attain its target faster than the 36 months case.

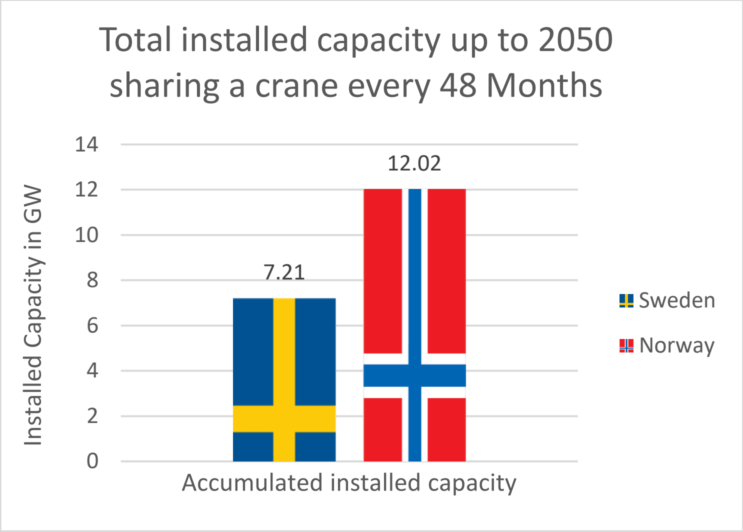


Figure 6.26: 48 months case, Norway`s and Sweden`s total installed capacity from 2023 – 2050.

2 GW Months Case

Compared to the other cases, this one is carried out by installed capacity and not by time. Figure 6.27 shows the annual installed capacity distribution of both countries, and when matched with table 6-7 the results are the following:

- In the case of Sweden, it will take approximately up to 2054 to achieve its Low scenario.
- Norway to reach its Low scenario, will have to install WTGs up to 2079 approximately.

This case shows the fact that Sweden will accomplish its target faster than the all the previous cases, 5 years earlier than the 48 months case, 8 years earlier than the 36 months case and 12 years earlier than the 24 months case, whereas Norway takes 11 years longer to fulfill its target compared to 48- and 36-months case and 9 years longer than the 24 months case.

As seen in figure 6.28, the total installed capacity of Sweden experiences an increase of almost 24.5 % compared to the 24 months case, and around 10% with 36- and 48-months case, whereas Norway sees a decrease of almost 13 % with respect to the 24 months case, 35% with regards to the 36 months case and around 15% with the 48 months case. Which is why for Sweden it takes less time but for Norway it takes considerably more. Table 6-8 summarizes the observations.

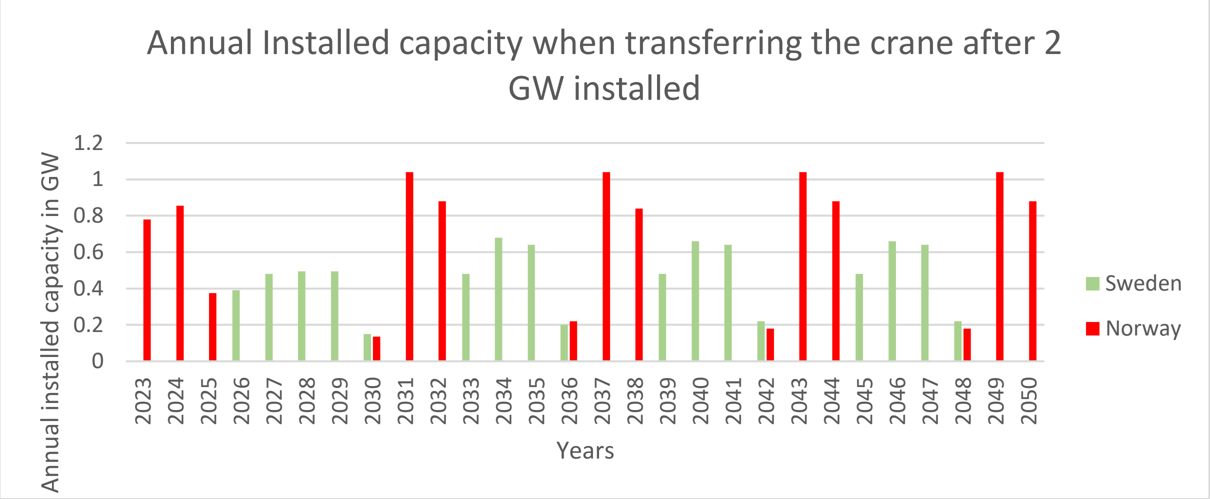


Figure 6.27: 2 GW case, Norway`s and Sweden`s annual installed capacity distribution.

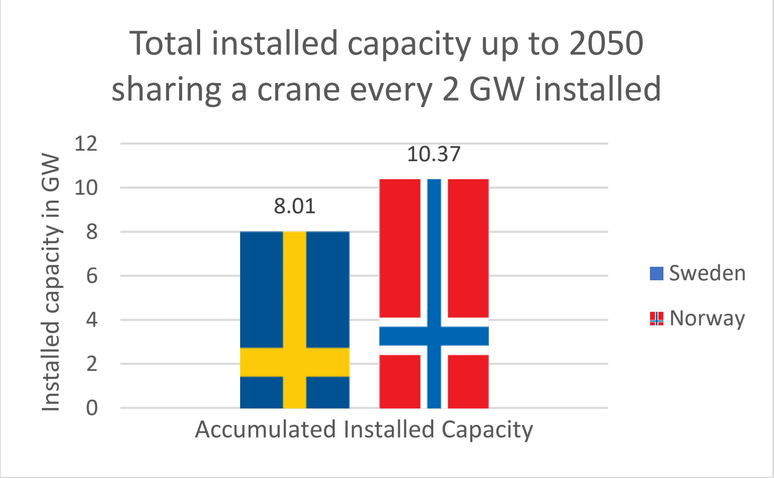


Figure 6.28: 2 GW case, Norway`s and Sweden`s total installed capacity from 2023 – 2050.

Table 6-8: Summary of crane transfer cases.

		Low Scenario	
		Sweden	Norway
Crane Transfer Every	24 months	2066	2070
	36 months	2062	2068
	48 months	2059	2068
	2 GW	2054	2079

Table 6-8 contains the results of this case scenario and shows that:

- Since Sweden has half of the lower scenario capacity, the longer the crane stays here, the shorter time this scenario will be reached (as expected).

- The reason why 48 months takes less than the rest of the cases, is because in those 4 years cycles there are at least 3 fully operational years in between the first and last year where, the installation starts and also must stop as soon as the time is completed (it is important to understand that a 48-month cycle includes the year where the installation process started. E.g., in the case of Norway that starts in March /2023, from March 2023 to December 2023 generates an annual installation year into the distribution which means the year of the commencement is included)
- The reason why 2GW makes Norway take longer to achieve its Low scenario is because the crane stays longer in Sweden to install 2 GW than it does in Norway.
- Norway could represent a potential installation hub ready for exporting Spar-type WTGS since it takes less time to assemble a greater annual capacity compared to semi-submersible hub ports (possibility of exporting to Sweden or even Scotland via tugging).
- Makes sense to use the 48 months case scenario for the following cases since it has a more balanced distribution.

6.6 Results Sixth case, Crane transfer Ireland – Wales

This case studies the effect of the crane transfer operations between Ireland and Wales. Figure 6.29 contains the annual installed capacity distribution of both countries, when comparing it with table 6-9 it allows to state that:

- In the case of Ireland, the Low 2030 scenario can be reached in 2036, five years later than when it has its own crane. Low 2050 scenario can be reached around 2072 (assuming the same technology), 19 years later than when it has its own crane.
- Wales` Low 2050 scenario can be reached by 2039, 7 years later that when it has its own crane. Whereas the High 2050 Scenario can be reached by 2054, 17 years later that when it has its own crane.

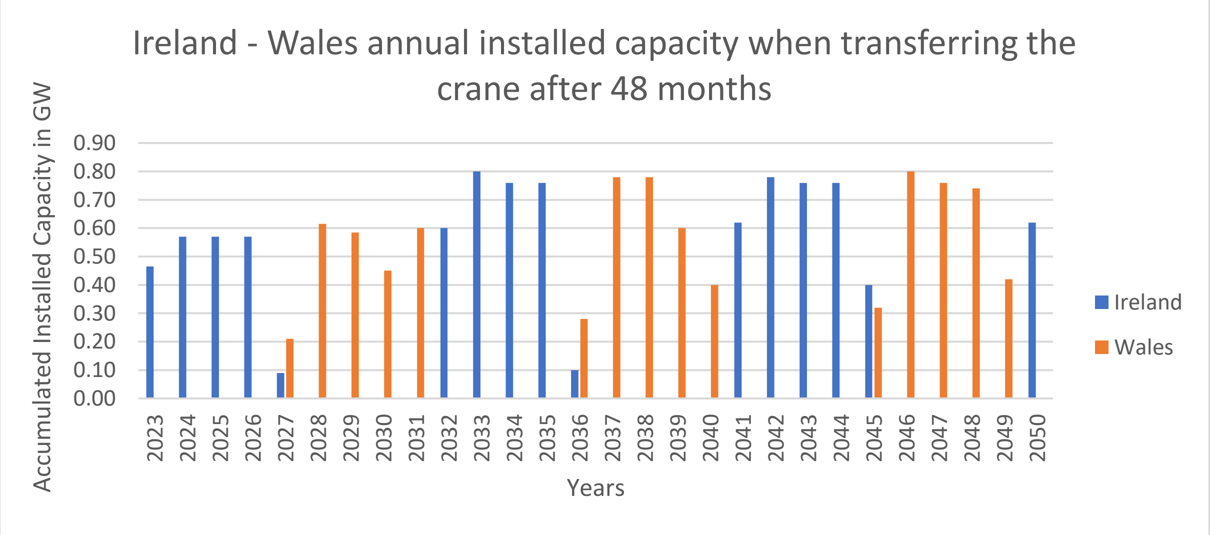


Figure 6.29: Ireland`s and Wales` annual installed capacity distribution.

Table 6-9: Offshore floating wind target scenarios Ireland – Wales. [45] [58] [84]

	Low Scenarios Installation cap.		High Scenarios Installation cap.	
Year	2030	2050	2030	2050
Ireland	5	20	10	25
Wales		4.5		9

Figure 6.30 shows the total accumulated capacity of both countries. This figure indicates that Ireland decreased its overall Installed capacity around 53% while Wales extended its completion time from 2037 up to 2049. i.e., 12 years later and presents a reduction of 8% of its installed capacity.

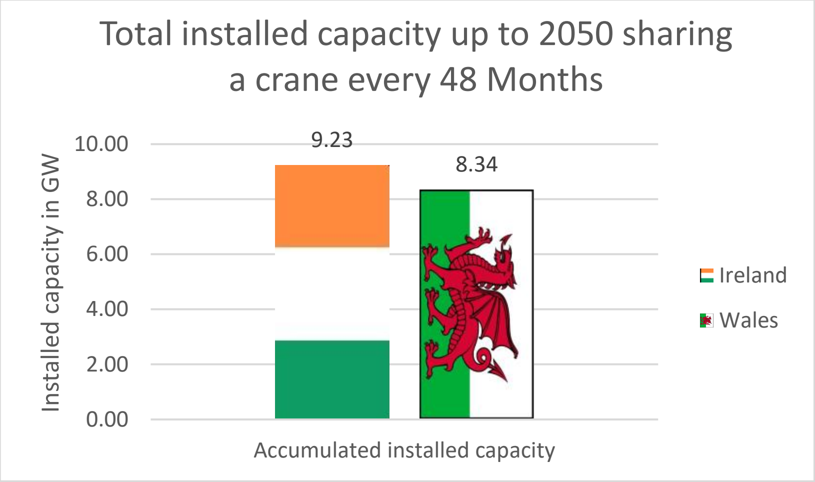


Figure 6.30: Ireland`s and Wales` total installed capacity from 2023 – 2050.

6.7 Results Seventh case, Crane transfer Spain – France

This scenario has the same purpose than the sixth case, but the difference is that this one is held between Spain and France. Figure 6.31 contains the distribution of both countries and when matching these results with table 6-10 it is possible to estimate when both nations can achieve their own offshore floating wind energetic targets. The scenario findings indicate the following statements:

- In the case of Spain, the Low 2030 Scenario was achieved by 2025 (no changes) while the Low scenario 2050 can be achieved by 2054.
- France reaches its Low 2030 scenario by 2036, while the Low 2050 scenario in 2067.

Since the Spanish Low 2030 scenario is quiet low (1 GW), there are no changes, but regarding the long term one, the Low 2050, it takes almost 15 years more to accomplish it in comparison to when it has its own dedicated crane. For France, its Low 2030 scenario is achieved 9 years later than when it has its own integration crane. For the Low 2050 Scenario it takes 23 years longer than when it has the dedicated crane.

Figure 6.32 represents the total installed capacity both nations, and as a result of the crane transfer operation, France reduced its installed capacity by approximately 58% while Spain reduced its installation capacity about 60% both by 2050.

Table 6-10: Offshore floating wind target scenarios Spain – France. [65] [76] [86] [92]

	Low Scenarios Installation cap.		High Scenarios Installation cap.	
Year	2030	2050	2030	2050
France	1.8	10	15	20
Spain	1	10	3	15

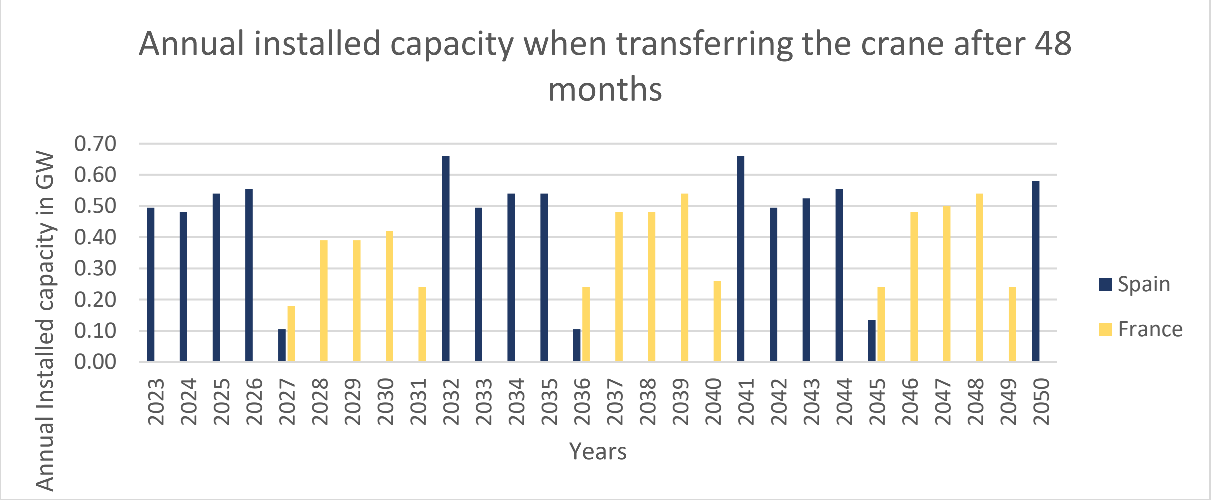


Figure 6.31: Spain`s and France`s annual installed capacity distribution.

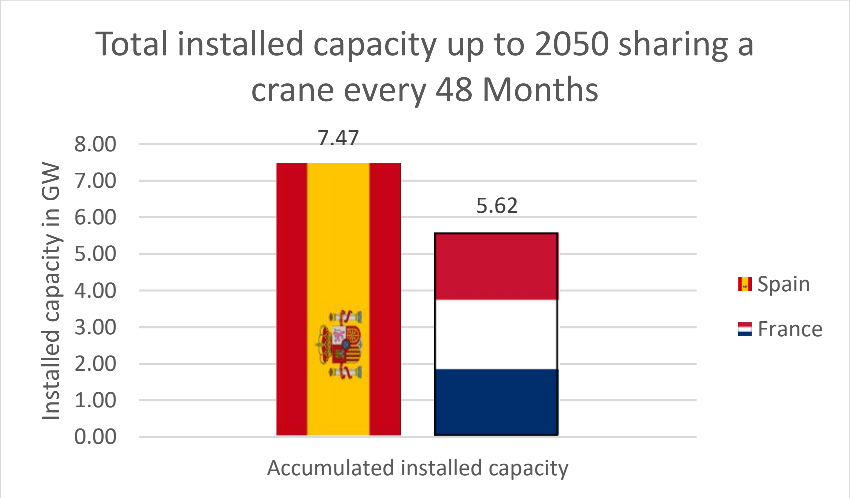


Figure 6.32: Spain`s and France` total installed capacity from 2023 – 2050.

6.8 Results Eighth case, 7 hub ports, 7 Integration cranes

This case was set in with the purpose of showing how does the *“best case scenario”* looks, ideally it is a very optimistic case that will serve to reflect how the lack of cranes affect the country`s expected offshore floating wind energetic target for the remaining 3 cases.

Figure 6.33 displays a map where all the hub ports were fully operational from 2023 up to 2050 (Norway has been extended from 2040 up to 2050 by extrapolating its distribution for 10 more years, while for Sweden the extrapolation was made from 2045 up to 2050) assuming that all components were on site, the number of integration cranes worldwide allows all these countries to start at the same time and all the assumptions from section 4, before mentioned.

Figure 6.33: 7 hub ports 7 Integration cranes total Installed capacity 2023 – 2050.

6.9 Results Ninth case, 7 hub ports, 6 Integration cranes

This case shows how the installed capacity gets affected by including into the map the crane transfer operation between Norway and Sweden. Figure 6.34 shows the map of interest and figure 6.35 shows the reduction rate for both countries from 2023 – 2050 in terms of installed capacity.

In the case of Norway, the total installed capacity 2023 – 2050 was reduced around 56% in comparison to when it has its own crane. Whereas for Sweden it is about 60% reduction.

Figure 6.34: 7 hub ports 6 Integration cranes total Installed capacity 2023 – 2050.

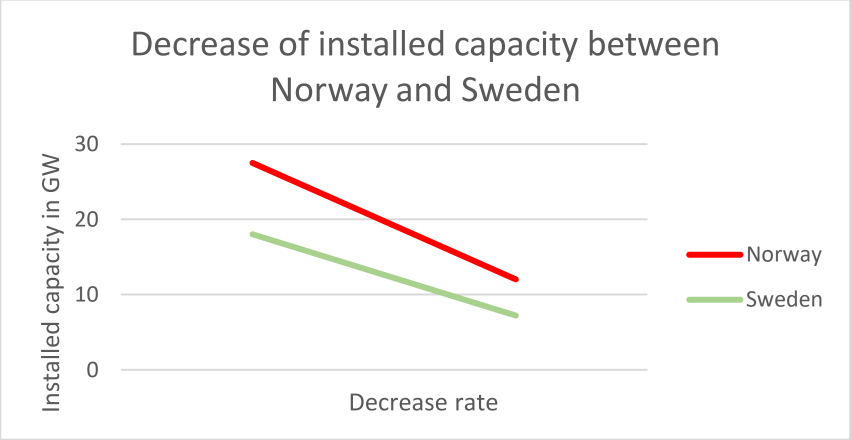


Figure 6.35: Decrease rate of installed capacity for Norway and Sweden 2023 – 2050.

6.10 Results Tenth case, 7 hub ports, 5 Integration cranes

An extra case of crane transfer will be added to the map in figure 6.36 to show in figure 6.37, the effect of 2 crane transfer operations happening at the same time in 4 countries, this will happen as per previous cases, by proximity. Meaning Norway – Swede and Spain – France will transfer their integration crane as per fifth case criteria, every 48 months.

Figure 6.37 indicates that the decrease rates of Spain resemble the one in Sweden, approximately 60% reduction, while France experiences 58% reduction as stated in the Seventh Case. And for Norway, as stated in previous case, reduction is 56%.

Figure 6.36: 7 hub ports 5 Integration cranes total Installed capacity 2023 – 2050.

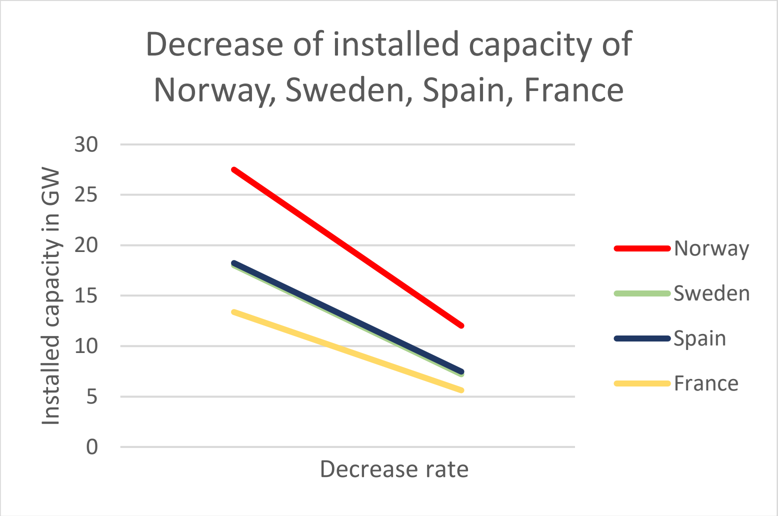


Figure 6.37: Decrease rate of installed capacity for the Tenth case 2023 – 2050.

6.11 Results Eleventh case, 7 hub ports, 4 Integration cranes

This case will involve in this instance, 3 crane transfer operations happening between Norway – Sweden, Spain – France and Ireland – Wales. The graphical representation can be seen in figure 6.38, while the decrease rates of all the countries together can be seen in figure 6.39. As stated in the crane transfer case between Ireland and Wales, Ireland experiences 53 % of reduction on its total installed capacity while Wales nearly 8 %.

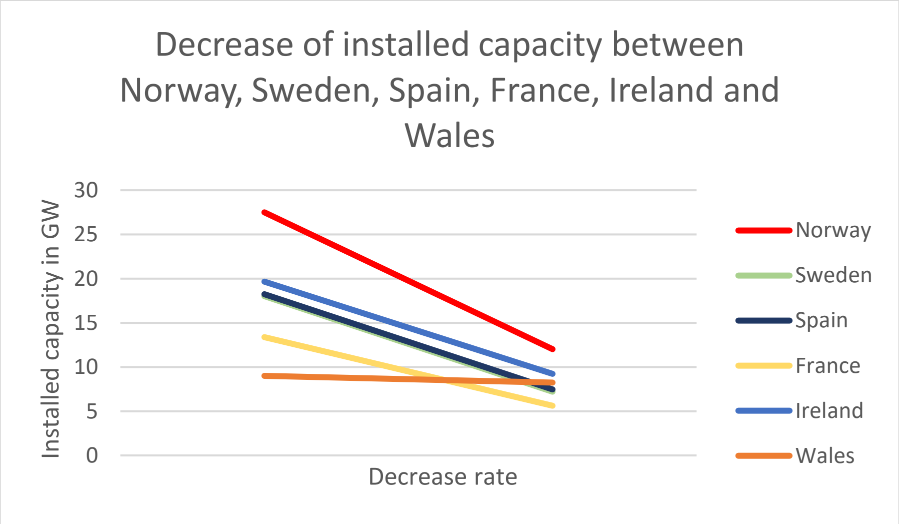


Figure 6.38: Decrease rate of installed capacity for the Eleventh case 2023 – 2050.

Figure 6.39: 7 hub ports 4 Integration cranes total Installed capacity 2023 – 2050.

Finally, table 6-11 summarizes the obtained results with regards to the Low 2050 scenario (2040 for Norway and 2045 for Sweden) while also showing the decrease rate in % of the countries sharing a crane i.e., having to transfer it via container ships among them.

Table 6-11: Summary of the Results for each country based on 2050 Low scenario.

		Low 2050 Scenario Achievement date	Reduction rate in % by 2050 when sharing a crane
Dedicated Crane	Ireland	2051	-
	Scotland	2051	-
	Wales	2032	-
	Spain	2039	-
	France	2044	-
	Norway *	2053	-
	Sweden**	2048	-
Crane Transfer	Ireland	2072	53
	Scotland	-	-
	Wales	2054	8
	Spain	2054	60
	France	2067	58
	Norway	2068	56
	Sweden	2059	60

- Only one country has a decrease rate below 50% and that is Wales, since it is able to install its desired capacity relatively fast does not seem to be affected in terms of decreased rate but, on the other hand, is the second country that extends its Low 2050 scenario for more than 21 years (right after France).
- **The country that takes less to reach its own target its Sweden, the reason is since it has a relatively low 2045 objective (15 GW) and the installation rate per year its approximately half GW it is reasonable that it only requires 11 years more to achieve its objective. (Assuming the same technology over 2050).
- *The second country that takes less to achieve its targets when sharing a crane is Norway, since it has a reasonably high target installation capacity by 2040 of 30 GW, but an exceptional annual installation rate in average of approximately 0.76 GW per year.

Conclusion

Since the objective of the EU is to reach the net zero standard, the application of new methods and technologies to cover the energy demand all over the region must be employed. One of the suggested methods that will help to reach this target is the application of OFWT. Since these are installed in deep waters far from shore two main advantages can be considered; first, problems linked to acceptance by habitants surrounding the planned area of the projects can be neglected. Secondly, since it is far from land, the roughness factor and wind profile properties provide a more appealing energy production prediction.

The targets set by the countries provide an ambitious number of projects that must be installed to achieve what is described in this master thesis as a "*High scenario*". The purpose of this research was to evaluate if it was feasible to reach this scenario. Multiple assumptions were taken in place with the intention of evaluating the feasibility of such goals from a purely logistics perspective, e.g., components already on site, ready to be installed (which is neglecting one of the factors that can add time to the fulfillment of any project which is the supply chain), and all those included in section 4.

Aspects such as the selection of the most optimal combination of assets designated to perform the installation process on each hub port, weather analysis impact, integration crane transfer operations were performed, and the results are listed below.

- It is necessary to find the most optimal combination of infrastructure first, in an effort to accelerate the process as much as possible. Since the assets that were manipulated in number represent a marginal increase in the cost of the project it is disregarded as a limit criterion.
    - In the case of the semi-submersible floater hub ports, adding an extra set of tugs and an extra floater assembly crane (2 sets of tugs and 2 Floater cranes in total) decreased the completion time of a 1.5 GW wind farm by approximately 3 years.
    - For Spar-buoy floaters it was necessary to employ 3 sets of tugs and 2 AHVs in order to significantly reduce the completion time by approximately the same amount of 3 years.

- The location of the hub port can determine the weather downtime of the assets. Since depending on the location of the hub port the weather conditions may change, the installation process may be affected by wind speeds and wave heights limiting cranes and tugs respectively.
    - France and Sweden have the lowest annual installation rate due to the geographical location of the hub ports. Endowed with the exact same combination of assets used to perform the installation process than the rest of the countries (excluding Norway) the weather downtimes in these two

locations was the highest among all the hub ports. France has in average 58% in yearly weather downtime and Sweden 44% (metrics given by the program to study the effect of weather) while countries as Scotland, Wales and Ireland are below 40%

  - For the semi-submersible hub ports, they are more sensitive to the downtime of the floater assembly cranes than to downtime experienced by the integration crane. This occurs since it takes longer to assemble the whole floater together than assembling the WTG and then mating it with the floater.

- Providing each country with its own dedicated integration crane seems to be a key element in achieving FOW goals for each one of the nations.

  - Due to all the assumptions taken into account in all of the cases, the completion dates of the targets represent a very idealistic result since important factors such as supply chain of the components and actual starting date of the projects are not considered.

  - Having a limited number of integrations in the market capable of assembly 15 MW WTG and greater capacities such as 20 MW, created the necessity to study the effects of transferring the crane among nearby countries.

  - Most of the countries are capable of at least reaching the Low 2050 Scenario when having a dedicated integration crane.

- Finding an optimal crane transfer period can enhance the productivity of the countries involved.

  - It is better to set up a time-limited criterion rather than an installed capacity one. Since the countries do not have the same conditions i.e., weather, water depth at the hub ports, among others, it will take longer for one country to install a certain capacity and therefore extend the target achievability of the other. A fact that will, in the end, delay the whole EU target.

  - According to different simulations using Shoreline, the best time-limited criterion turned out to be the 48 months case. Since shows better overall results for both countries (Norway and Sweden) on the long run. This case showed a shorter completion time for both parts in comparison to 24 months or even 2 GW criterion. When comparing the 48 months case scenario and the 24 months one, the 48 months case reduces the target completion by 7 years for Sweden and 2 years reduction for Norway. Whereas, while comparing it to the 2 GW case, Norway`s target gets extended 11 more years, while Sweden`s one is two years shorter.

- Norway could, potentially export units to Sweden and Scotland assuming more hub ports were identified, because it takes less time to install Spar-type WTG than Semi-submersibles (due to the absence of the assembly process of the floater), since Spar floaters, once constructed must be towed out and assembled to its respective WTG by the integration crane.

- Transferring the crane represents a reduction of more than 52% of the estimated accumulated installed capacity 2023 – 2050 for most of the countries, while also experiencing an extension in the completion dates of their desired targets.

    - Ireland suffers a decrease of 53% of its installed capacity when transferring the crane to Wales.

    - Spain and Sweden experience a reduction of approximately 60% of its estimated installed capacity.

    - France sees a reduction of 58% of its estimated installed capacity.

    - Norway has the third lowest reduction, with approximately 56%.

    - Wales has only 8% in reduction but an extension of more than 21 years to achieve its Low 2050 scenario.

- All the accumulated installed capacities estimates were made by extrapolating the annual installation rates of each country, based on the weather conditions provided by ERA5, while using 20 years of data and analyzing the P50 value. It is important to note that the further the analysis is carried out, the more uncertainties will be present in comparison with real life situations and therefore, these estimates will not be 100% accurate.

The above statements indicate that in order for the EU to achieve their desired energetic milestones on time, huge investments shall be done by governments in order to enhance all the aspects that shall be covered regarding OFW farms, e.g., supply chains (accelerate/facilitate the transport of components), increase the rate of licensing of the projects, adaptation of hub ports, substations, electrical power grids, and more importantly, integration cranes capable of lifting the nacelles of new generation of WTGs, since the tendency is for them to grow not only in size but also in capacity. The presence of these cranes will allow more hub ports to operate and therefore increase the annual installed capacity per year per country. Otherwise, it will not be possible to achieve these targets.

Further work

As recommended by Mr. Sverre Olden Mala (Head of communications Gas & Power and New value chains, Equinor), during personal communications; it is important to make qualitative analysis with profound experts, since their expertise will help to scope the project in a more realistic way considering latest news in the market. A meeting was carried out with Mr. Sverre O. and Øystein Håland (Senior Advisor on global energy markets, Equinor) with the purpose to understand the latest tendencies of the market towards offshore wind. Some recommendations were made with a view to considering factors such as “elements impacting the capacity to do the installations. Not only focus on the windmills and wind turbines, but also include other elements that are needed before electrons can be put into the grid.” Meaning by this, the actual situation of electrical substations (considered critical), the uncertain future of raw materials such as copper (essential for electric cables) with a possibility of being replaced by aluminum (which has a background of environmental and greenhouse concerns) and other uncertainties related to the future of offshore wind.

Therefore, the recommendations for future work could be:

- Consider the actual situation towards the wind industry when analyzing projects of this nature. And try to find advice from experts that can lead to an increase in the closeness of the project to a real-life case scenario.

- Including the installation of cabling when performing analysis with Shoreline, this will provide a more accurate completion time of a wind farm.

- Lastly, Including supply chain logistics. This will enhance the closeness to real life case scenarios.

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A. Fully Commissioned / Partial Generation / Under Construction Wind Farms Across Europe.

Table A-1: Operational/Consented Projects in Scottish waters [47][48]

Name of the development	Capacity (MW)	Substructure	Status	Country
Robin Rigg	174	Fixed	Operational	Scotland
Moray West	882	Fixed	Under Construction	
Moray East	950	Fixed	Operational	
Beatrice	588	Fixed	Operational	
Hywind Scotland	30	Floating	Operational	
Aberdeen Bay	93	Fixed	Operational	
Kincardine FOW	48	Floating	Operational	
NNG	448	Fixed	Under Construction	
Seagreen 1	1140	Fixed	Under Construction	
Seagreen 1a	420	Fixed	Consented	
Inch Cape	1080	Fixed	Consented	
Pentland FOW	10	Floating	Consented	
Total	5863 MW			

Table A-2: Details about existing wind farms in Wales. [50]

Name of the development	Capacity (MW)	Substructure	Status	Country
North Hoyle	60	Fixed	Operational	Wales
Rhyl Flats	90	Fixed	Operational	
Gwynt-y-Môr	576	Fixed	Operational	
Total	726 MW			

Table A-3: Operational Projects in English waters [48] [49]

Name of the development	Capacity (MW)	Substructure	Status	Country
Barrow	90	Fixed	Operational	England
Blyth Demo	42	Fixed	Operational	
Burbo Bank	90	Fixed	Operational	
Burbo Bank Extension	259	Fixed	Operational	
Dudgeon	402	Fixed	Operational	
East Anglia ONE	714	Fixed	Operational	
Galloper	353	Fixed	Operational	
Greater Gabbard	504	Fixed	Operational	
Gunfleet sands Demo	12	Fixed	Operational	
Gunfleet Sands I	108	Fixed	Operational	
Gunfleet Sands II	65	Fixed	Operational	
Honrsea 1	1218	Fixed	Operational	
Hornsea 2	1386	Fixed	Operational	
Humber Gateway	219	Fixed	Operational	
Inner Dowsing	97	Fixed	Operational	
Kentish Flats	90	Fixed	Operational	
Kentish Flats Extension	50	Fixed	Operational	
Lincs	270	Fixed	Operational	
London Array	630	Fixed	Operational	
Lynn	97	Fixed	Operational	
Ormonde	150	Fixed	Operational	
Race Bank	573	Fixed	Operational	
Rampion	400	Fixed	Operational	
Scroby Sands	60	Fixed	Operational	
Sheringham Shoal	317	Fixed	Operational	
Thanet	300	Fixed	Operational	
Triton Knoll	857	Fixed	Operational	
Walney 1	184	Fixed	Operational	
Walney 2	184	Fixed	Operational	
Walney Extension	659	Fixed	Operational	
West of Duddon Sands	389	Fixed	Operational	
Westermost Rough	210	Fixed	Operational	
Total	10979 MW			

Table A-4: Operational Projects in English waters. [48]

Name	Capacity (MW)	Substructure	Status	Country
Samsø	23	Fixed	Operational	Denmark
Horns Rev 1	160	Fixed	Operational	
Rønland	17.2	Fixed	Operational	
Tunø Knob	5	Fixed	Operational	
Nysted	165.6	Fixed	Operational	
Middelgrunden	40	Fixed	Operational	
Frederikshavn	10.6	Fixed	Operational	
Horns Rev 2	209.3	Fixed	Operational	
Rødsand 2	207	Fixed	Operational	
Sprogø	21	Fixed	Operational	
Anholt	399.6	Fixed	Operational	
Avedøre Holme	10.8	Fixed	Operational	
Horns Rev 3	406.7	Fixed	Operational	
Kriegers Flak	605	Fixed	Operational	
Nissum Bredning Vind	28	Fixed	Operational	
Vesterhav Nord/Syd	344	Fixed	Operational	
Total	2652.8 MW			

Table A-5: Operational Projects in Swedish waters. [48]

Name of the development	Capacity (MW)	Substructure	Status	Country
Bockstigen	3.3	Fixed	Operational	Sweden
Lillgrund	110.4	Fixed	Operational	
Vindpark Vänern	30	Fixed	Operational	
Kårehamn	48	Fixed	Operational	
SeaTwirl S1	0.03	Floating	Operational	
Total	191.73 MW			

B. Specifications of vessels used for the simulation.

Table B-1: Parameters for AHV. [93]

Anchor Handling Vessel (AHV) Parameters	
Transit speed	15 Kn
Towing speed	5 Kn
Dynamic positioning speed	2 Kn
Dynamic position activation time	1h
Capacities	
Mooring Lines	4 Units
Mooring Line Anchors	4 Units
Fuel Oil Consumption	
Fuel consumption in transit (loaded)	$0.025637 \frac{ton}{km}$
Fuel consumption in transit (empty)	$0.025637 \frac{ton}{km}$
Fuel consumption during disconnect/hook up	$0.5 \frac{ton}{hr}$
Fuel consumption while installing mooring line	$0.5 \frac{ton}{hr}$
Fuel consumption while installing mooring anchor	$0.5 \frac{ton}{hr}$
Fuel consumption while towing	$0.025637 \frac{ton}{km}$
Weather Restrictions	
Wave height	3 m
Wind speed when towing at 150	10 $\frac{m}{s}$
Costs of operation (in NOK)	
Day Rate	700000
Fuel Cost	12310
Port Fee	1544

Table B-2: Parameters Crew transfer vessel. [93]

Crew Transfer Vessel (CTV)	
Transit speed	20 Kn
Capacity	
Technician capactiy	12 technicians
Fuel Oil Consumption	
Fuel consumption in transit	0.004499437 $\frac{ton}{km}$
Fuel consumption when pushing on asset	0.16647919 $\frac{ton}{km}$
Fuel consumption when idle offshore	0.16647919 $\frac{ton}{km}$
Weather Restrictions	
Wave height	2.25 m
Costs of operation (in NOK)	
Day Rate	37500
Fuel Cost	12310
Port Fee	1000

Table B-3: Parameters of the Tug vessel. [93]

Tug AHTS		
Transit speed	15 Kn	
Towing speed	3 Kn	
Capacity		
WTG capacity	1	
Fuel Oil Consumption		
Fuel consumption in transit	0.025367	$\frac{ton}{km}$
Fuel consumption when pushing on asset	0.0.02973	$\frac{ton}{km}$
Fuel consumption while disconnect/ hook up	0.5	$\frac{ton}{km}$
Weather Restrictions		
Wave height when towing	1.5	m
Wind speed when towing at 150m	12	$\frac{m}{s}$
Costs of operation (in NOK)		
Day Rate	137150	
Fuel Cost	12310	
Port Fee	1500	

Table B-4: Inland Cranes parameters (Floater, Integration and Spar assembly). [93]

Inland Crane Parameters	
Port	Wergeland Base
Transit speed	15 Kn
Fuel Oil Consumption	
Fuel consumption while moving	39 $\frac{litre}{km}$
Fuel consumption while working	39 $\frac{litre}{km}$
Costs of operation (in NOK)	
Day Rate	200000
Fuel Cost	22
Port Fee	18020
Weather Criteria	
Wind speed at 150m	12 $\frac{m}{s}$

C. Hub Ports bases input

Table C-1: Properties of the bases. [93]

Base Parameters	
Location	Vary according to location
Storage Units	10
Capacities	
Mooring Lines	200 Units
Mooring Anchors	200 Units
WTG	10
Floating WTG	10

D. Arrays

D.1 First Case`s Array

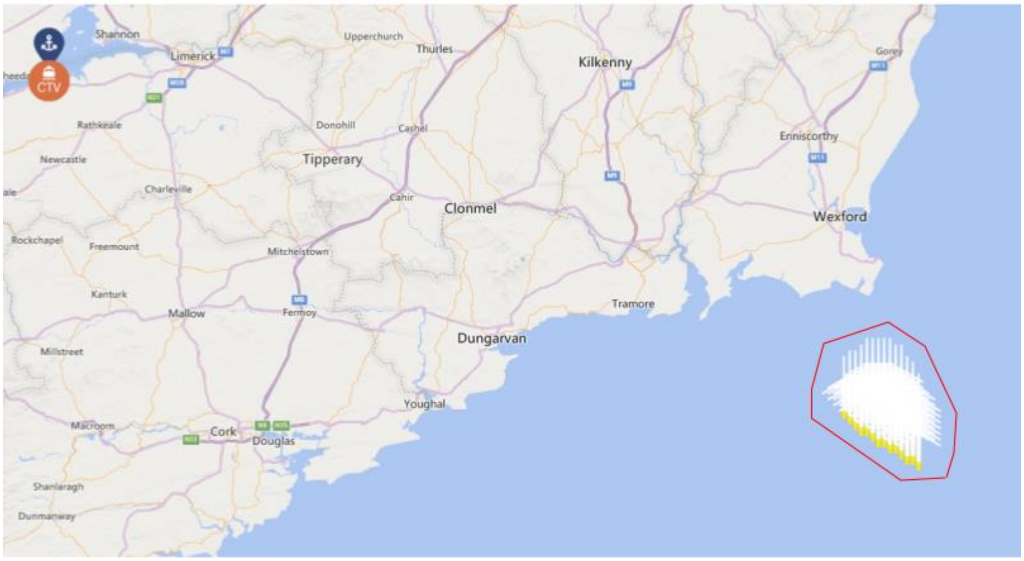

Figure D.1: Ireland`s first case Array. Capacity 1.5 GW.

D.2 Second Case`s Array

Figure D.2: Norway`s second case Array. Capacity 4.5 GW.

D.2. 7 Hub Ports 7 Integration cranes Case

D.2.1 Scotland

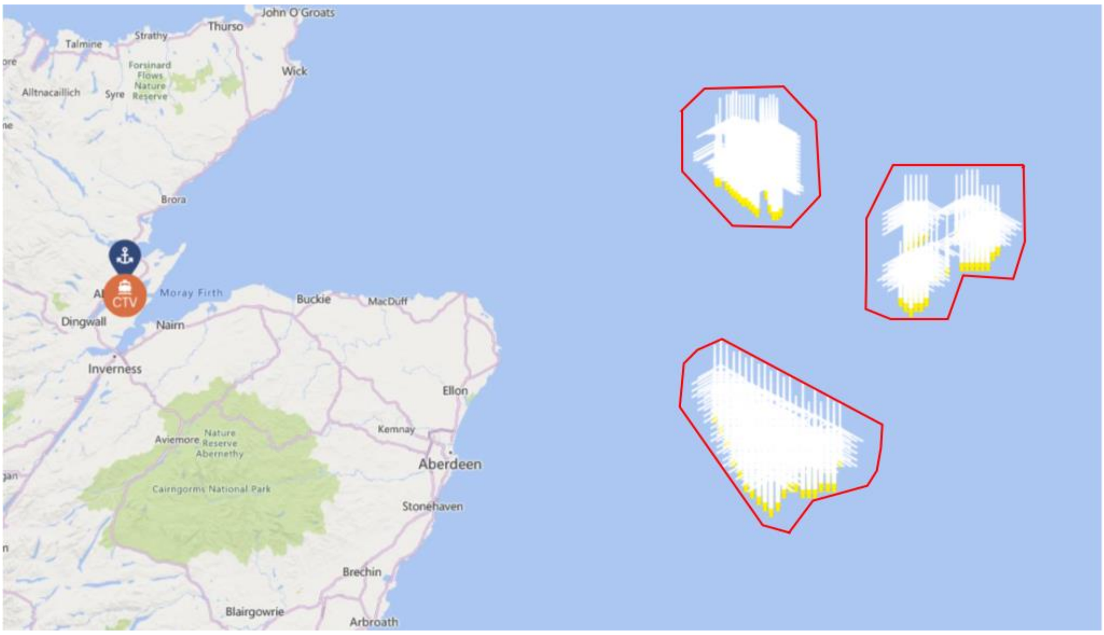

Figure D.3: Scotland`s Array, total capacity: 5.8 GW.

D.2.2 Wales

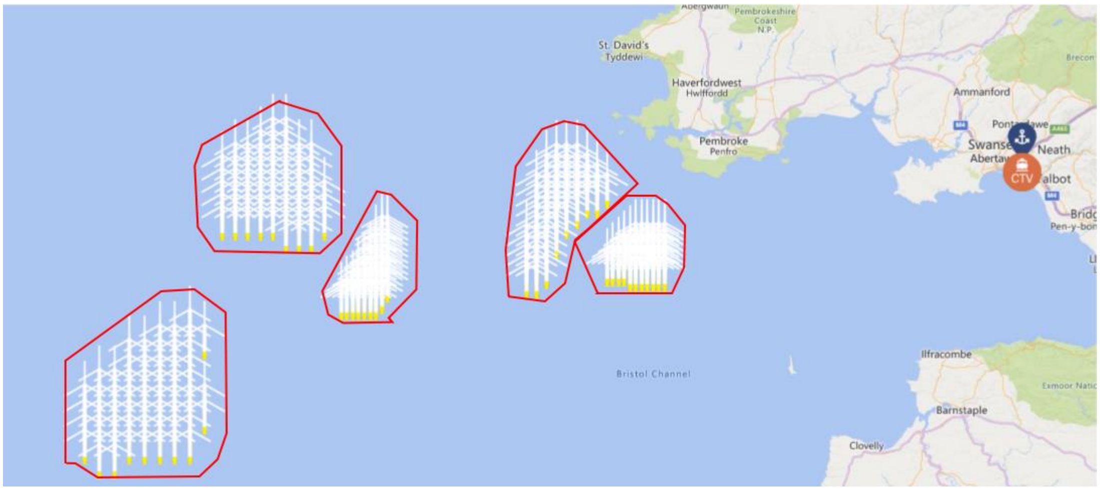

Figure D.4: Wales`s Array, total capacity: 4.2 GW.

D.2.4 Ireland

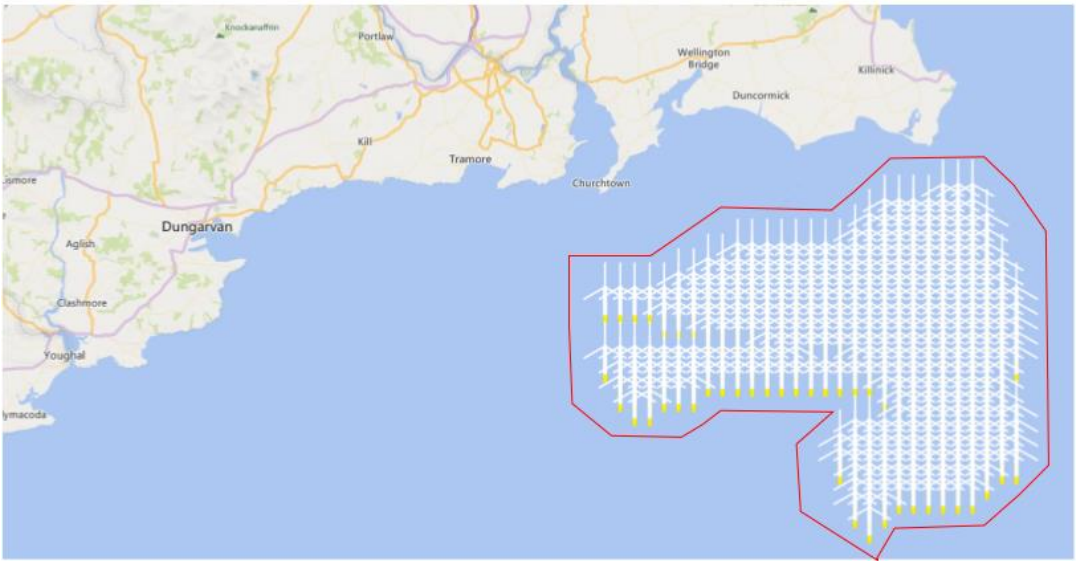

Figure D.5: Ireland`s Array, total capacity: 5.2 GW.

D.2.5 Spain

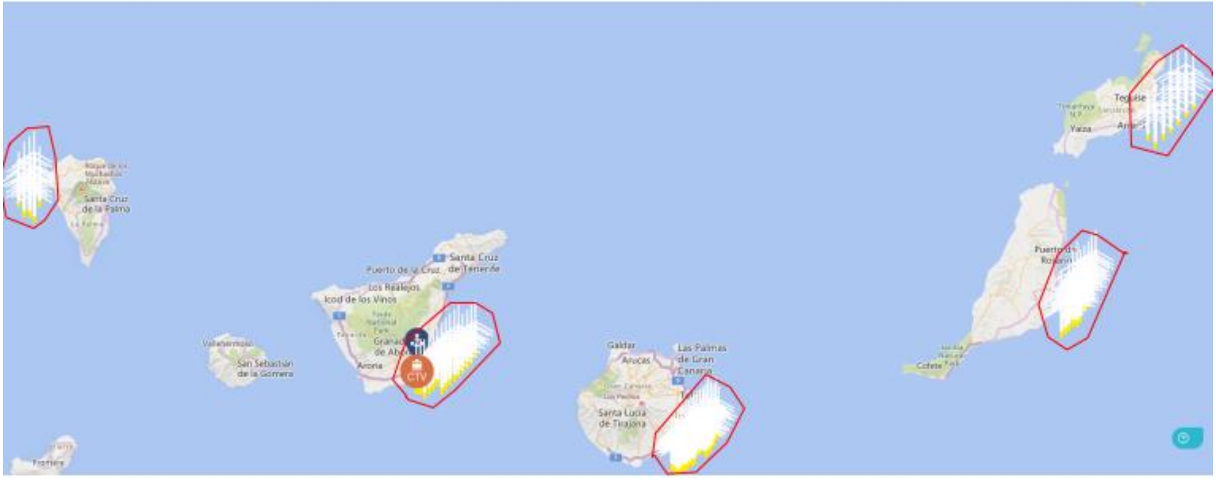

Figure D.6: Spain`s Array, total capacity: 3.68 GW.

D.2.6 France

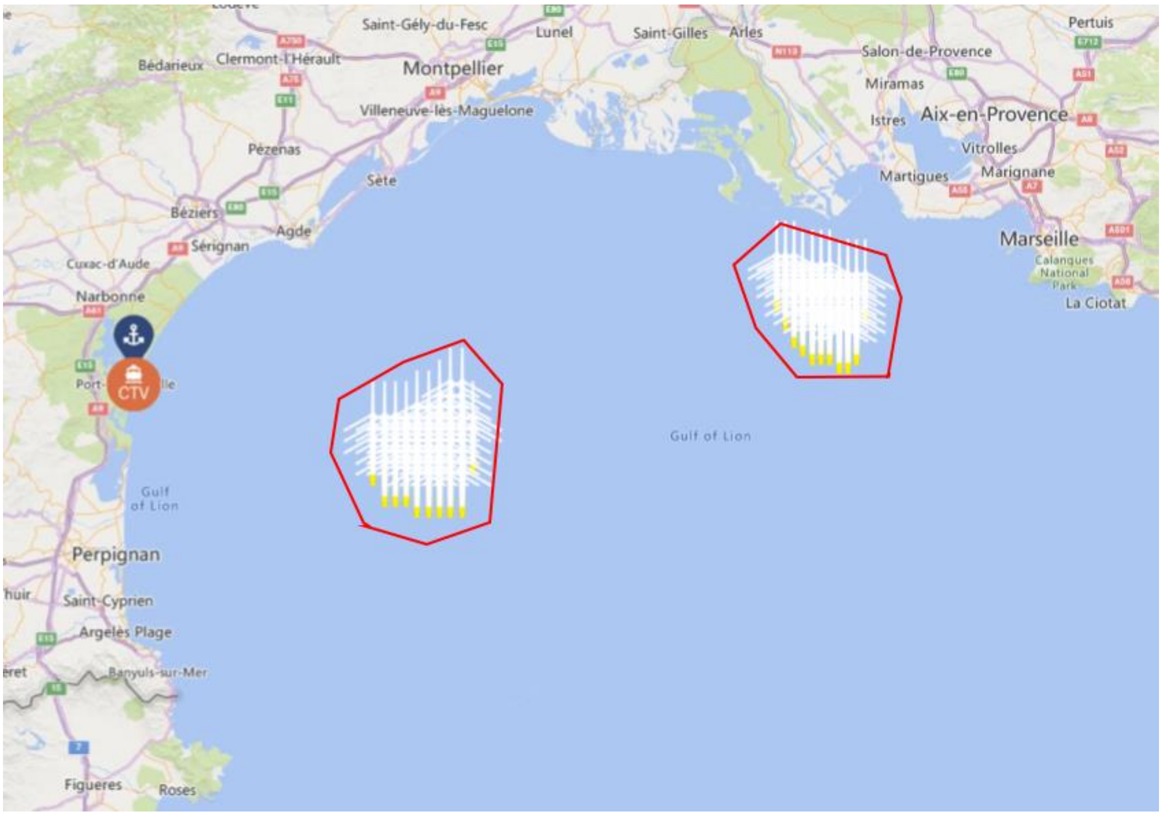

Figure D.7: France`s Array, total capacity: 3.66 GW.

D.2.7 Sweden

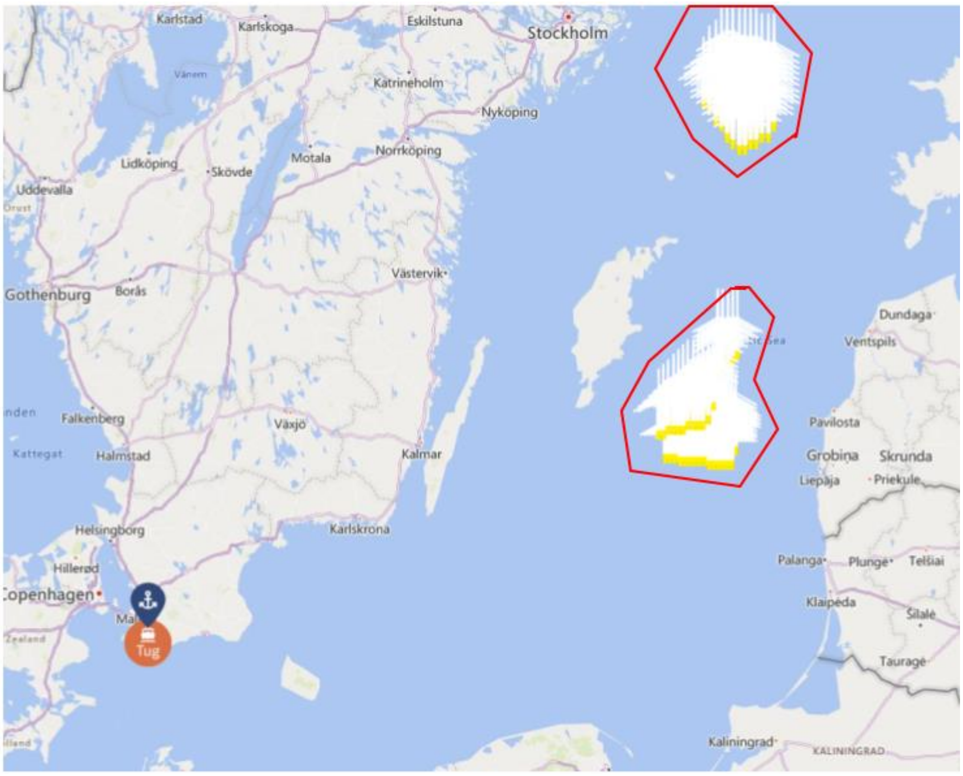

Figure D.8: Sweden`s Array, total capacity: 4.77 GW.