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Master's Thesis

The scalability of floating wind installations in Norway and beyond

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Abstract

Offshore wind energy has recently become a big industry in many countries [89]. However, offshore floating is still at the beginning of its commercial use, and the number of projects under development has increased. Future offshore wind projects are expected to increase in size, using wind turbines with larger design capacities but in deeper waters and further offshore. As a result, ports need to be modified to handle the larger turbines and substructures [33, 6]. The North Sea has great potential for offshore wind parks in intermediate deep waters; therefore, many projects are planned in this area. However, this study focuses on developing an offshore wind park with turbines mounted on a spar substructure. In particular, this thesis investigates the development of the Utsira Nord project in Norwegian waters, with Wergeland Base as an assembling port and gives a short outlook of a project in Scottish territories.

Different parameters such as storage capacity, scaling up infrastructure in terms of the number of cranes and vessels, and shift rotation has been analyzed and compared. Further, the size of the wind turbine has been scaled up, as well as the installation from different ports for two different sites. Analysis showed that the crane has a major influence on the costs, and its usage should therefore be reduced to a minimum. However, having sufficient storage capacity is essential for the efficient usage of the crane. In our simulations, the crane and storage capacity did not influence the completion time significantly. Similar reductions in the completion time can be obtained by using more or faster tugs and anchor handling vessels (AHV), but using more vessels did increase the cost. Our simulations showed that having more tugs is more profitable in combination with an increased storage capacity. Nevertheless, using faster tugs gives an improved cost-benefit when a smaller storage capacity is available. When comparing the installation for a site from two different ports, it was assumed that both ports have the same infrastructure. The port closest to the project site has a big advantage as the installation from that port takes less time due to the lower transit times. However, it is important to note that the port in Scotland does not have deep water close to shore or the same crane and storage space that Wergeland Base has in Norway. Norway's unique geography means that we have deep water and sheltered wave conditions that are ideal for the assembly of deep and shallow draft floating wind turbines.

Contents

List of Tables

List of Figures

1. Introduction

1.1. Background

In the past years, offshore wind energy has become a popular method for governments in different countries to produce "green" energy. Figure 1.1 shows how much capacity has been installed in the past ten years in several countries in Europe. The cumulative installed capacity increased year by year.

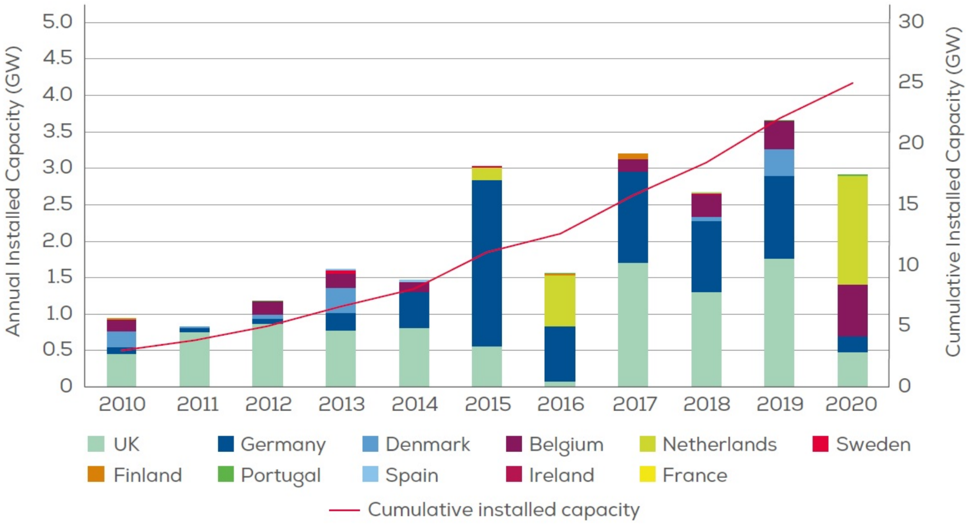

Figure 1.1.: Installation of offshore wind capacity in Europe in the years from 2010 to 2020 [120]

The European Union (EU) aims to become net-zero CO2 by 2050. Therefore it announced to reduce the emission until 2030 by 55 % compared to 1990 [62]. The EU stated that renewable energy sources should produce up to 40 % of the required energy to meet this goal. Therefore, governments of several European countries obligated themselves to add up the offshore wind capacity from 25 gigawatts (GW) to 111 GW during the next eight years. Until 2050 it is aspired to have an offshore wind capacity of 450 GW, of which 100 to 150 GW are assumed to be based on a floating structure. Currently, each year a capacity of 3 GW is installed, but this yearly installed capacity of 3 GW should be increased to 11 GW/year in 2026 [33, 148, 6]. Figure 1.2 demonstrates an installation outlook for offshore wind capacity of different countries inside the EU. The figure 1.4 shows a chart of the European continent pointing out the locations of WindEurope ports, as well as already operating and planned offshore wind farms.
Most existing sites and those under construction are located in shallow water relatively close to shore, as indicated in figure 1.3. Therefore, most wind turbines are based on monopiles, while the minority are installed on floating structures [120]. Nevertheless, figure 1.3 also indicates that newly permitted sites are further offshore or in deeper waters. Another trend that is observed is that the average size of OWPs grows [121].

Not only the size of OWPs but also the size of wind turbines has increased in the past years. For example, the offshore wind park Middelgrunden in Denmark was commissioned in 2001

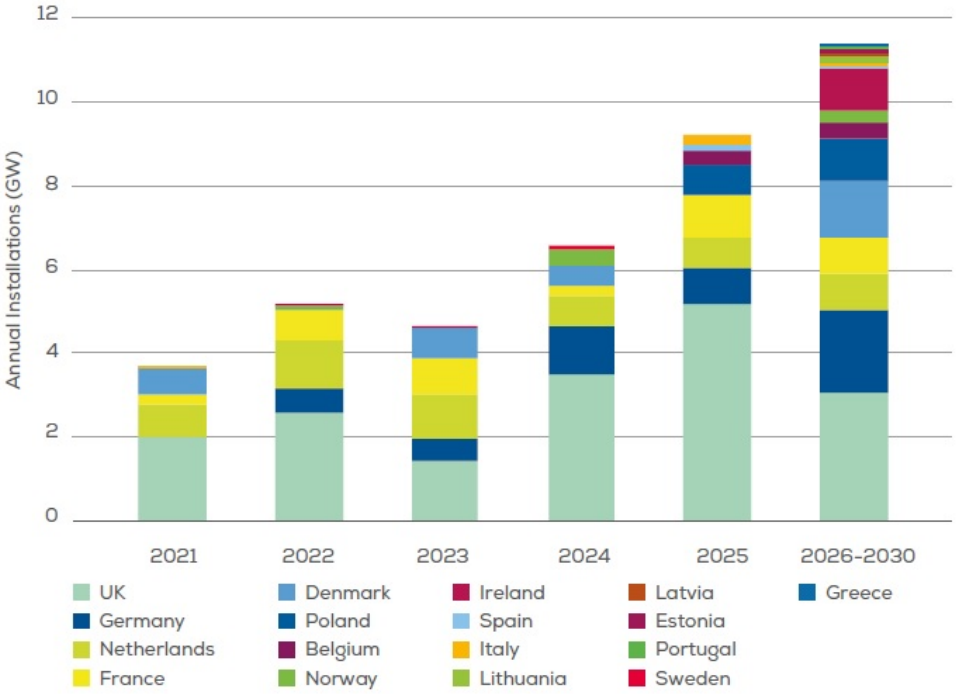

Figure 1.2.: Outlook for offshore wind in Europe until 2030 [33]

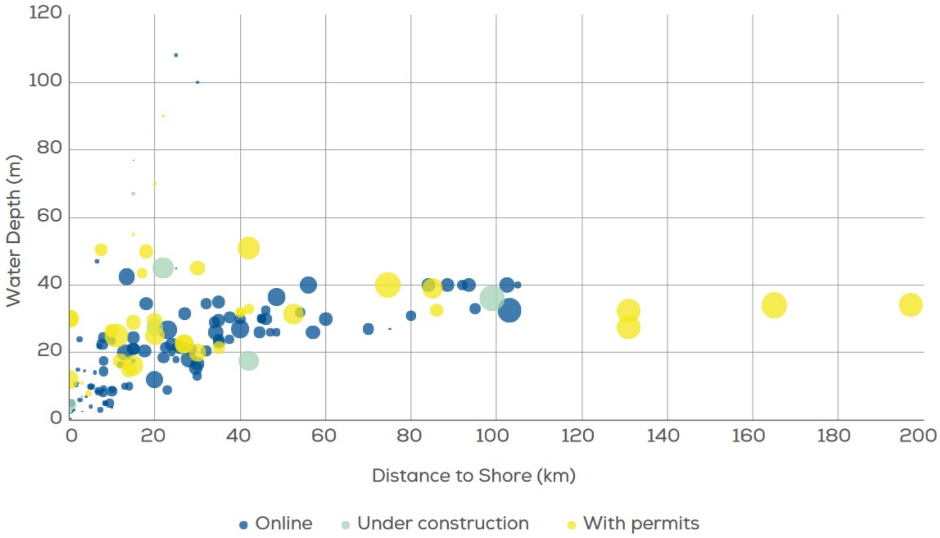

Figure 1.3.: Distance to water depth of offshore wind parks. The capacity of the size is indicated by the size of the circle. [120]

with 20 turbines á 2 megawatts (MW) and was once the largest of its kind. [121] This year (2022), two decades later, wind turbines of size of 14 and 15 MW are tested [149, 134]. Different institutes and manufacturers are currently working on the next milestone of having a 20 MW wind turbine [135] and having larger wind turbines and new types of substructures (floating) bring new challenges to the ports. The existing ports have to be modified to satisfy the new demands of the larger turbines and substructures. [43]

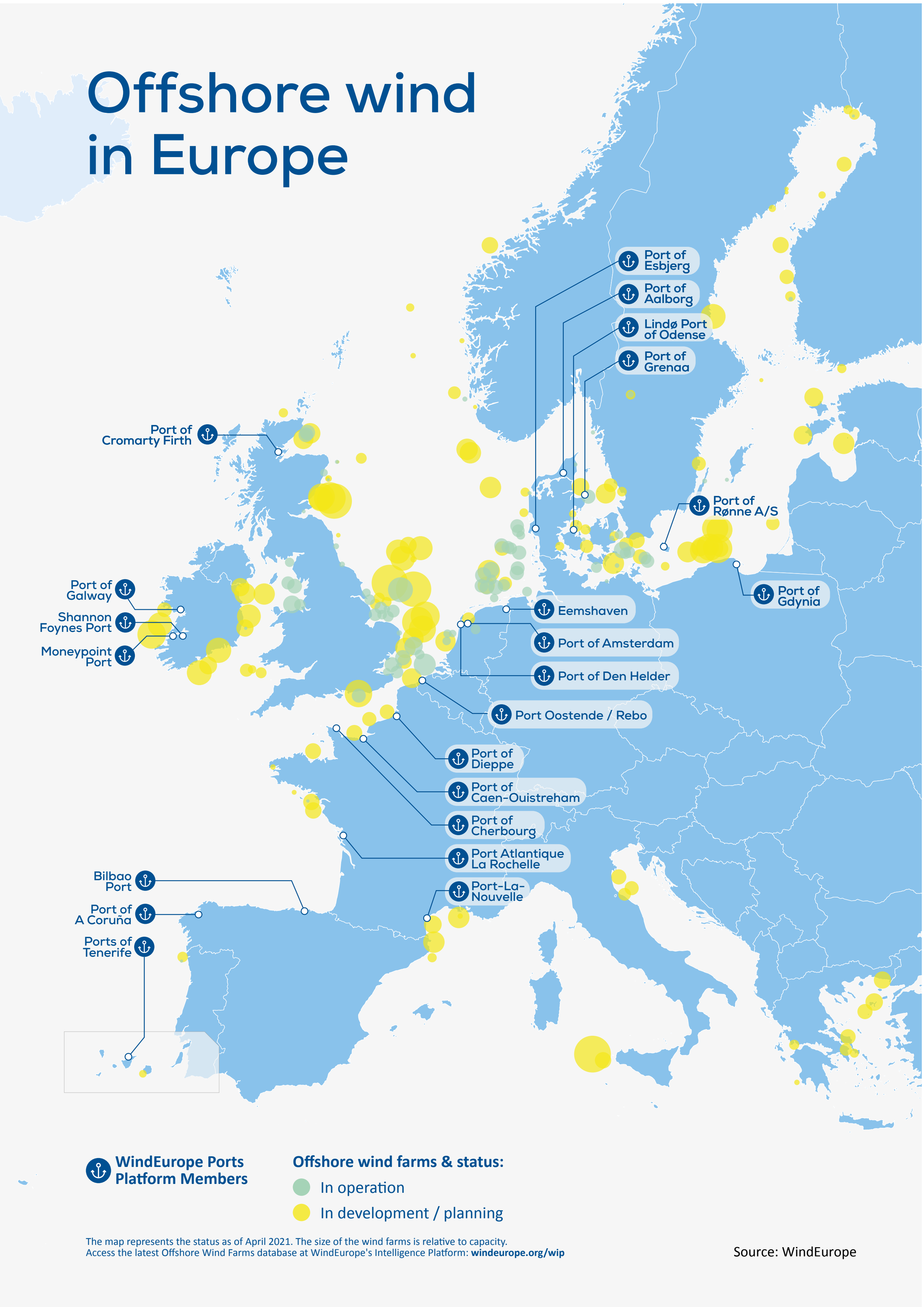

Figure 1.4.: Chart of WindEurope Ports, planned and operating offshore wind farms in Europe [33]

1.2. Research question

Wind turbines are getting bigger, and the new generation will soon be commercially available. Up to now, there is little to no experience of installing units of this size and mass. Moreover, there is even less knowledge about floating wind turbines. However, this will be the future of the offshore wind industry as we move into deeper waters, and there is a need to cut costs. For this reason, the main research question to be answered in this Master Thesis is

"How does scaling up of the wind turbine size effect the costs and completion time of a wind park installation."

And secondly, the question

"How competitive can assembly sites in Norway with wind projects in Scotland?"

2. Areas for floating offshore wind

2.1. Potential of offshore floating wind turbine

Up to now, most constructed wind farms are based on a bottom fixed structure. The offshore floating wind would allow developing areas in deeper waters and expand other potential areas for wind energy. Figure 2.1 indicates the typical use of substructures for different water-depth. With the development in technology, an XXL monopile was designed to cover water depths up to 65 m for up to 15 MW turbines [8].

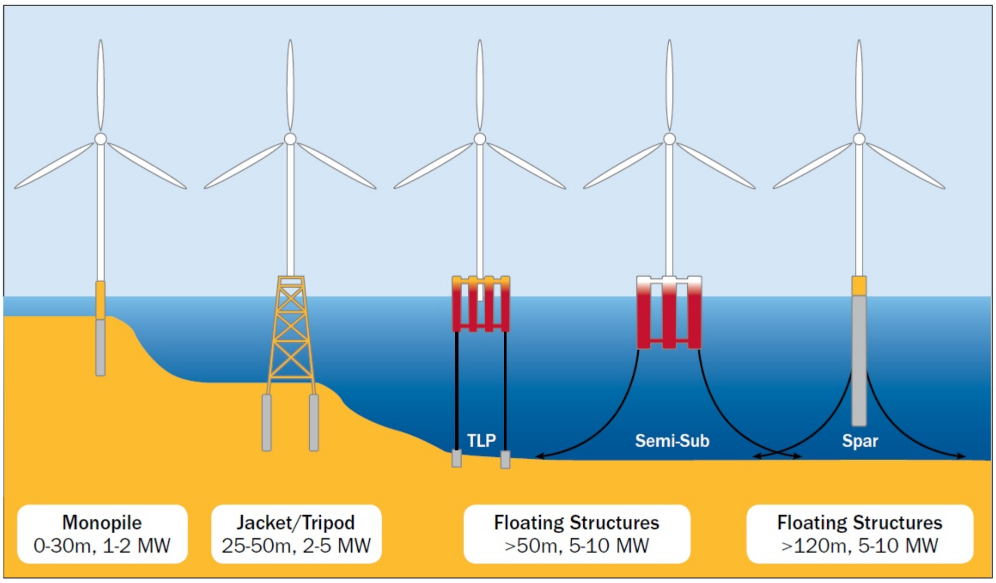

Figure 2.1.: Support structure options with typical water-depth ranges [96]

Figure 2.2 shows in which relationship distance to water depth wind parks are currently online, under construction, consented, and planned. The trend of going further offshore into deeper waters can be observed in this figure. Because of this development, there is a smooth transition between the bottom fixed and floating structure. However, it can also be noted that the planned floating projects are closer to shore. The reason for this is fewer costs for exportation cables and little experience in deep waters, which would be even further offshore.

Figure 2.3 shows a selection of offshore floating wind projects with their capacities and country of location along a timeline. In 2020 only a small capacity of 62 MW was installed on floating substructures in Europe. By 2022, the floating structure's capacity should rise to 330 MW. The biggest floating projects are Hywind in Scotland with 30 MW (5 turbines each 6 MW) and Windfloat Atlantic in Portugal with 24 MW. Within 2022 nine floating projects shall be realised. These projects are developed in different countries in Europe with a total capacity of 260.6 MW. The name, country, capacity commissioning date, number of turbines, and their capacity, as well as the project developer of these nine projects, can be found in table 2.1[148, 58].

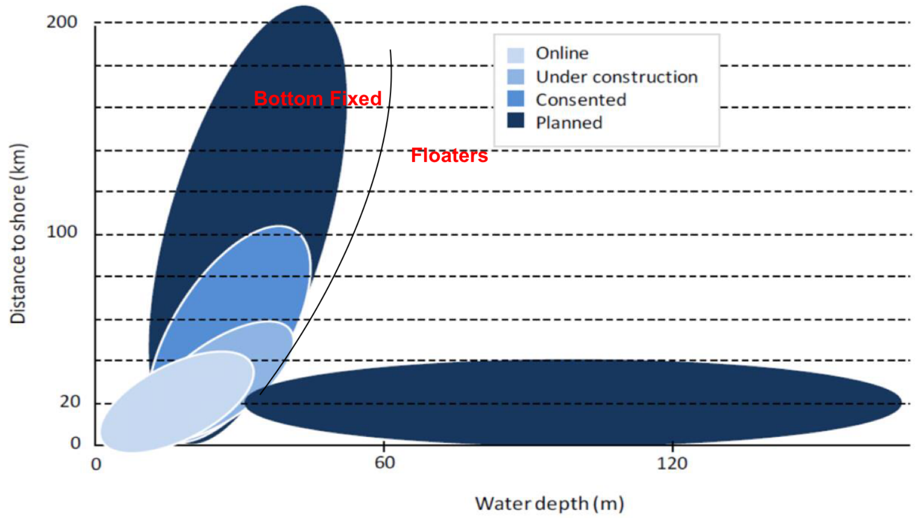

Figure 2.2.: International offshore wind projects [106]

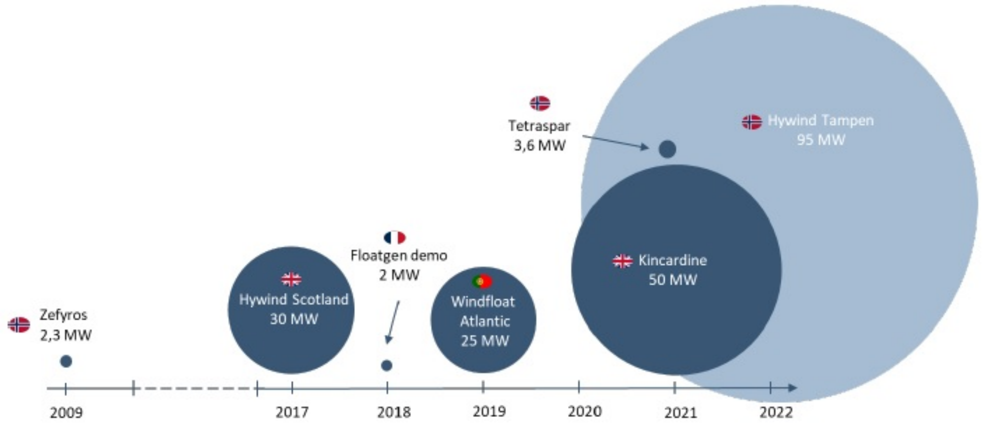

Figure 2.3.: Timeline of offshore flaoting wind projects that have been realized (dark blue) and under development (light blue) [6]

2.2. Potential areas in Europe

The question of legitimation has to be clarified before defining potentially new areas for floating offshore wind. Furthermore, boundary conditions for potential areas have to be defined. The "United Nations Convention on the Law of the Sea of 10 December 1982" (UNCLOS) [101] regulates the sovereignty, rights, and duties of a coastal state. This convention implies that every coastal state has the right to establish a territorial sea of 12 nautical miles. Within this zone, the state has full sovereignty of the air space, its sea bed, and subsoil (UNCLOS, Part 2 Article 2 and 3). Further, every coastal state has the right to establish an exclusive economic zone (EEZ) up to 200 nautical miles from the baseline[1] (UNCLOS, Part 5 Article 57). Within the exclusive economic zone, "the state has sovereign rights for the purpose of exploring and exploiting, conserving and managing the natural resources, whether living or non-living, of the waters su-

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[1] Baseline is: "... the low-water line along the coast as marked on large-scale charts officially recognised by the coastal State" (UNCLOS, Part 2 Article 5)[101]

Table 2.1.: Current on going floating wind projects in Europe[148]

Name	**Country**	**Total Project Capacity**	**Commissioning Date**	**Turbine number and capacity**	**Project developer**
TetraSpar Demo	Norway	3.6 MW	2020	1 x 3.6 MW	Shell, RWE, Stiesdal
DemoSATH	Spain	2 MW	2021	1 x 2 MW	RWE, SAITEC
Kincardine A	UK	50 MW	2021	5 x 9.5 MW + 1 x 2MW	KOWL, COBR
EFGL	France	30 MW	2022	3 x 10 MW	Ocean Winds
Groix-Belle-Ile	France	28.5 MW	2022	3 x 9.5 MW	Ferme Eolienne Flottante de Groix & Belle-Île
EolMed	France	28.5 MW	2022	3 x 9.5 MW	EolMed SAS
Provence Grand Large (PGL)	France	24 MW	2022	3 x 8 MW	EDF, Enbridge
AFLOWT	Ireland	6 MW	2022	1 x 6 MW	EMEC, SAIPEM, MARIN, ESB, Frunhofer, CaLiCyA, University College Cork, SEAI
Hywind Tampen	Norway	88 MW	2022	11 x 8 MW	Equinor ASA

perjacent to the seabed and of the seabed and its subsoil, and concerning other activities for the economic exploitation and exploration of the zone, such as the production of energy from the water, currents and winds" (UNCLOS, Part 5 Article 56) [101]. These articles give every coast state the right to establish an offshore wind park in its territorial sea and EEZ.

Besides the legitimation of the state, building an offshore wind park, the mean wind speed and water depth play an important role. Potential areas for offshore wind are to obtain a mean wind speed greater than 6 to 8.5 meters per second [79, 1]. Also, the impact of environmental, business and public interests should be analysed when releasing areas for the construction of offshore wind. [138, 104].

Some potential areas for floating offshore wind in Europe will be pointed out in the following. Figure 2.4 shows the average wind speed on the European continent. The violet/red colour, which indicates an average wind speed between 7.5 and 10 meters per second, dominates in the North and Baltic sea, but also the Atlantic cost gives promising wind speeds.

Besides the wind speed, also the water depth plays an important role in the offshore floating wind. As in the section 3 described, offshore floating wind requires a minimum water depth of 40 m. Figure 2.5 indicates the water depth on the European continent. The areas of interest for this study are specified in yellow and green to light blue colours (40 to 500 m water depth).

Fulfilling the boundary conditions of wind speed, water depth and legitimation give many areas where potentially floating wind turbines could be installed. Hence many more investigations are required until a wind park can be constructed. As mentioned earlier, the coastal state must analyse the environmental impact and business and public interest in the areas where a wind park should be constructed. These analyses include the impact on animals in the air and sea, as well the environmental risk (pollution in case of an accident). Further, the impact on

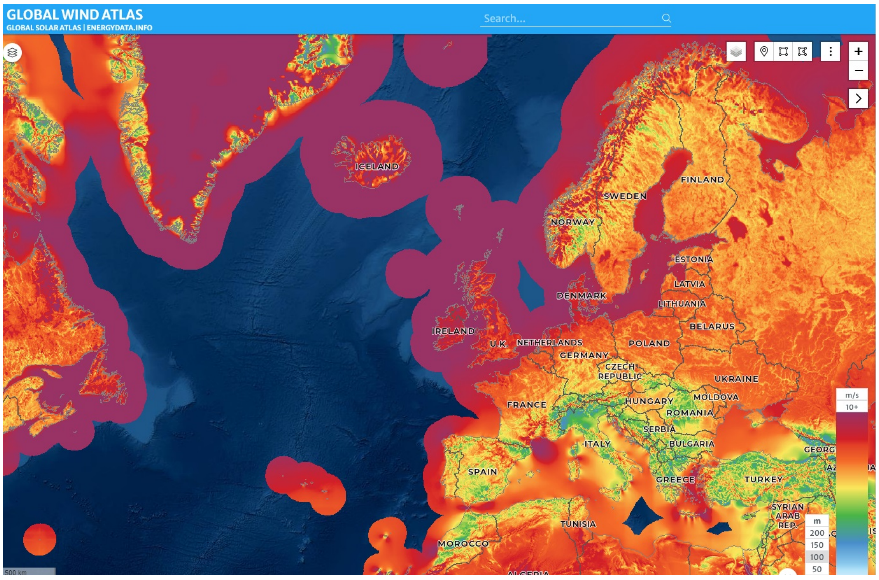


Figure 2.4.: Chart of average wind speed on European continent [66]

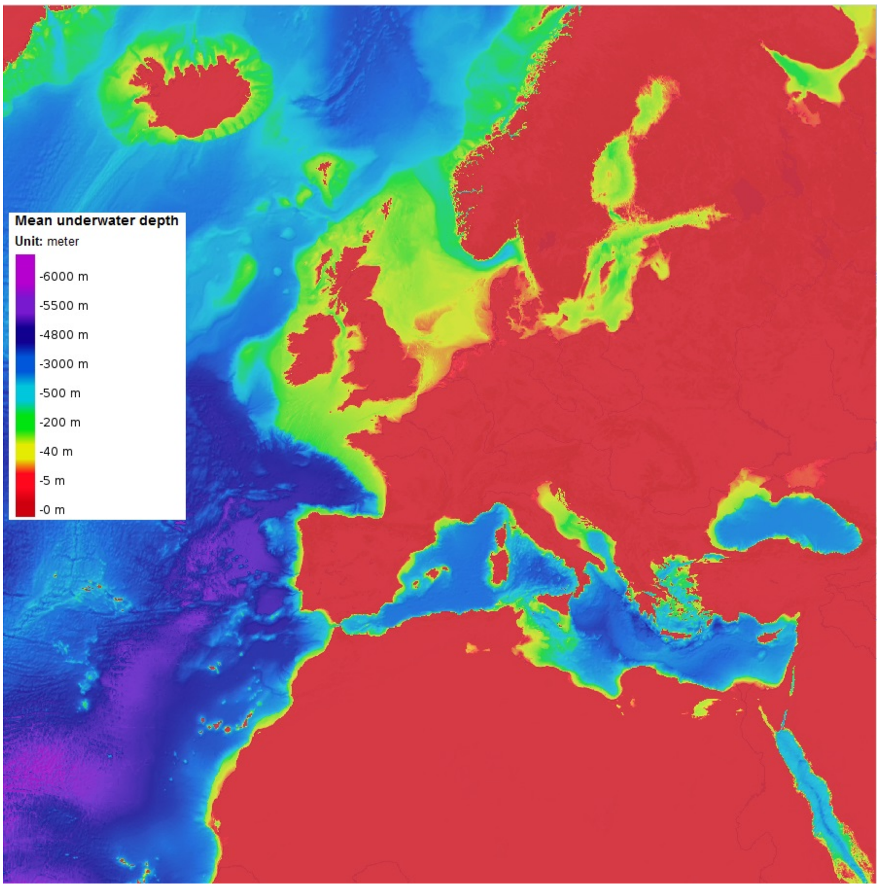


Figure 2.5.: Chart of water depth on European continent [54]

shipping, fisheries, landscape, tourism, historical monuments, cultural heritage sites, other interests (for example, air force or navy) and in the case of Norway; also the impact on the oil and gas industry has to be analysed [104]. When the analysis is completed, the country can decide whether it wants to open the areas for auctions/licensing. Companies can then apply for the right of development for the areas [140, 103]. In the following, some areas that have already been advertised by the state or that might be interesting to investigate further will be pointed out. Norway, Spain, France, and the UK, including Scotland and Ireland, are considered countries.

2.2.1. Norway

The construction of offshore wind parks in the Norwegian EEZ can only occur in areas the Norwegian government has opened for license applications. Therefore a static environmental assessment (SEA) was carried out, and the results were represented in January 2013. Within this assessment, 15 areas along the Norwegian coast have been found and divided into three categories: A, B, and C [104]. The different categories stand for:

- "**Category A:** Wind power development within the zone is technically and economically feasible and will have relatively few negative impacts. Grid connection is possible before 2025." [104, P. 8]
- "**Category B:** Wind power development within the zone will have challenges related to either technical aspects or conflict of interests/negative impacts. The challenges might be resolved in the future through technology development, grid measures and mitigation measures. NVE considers that zones in this category can be opened when technology matures, or when existing use of the areas changes." [104, P. 8]
- "**Category C:** Wind power development within the zone represents greater challenges than in the other two categories. Conflicts of interest in the areas are not easily resolved. Foreseen negative impacts are still considered acceptable. Zones in this category should not be opened at the expense of zones in the two other categories." [104, P. 8]

Table 2.2.: Areas sorted by their category[104]

Category A	**Category B**	**Category C**
Sandskallen - Sørøya nord	Vannøya	Nordmela
Frøyagrunnene	Auvær	Gimsøy nord
Utsira nord	Trænafjorden - Selvær	
Sørlige Nordsjø I	Træna vest	
Sørlige Nordsjø II	Nordøyan - Ytre Vikna	
	Frøyabanken	
	Stadthavet	
	Olderveggen	

Table 2.2 divided the 15 areas NVE has specified into the three earlier mentioned categories. The areas, including their name, approximate location and category, can be found in figure 2.6. Figure 2.7 indicates the relationship between distance to shore and the water depth of the areas along the Norwegian coast.

At the Floating Wind 2021 conference in Haugesund, Minister of Petroleum and Energy Tina Bru announced the opening of Sørlige Nordsjø II for applicants to apply for their development. The auction is planned for the 1st quarter of 2022. Utsira Nord was already announced to open in June 2020 [140]. Here a licensing process is destined differently to Sørlige Nordsjø II because of the costs of floating wind. The government believes "the best way forward is to develop projects through the licensing process"[49].

Figure 2.6.: Considered areas for offshore wind in Norway. Recommendations regarding further process based on challenges and possibilities are indicated by the categories. [138, 104]

Further, Tina Bru announced that the government's budget for technology development in floating offshore wind would be considered to increase in case of promising assessments showing sufficiently mature and profit for the society by a grant to the project. The area of Utsira Nord shall be divided into three areas for up to 500 MW each. Awarding areas shall be based on qualitative criteria as soon as the setting is in place. This process was expected to start at the end of 2021 [49, 103]. In Sørlige Nordsjø II and Utsira Nord, a combined capacity of 4.5 GW shall be installed [11].

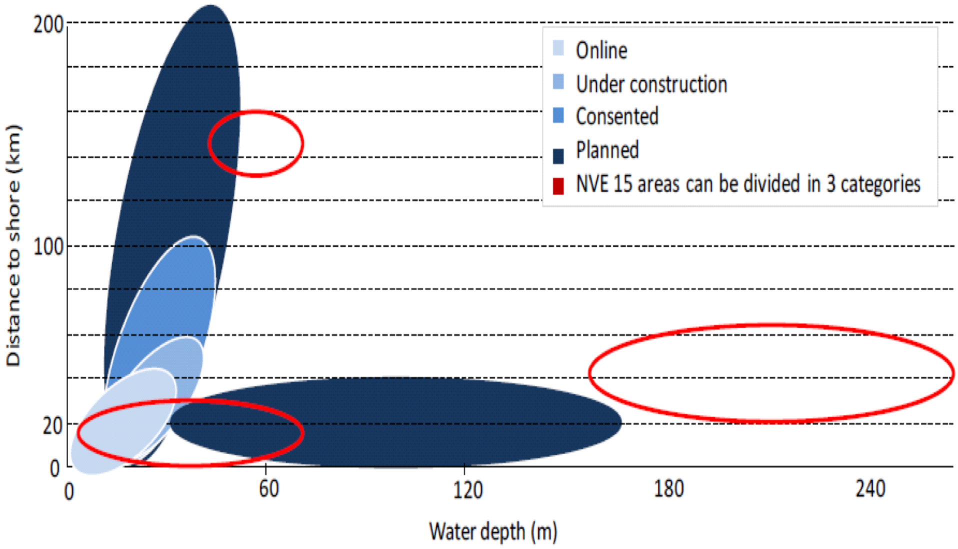


Figure 2.7.: Relationship distance to shore and water depth of the 15 areas announced by NVE as well as international offshore wind projects. [106, 138]

2.2.2. Spain

In December 2021, the Spanish government published a roadmap for offshore wind. Within this publication, it was announced that the government aims to have 3 GW of floating offshore wind by 2030 [46]. Spain has already the second largest onshore wind capacity in Europe with 27 GW (first is Germany with 56 GW [89]), but no commercial used offshore wind farm. Spain's only offshore wind turbine is a pilot project close to Gran Canaria (Canary Islands). The government is eager to develop technologies of offshore floating wind further and provide at least €200m for research and development [136]. Within this study, the three areas at Canary Island, North Spain (Galicia), and the Mediterranean Sea (Cataluña) will be considered closer.

2.2.2.1. Canary Island

The Canary Islands are a volcanic archipelago located in the Atlantic off the north-western coast of the African continent. Fossil fuels produced the majority (98 %) of the energy consumption within a small isolated energy system for each island. Around 15 million Europeans live on islands, approximately 2.2 million of them on the Canary Islands [76]. Therefore, islands have great potential to become leaders in the energy transition [42].

The waters around the Canary Islands are quite deep, making the area unsuitable for the bottom fixed substructure. As volcanic rock is not a firm foundation, floating offshore wind turbines are the only alternative. Hugo Díaz and Carlos Guedes Soares [42] analysed the Canary Islands for suitable offshore floating wind and came up with four areas.

Table 2.3.: Coordinates (WGS84) and average water depth of the four found locations at Canary Islands [42]

Location	**Latitude**	**Longitude**	**Water depth**
Lanzarote	N 29° 09’ 00”	W 013° 51’ 36”	800 m
	N 29° 15’ 00”	W 013° 45’ 36”	
	N 29° 13’ 12”	W 013° 44’ 24”	
	N 29° 07’ 48”	W 013° 48’ 00”	
Fueteventura (1)	N 28° 37’ 12”	W 014° 11’ 24”	800 m
	N 28° 37’ 12”	W 014° 09’ 36”	
	N 28° 33’ 00”	W 014° 11’ 24”	
	N 28° 33’ 00”	W 014° 12’ 36”	
Fueteventura (2)	N 28° 28’ 48”	W 014° 18’ 00”	500 m
	N 28° 31’ 12”	W 014° 16’ 12”	
	N 28° 30’ 00”	W 014° 13’ 24”	
	N 28° 24’ 00”	W 014° 17’ 24”	
	N 28° 24’ 36”	W 014° 18’ 00”	
Gran Canaria	N 27° 51’ 36”	W 015° 18’ 00”	400 m
	N 27° 51’ 36”	W 015° 15’ 36”	
	N 27° 46’ 48”	W 015° 18’ 36”	
	N 27° 48’ 00”	W 015° 19’ 12”	

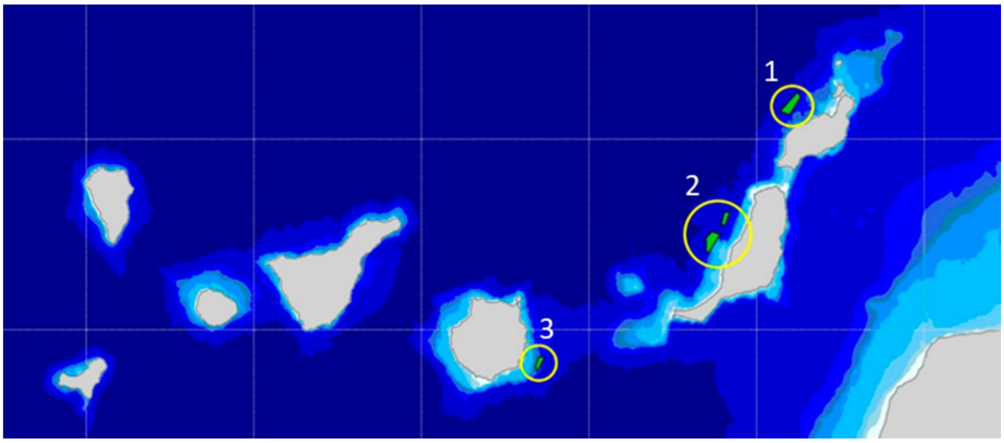


Figure 2.8.: From Hugo Díaz and Carlos Guedes Soares proposed locations for floating offshore wind. (1) Lanzarote, (2) Fueteventura 1 and 2 and [42]

The coordinates of the areas found are listed in the table 2.3 and are illustrated in figure 2.8. After evaluating different parameters and weighting criteria following ranking of the locations was made by Hugo Díaz and Carlos Guedes Soares[42]:

1. Gran Canaria
2. Lanzarote
3. Fuerteventura (2)

4. Fuerteventura (1)

There are already projects planned/permitted for the area of Gran Canaria. Figure 2.9 shows the areas of the planned offshore wind farms, and table 2.4 summarises the information available for them. The wind parks Guanche, Cardon, Dunas, Mojo and Gofio are planned to be commissioned in 2025 [16, 17, 29, 21, 26]. Summing up the capacities of the planned areas, 1,046.6 MW can be installed in this area.

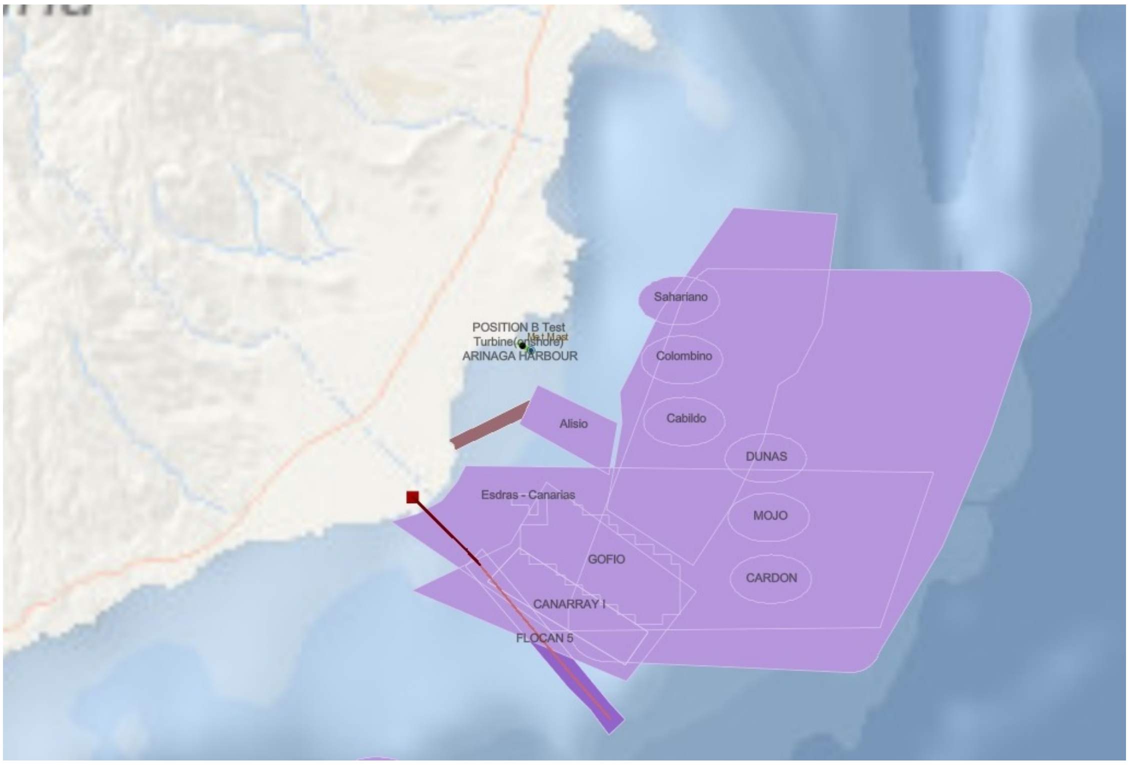


Figure 2.9.: Planned projects in the area of Gran Canaria [65]

2.2.2.2. North Spain (Galicia)

Iberdrola, BlueFloat Energy, and SENER Grupo de Ingenieria plan to develop three floating offshore wind projects in the northwest of Spain (Galicia - A Coruña). The project are named San Cibrao, San Brandan (Iberdrola), and Nordés (BlueFloat Energy and SENER Grupo de Ingenieria).

The project area Nordés is divided into two developing phases with a cumulative capacity of 1.2 GW. The construction of the project is expected to start in 2024, and the commercial use is awaited for 2028 [27].

For the other two projects, San Cibrao and San Brandan, the developer plan to establish each of them with a capacity of 490 MW. For both projects the construction and commissioning are expected for the years 2024 and 2027 [31, 30].

Table 2.4.: Projects planned in Gran Canaria with Capacity [99, 74, 125, 123, 72, 67, 60, 44, 15, 14, 13, 4, 26, 21, 29, 17, 16]

Name	**Development Status**	**Developer/Owner**	**Capacity (MW)**	**Foundation**	**Turbine**	**Number of Turbines**
Guanche	Permitted	Greenalia	50	Floating: Semi-Submersible Platform	12.5 MW	4
Cardon	Permitted	Greenalia	50	Floating: Semi-Submersible Platform	12.5 MW	4
Dunas	Permitted	Greenalia	50	Floating: Semi-Submersible Platform	12.5 MW	4
Mojo	Permitted	Greenalia	50	Floating: Semi-Submersible Platform	12.5 MW	4
Gofio	Permitted	Greenalia	50	Floating: Semi-Submersible Platform	12.5 MW	4
Sahariano	Concept/Early Planning	COBRA INSTALACIONES Y SERVICIOS, S.A.	49.9	Grounded: Gravity-Base	12 MW	4
Cabildo	Concept/Early Planning	COBRA INSTALACIONES Y SERVICIOS, S.A.	49.9	Grounded: Gravity-Base	12 MW	4
Alisio	Concept/Early Planning	COBRA INSTALACIONES Y SERVICIOS, S.A.	49.9	Grounded: Gravity-Base	12 MW	4
Colombino	Concept/Early Planning	COBRA INSTALACIONES Y SERVICIOS, S.A.	49.9	Grounded: Gravity-Base	12 MW	4
San Borondón	Concept/Early Planning	Iberdrola Renovables Energia, S.A.	238	Floating: Semi-Submersible Platform	14 MW	17
Gran Canaria Este	Concept/Early Planning	Ocean Winds	144	Floating: Semi-Submersible Platform - Steel	12 MW	12
Canary I	Concept/Early Planning	EnerOcean S.L.	48	Floating: Semi-Submersible Platform - Steel		
Canary II	Concept/Early Planning	EnerOcean S.L.	132	Floating: Semi-Submersible Platform - Steel		
Esdras - Canarias	Consent Application Submitted	Esdras Automática, S.L.	10	Various		
FLOCAN 5	Consent Application Submitted	Gobierno de Canarias/ Gobierno de Canarias (20%), COBRA INSTALACIONES Y SERVICIOS, S.A. (80%)	25	Floating: Semi-Spar - Concrete	5 MW	min. 4

2.2.2.3. Mediterranean Sea (Cataluña)

Further in the Gulf de Roses area (in the Mediterranian sea), the "Parc Tramuntana Floating Offshore Wind Project" has been announced. Within the initial document of the "Parc Tramuntana Floating Offshore Wind Project," five areas (Alternativa) were analysed with regards to:

- Wind resource
- Water depth
- Distance to shore/ Visual impact
- Connection to the electricity network
- Strategic zoning of maritime space
- Aerial interference
- Maritime traffic
- Fishing activity
- Protected areas
- Habitats and Komplett.no
- Other uses of marine space
- Other conditioning factors

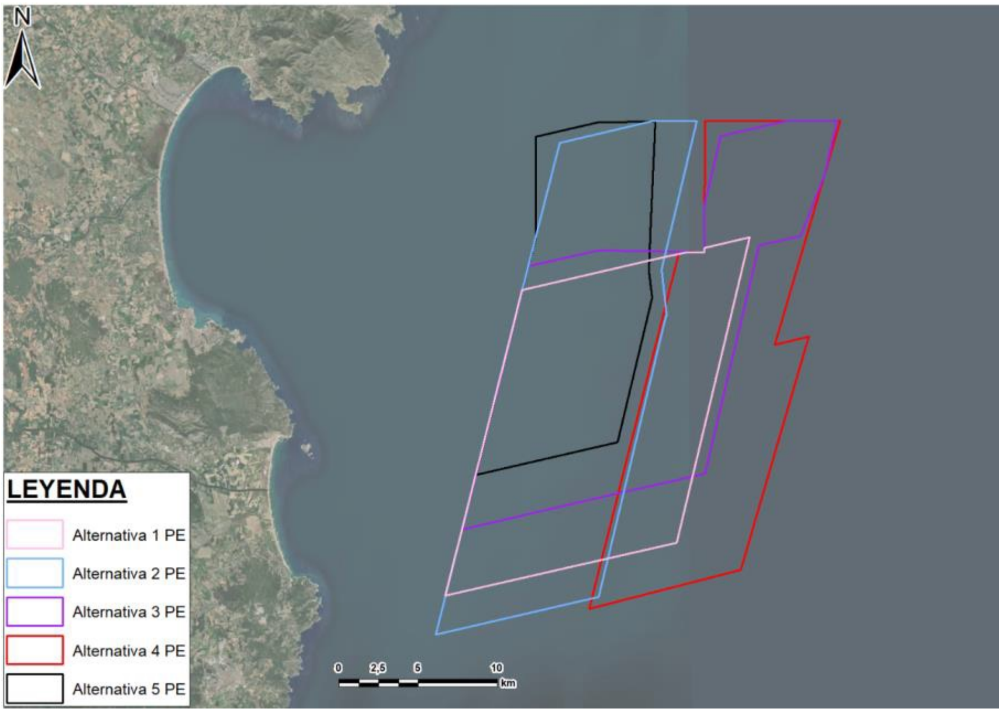


Figure 2.10.: Areas layout alternatives for the Parc Tramuntana Floating Offshore Wind Project in the Golf de Roses in Cataluña [115]

The different areas that have been analysed are drawn in figure 2.10. After evaluating the different alternatives, alternative 5 became the favourite for the project developers [115, P. 148]. Alternative five is located approximately 10.2 km from the coast, with a water depth in the area of 119 to 182 m—the maritime area occupied by the wind park is 159 km². Further, the gradient of the sea bed in the largest part does not exceed 0.85°. Only in a small area close to the north-east boundary the gradient varies between 0.86 and 3.13°. Steep slopes shall be avoided as they make the exploration more difficult [115].
The Parc Tramuntana Floating Offshore Wind Project is expected to be commissioned in 2026. A combined capacity of 1,035 MW shall be installed in this area, developed in two phases. In the first phase, the developers BlueFloat Energy and SENER Grupo de Ingenieria plan to install 30 to 34 turbines with each of 15 MW capacity (= max. 510 MW combined). The second phase includes 35 turbines with a combined capacity of 525 MW. [28, 115]

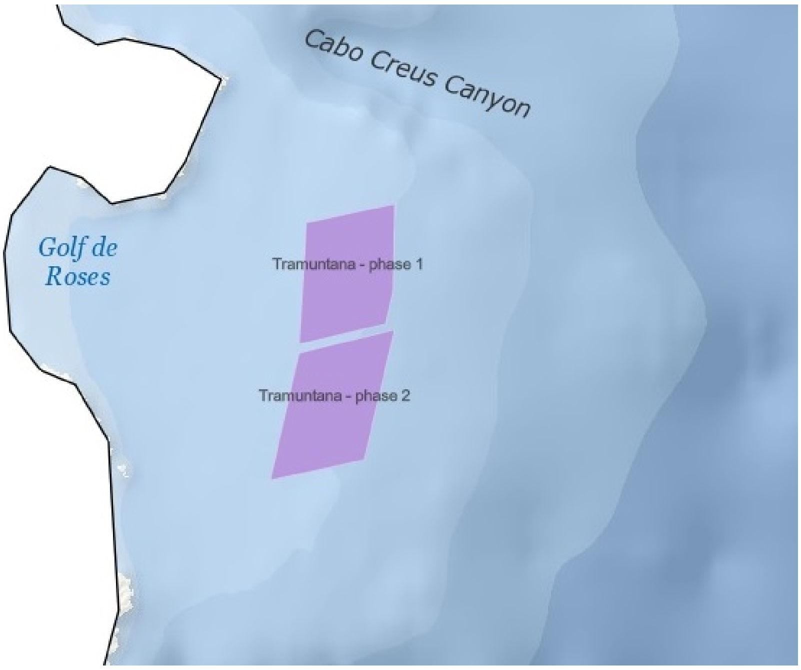


Figure 2.11.: Planned projects in the Golf de Roses in Cataluña [65]

2.2.3. UK and Ireland

As part of becoming net-zero by 2050, the UK government announced that by 2030 40 GW offshore wind capacity shall be installed. With more than 10 GW cumulative installed capacity in the UK, the UK is the world's largest offshore wind market. Another 5 GW offshore wind capacity is under construction, and 11 GW more are planned to be installed in British water [107]. More projects are announced to achieve the set goal, some of which are described in the following.

2.2.3.1. Scotland

Scotland has high offshore wind potential, and combined, they already produce 1,890 MW of electricity (compare table 2.5). Further, table 2.5 gives information about projects that are under construction, consented, with seabed lease and in the early stage. The location of the projects mentioned in this table can be found in figure 2.12. Figure 2.12 indicates the sites of ScotWind and other projects, and figure 2.13 shows the INTOG Areas of Search.

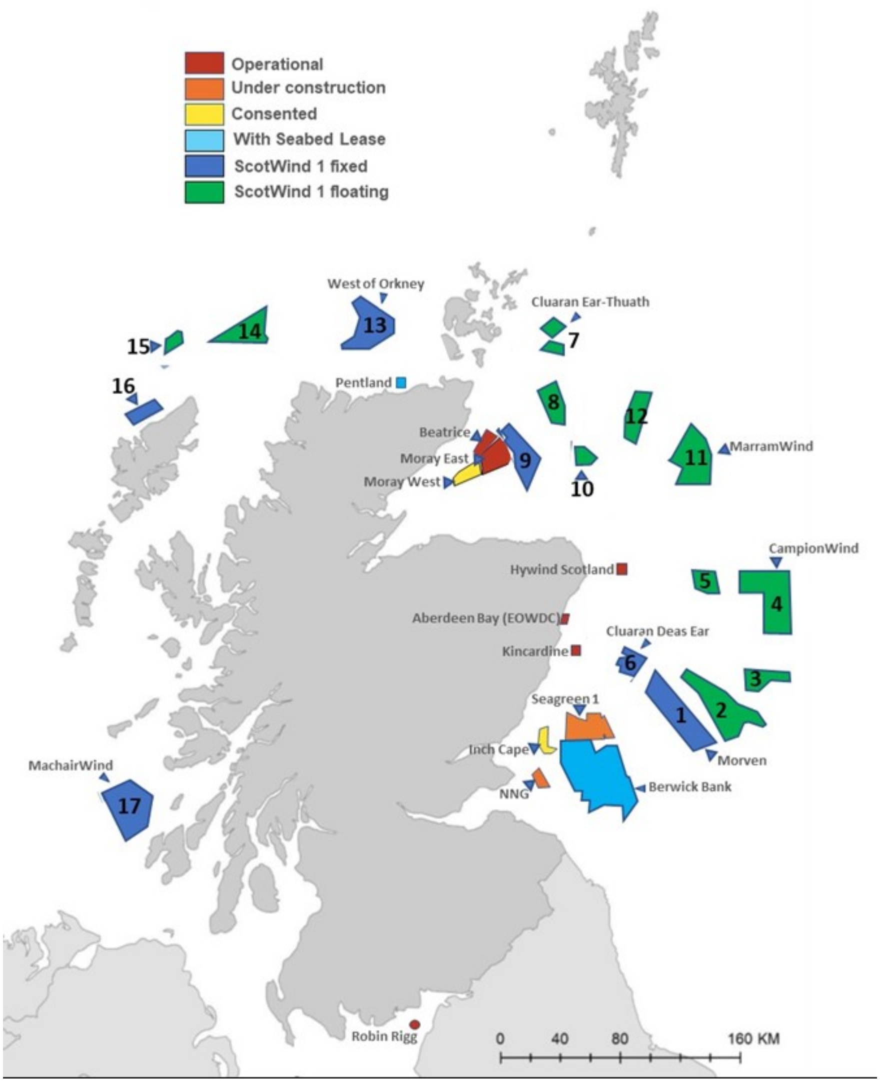


Figure 2.12.: From Crown Estate Scotland awarded offshore wind sites in the ScotWind seabed [131]

The target of the Scottish government is to generate 50 % of the Scottish overall electricity consumption until 2030 from renewable sources. Therefore ScotWind Leasing was launched in 2020 [129]. In the first leasing round, the Crown Estate Scotland received 74 applications for building projects in the areas that have been put out to tender. From these applications, 17 projects have received an option agreement for the rights for specific areas. In case of a successful deal, the applicants will, in total, pay an option fee of £700m to the Scottish government, which will use this money for public spending [132]. The locations of the projects can be found in figure 2.12, as well as the already operating, under construction, consented, and with seabed lease offshore wind farms in the Scottish territory. Further, figure 2.12 indicates which area is intended for the bottom fixed or floating foundation. Table 2.6 extends information about the company applied for the area and the planned installation capacity. Corresponding to the table 2.6 nearly 25 GW shall be installed, whereof 60 % (15 GW) of the capacity is planned on floating structure [131].

As figure 2.13 and table 2.5 already indicate, ScotWind is not the only round of projects coming up in the nearer future. By the attorney of Marine Scotland, a consultation looking for other suitable areas was launched (INTOG and INTOG Innovation) as shown in figure 2.13. The IN-

Table 2.5.: List of all projects in the Scottish offshore wind project pipeline with their current status, developer and capacity[131]

Stage	Site	Developer	Capacity (MW)	Combined Capacity (MW)
Opertional	Robin Rigg	RWE Renewables	174	1890
	Hywind Scotland	Equinor	30	
	Aberdeen Bay	Vattenfall	93	
	Levenmouth	ORE Catapul	7	
	Beatrice	SSE/Red Rock Power	588	
	Kincardine FOW	Cobra/Pilot Offshore	48	
	Moray East	Ocean Winds	950	
Under Construction	MMG	EDF Renewables/ ESB	448	1528
	Seagreen 1	SSE Renewables/ TotalEnergies	1080	
Consented	Seagreen 1a	SSE Renewables/ TotalEnergies	420	2362
	Inch Cape	Red Rock Power	1080	
	Moray West	Ocean Winds	850	
	ForthWind	Cierco	12	
With Seabed Lease	Berwick Bank	SSE Renewables	4150	4250
	Pentland FOW	Copenhagen Infrastructure Partners	100	
Early Stage	ScotWind 1	17 sites with multiple developers	24826	29326
	INTOG	Various sites with developers TBC	4000	
	INTOG Innovation	Various sites with developers TBC	500	

Table 2.6.: Planned installation capacity, used technology and developer for the 17 projects from figure 2.12 [132]

Map reference (figure 2.12)	Lead applicant	Technology	Total capacity (MW)
1	BP Alternative Energy Investments	Fixed	2,907
2	SSE Renewables	Floating	2,610
3	Falck Renewables	Floating	1,200
4	Shell New Energies	Floating	2,000
5	Vattenfall	Floating	798
6	DEME	Fixed	1,008
7	DEME	Floating	1,008
8	Falck Renewables	Floating	1,000
9	Ocean Winds	Fixed	1,000
10	Falck Renewables	Floating	500
11	Scottish Power Renewables	Floating	3,000
12	BayWa	Floating	960
13	Offshore Wind Power	Fixed	2,000
14	Northland Power	Floating	1,500
15	Magnora	Mixed	495
16	Northland Power	Fixed	840
17	Scottish Power Renewables	Fixed	2,000
Total			24,826

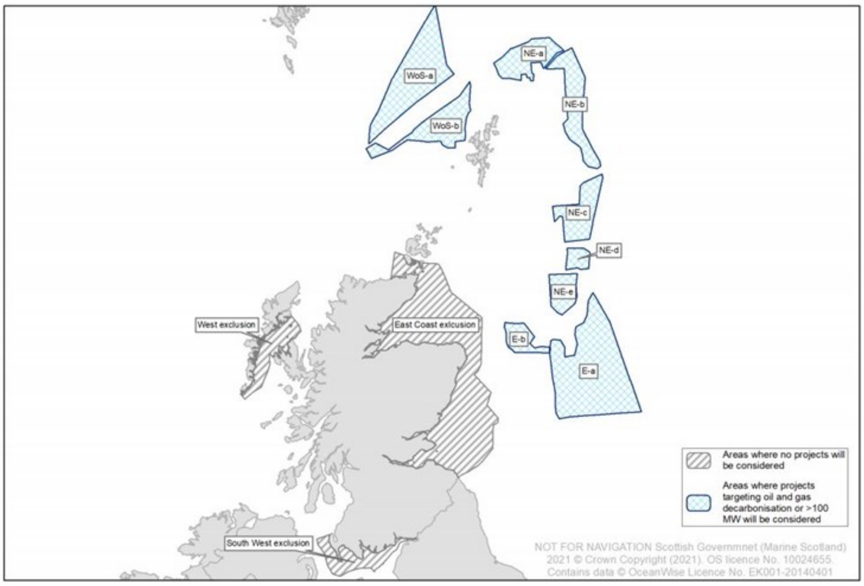


Figure 2.13.: Area of INTOG [131]

TOG projects shall provide a combined capacity of 4.5 GW, and the site application is expected to start at the end of 2022 or the beginning of 2023. The INTOG projects, together with the other projects, will provide Scotland with 40 GW by 2033. With the second round of ScotWind (expected in 2024/25), Scotland will have the largest offshore wind market in Europe with [131].

2.2.3.2. Wales

The company ITPEnergised carried out an analysis for offshore floating wind in the Irish and UK waters of the Celtic Sea and Wales. Figure 2.14 show the ten potential zones ITPEnergised found in the Celtic Sea [70].

Within this investigation, eight sites were found in zone seven of the analysis from ITPEnergised. Six of the eight sites shown in figure 2.17 are located in Wales, and table 2.7 summarises the details of the planned projects in this area. In total, nearly 1.2 GW could be installed in this area. Most of the projects are expected to be operational in 2026.

Furthermore, two sites in the Celtic and the Irish Sea have been selected for a case study, and the locations can be found in figure 2.15. Table 2.8 summarises the boundary conditions of South and North Wales sites.

The case study also includes a port assessment. Figure 2.16 indicates ports around Wales that have been considered within the assessment. Port Talbot will be capable after upgrading for fabrication, assembly, and staging. The ports of Mostyn, Talbot and Pembroke Dock would be suitable for assembly and staging and mooring. For wind turbine staging, the ports of Holyhead and Pembroke Dock would be capable after upgrading of current infrastructure [70].
The ports Holyhead, Mostyn, Milford Haven and Port Talbot, were selected for port strategy study for the port selection for the two offshore floating wind sites. The port strategies found in "NON-TECHNICAL SUMMARY: FLOATING WIND IN WALES – SUBSTRUCTURE AND PORT REVIEW" [70] is summarised in table 2.9. Important drivers for the port selection are water depth, wind speeds, capacities and distances to the site.

In addition, the case study analysed the port activity costs for the two sites with two different substructures (Steel semi-sub substructure and Concrete semi-sub substructure). The study includes the costs for the turbine, assembly (and wet storage), mooring line and anchor for

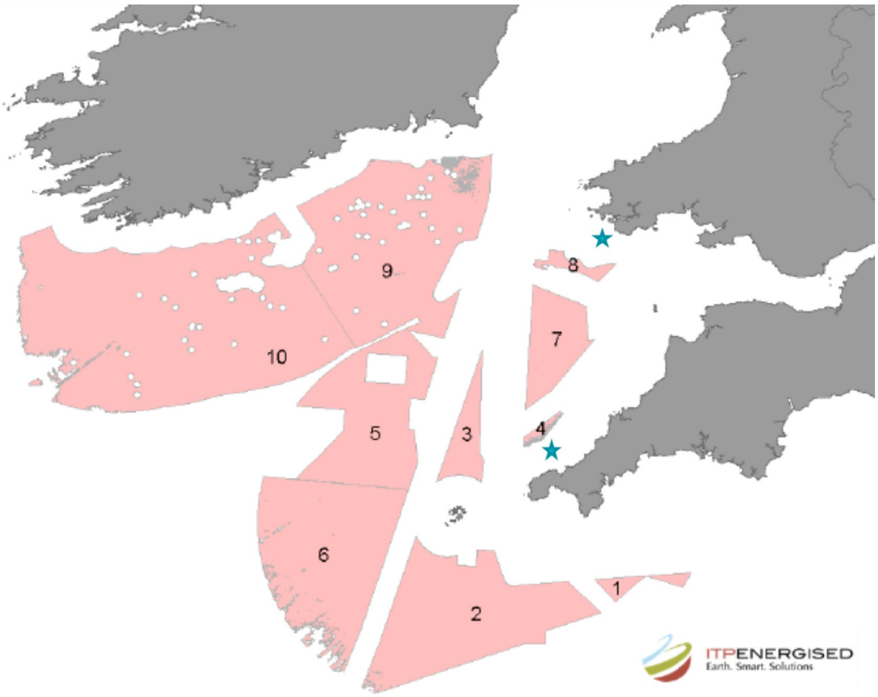


Figure 2.14.: Potential zones of offshore floating wind development in South England, Wales and Ireland as identified by ITPEnergised [70]

Table 2.7.: Concept/Early Planning offshore floating wind projects in Wales [65]

Name	Development Status	Owner	Capacity (MW)	Foundation Type	Operational	Ref.
Llyr 1	Concept/ Early Planning	Cierco Ltd. (50 %) SBM Offshore N.V. (50 %)	100	Floating: Not Specified	2026	[91, 24]
Llyr 2	Concept/ Early Planning	Cierco Ltd. (50 %) SBM Offshore N.V. (50 %)	100	Floating: Not Specified	2026	[92, 25]
Llywelyn	Concept/ Early Planning	Falck Renewables, BlueFloat Energy	300	Floating: Not Specified	2029	[93, 94]
Gwynt Glas	Concept/ Early Planning	DP Energy Ireland	300	Floating: Not Specified	2026	[75, 22]
Erebus Demonstration	Concept/ Early Planning	Blue Gem Wind Ltd. (Developer) TotalEnergies (80 %) Simply Blue Energy Ltd. (20 %)	96	Floating:Semi-Submersible - Steel	2026	[53, 19]
Valorous	Concept/ Early Planning	Blue Gem Wind Ltd.(Developer) Total New Energies (80 %) Simply Blue Energy Ltd. (20 %)	300	Floating:Semi-Submersible - Steel	2026	[143, 32]

two different site capacities (300 MW and 1,000 MW). Comparing the total Gross Value Added (GVA), the 300 MW solution with a steel semi-sub is the cheapest solution for both sites. The concrete semi-sub solution for the 1,000 MW option is cheaper than the steel option. However, calculating the costs per kW, the 1,000 MW solution is between 32 % and 37 % cheaper than the

Table 2.8.: Boundary conditions at the sites South and North Wales [70]

Case Study	**Unit**	**South Wales**	**North Wales**
Average water depth	m	115	80
Distance to port	km	60	75
Grid Connection Zone		Pembrokeshire	Pentir
Distance to cable landfall	km	40	38
Onshore cable distance	km	10	63
Mean wind speed at site (@ 150m height)	m/s	10.7	9.9
Annual mean significant wave height	m	1.9	1.5
Seabed conditions		Hard (Rock-based)	Normal (Sand, sandy mud, mud, clay)

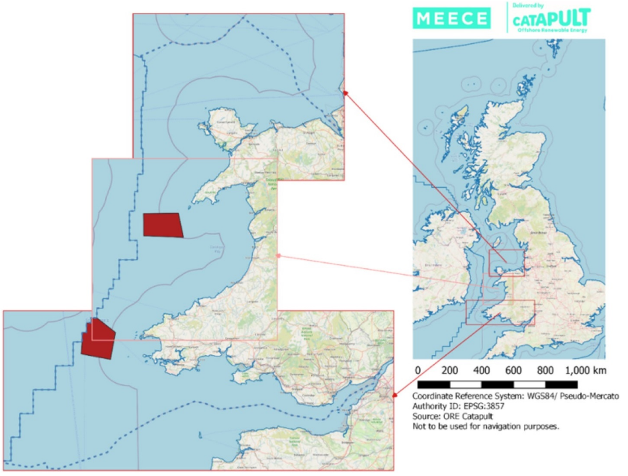


Figure 2.15.: Locations of Welsh floating offshore wind case study [70]

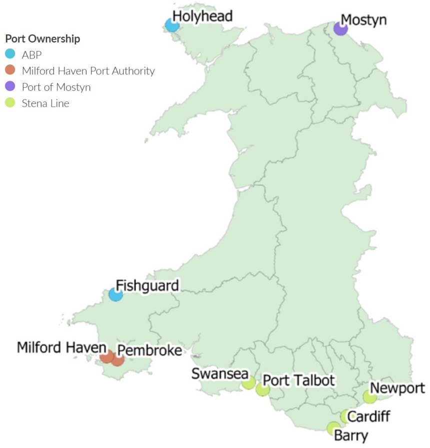


Figure 2.16.: "Location of ports around Wales" [70]

Table 2.9.: Port strategies for floating offshore wind sites north and south Wales [70]

Port Activity (Option strategy in blue)	**North Wales**	**South Wales**
Substructure Assembly (steel)	Mostyn / Port Talbot	Port Talbot
Concrete Substructure	Mostyn / Pembroke Port	Pembroke Port
Mooring Line & Anchor Installation	Holyhead	Port Talbot
Wet Storage	Holyhead / Mostyn / Port of Milford Haven	Port of Mildord Haven
Turbine Assembly	Pembroke Port	Pembroke Port

300 MW concept [70].

First, it is asserted that there is no cost difference between the two sites in any option. Also, is the 1,000 MW solution always cheaper per kW than the 300 MW option.

2.2.3.3. England

The water depth in the east and south of England does not drop significantly below 50 m. Therefore bottom fixed foundations are used for most of the new planned offshore wind parks in England. Nevertheless, in the north of Cornwall, the water depth drops significantly. Hence the projects planned in this area are based on a floating substructure.

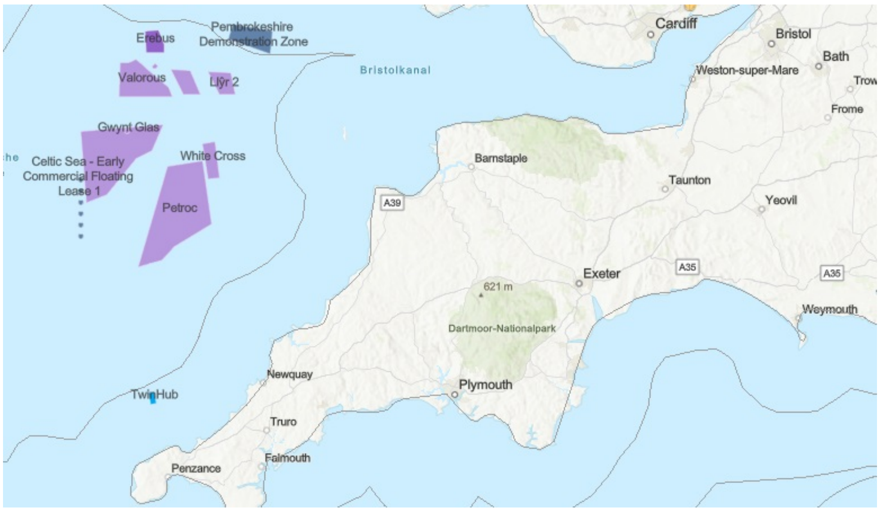


Figure 2.17.: Floating projects in English and Welsh Territory [65]

Figure 2.17 shows eight projects which are currently in planning / Consent Application Submitted in England and Wales (Celtic Sea). The projects are located in zone seven, identified by the study of ITPEnergised as a potential zone for offshore floating wind (comparing figure 2.14). The two projects that are located in English territory are Petroc and White Cross. Petroc is developed by Falck Renewables and BlueFloat Energy, with a planned capacity of 300 MW and shall be operational in 2029 [111]. White Cross offshore wind farm is located approximately 50 km off the coast of Cornwall. The developer Cobra and Flotation Energy are planning to install 100 MW on an innovative floating substructure on the site and shall be operational in 2026/27 [146].

2.2.3.4. Ireland

The Irish government announced the development of a 5 GW offshore wind capacity by 2030. With more than 30 projects in different planning stages and an approximated total capacity of 29 GW, the target of 5 GW by 2030 seems feasible, says PhD researcher Aldert Otter from University College Cork [108]. The 5 GW planned by 2030 are mainly planned on a bottom fixed structure. The Irish government plan to have more offshore floating wind in the south and west to comply with their goal of having 35 GW offshore wind capacity by 2050. [85]
Figure 2.18 shows a map of Ireland with its maritime boundaries and the offshore wind sites, which are most in the concept/early planning stage. Most of the projects are located east and south of the island. Due to the relatively small water depth (up to 50-60 m) in the east, these projects are planned on bottom fixed substructure solutions (mostly monopile). Projects planned on floating substructure can be found in the south, and (north) west of the Irish coast [65]. The table 2.10 summarises the current floating projects, which could provide up to 9.9 GW. 4.4 GW of the total 9.9 GW from the offshore floating projects in table 2.10 shall be in operation by 2028.

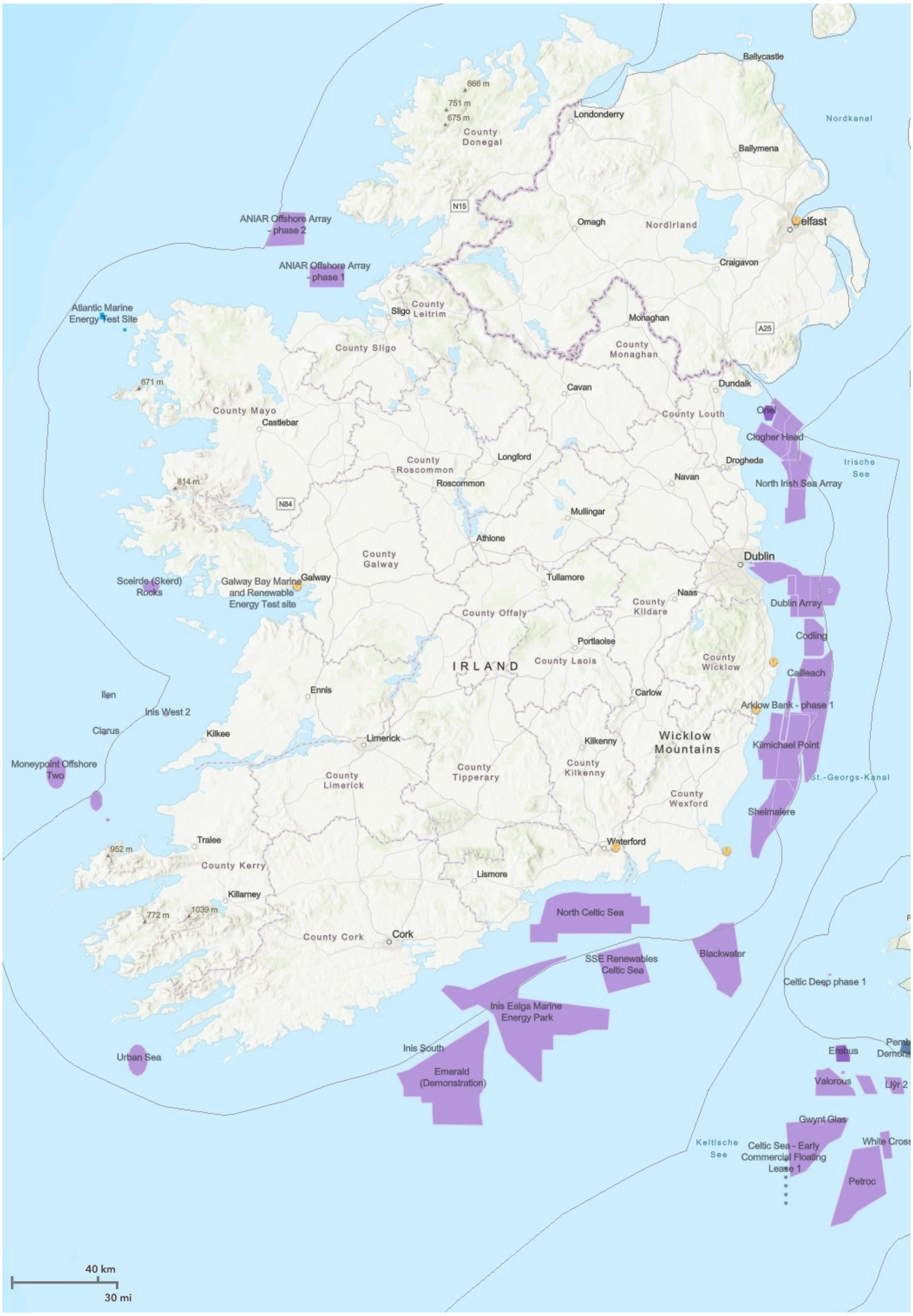


Figure 2.18.: Map of Ireland with offshore wind projects, most in concept/early planning stage [65]

Table 2.10.: Concept/Early Planning offshore floating wind projects in Ireland [65]

Name	**Development Status**	**Owner**	**Capacity (MW)**	**Distance (km)**	**Foundation Type**	**Commissioning**	**Ref.**
Inis Ealga Marine Energy Park	Concept/ Early Planning	DP Energy Ireland Ltd (49 %) Iberdrola Renovables Energia, S.A. (51 %)	1000	22	Floating: Not Specified	2030	[84, 83]
Emerald	Concept/ Early Planning	Shell New Energies (51 %) Simply Blue Energy Ltd. (49%)	1000	35	Floating: Semi-Submersible - Steel	2027/28	[48, 47]
SSE Renewables Celtic Sea	Concept/ Early Planning	SSE Renewables (formerly Airtricity)	800	25	Floating: Not Specified	2027	[137, 34, 35]
Blackwater	Concept/ Early Planning	COBRA INSTALACIONES Y SERVICIOS, S.A. (50 %) Flotation Energy plc (50 %)	1500		Floating: Not Specified	2027	[10, 9]
ANIAR Offshore Array - phase 2	Concept/ Early Planning	Aniar Offshore ltd.	500	14	Floating: Not Specified		[5]
Moneypoint Offshore Two	Concept/ Early Planning	ESB	1100		Floating: Not Specified	2028	[100, 64]
Urban Sea	Concept/ Early Planning	Enterprize Energy PTE. LTD.	4000		Floating: Not Specified		[142]

2.2.4. France

French President Macron announced that France will aim to be carbon-neutral by 2050. To accomplish this goal, the president also announced that by 2050 France should have a capacity of 40 GW of offshore wind. [95]

As per table 2.1 in France, there are currently four ongoing projects with a commission date in 2022/23. Table 2.11 gives more information about the four projects. Additionally, table 2.11 contains four more floating offshore wind projects in french waters. Both projects, EOLINK and Floatgen, are located at SEM-REV - SITE D'EXPERIMENTATION EN MER - MARINE TEST SITE located at the french west coast (English Channel/ Atlantic Ocean) [65]. Two other projects are planned for the Mediterranean sea.

Table 2.11.: Offshore floating wind projects in France

Name	**Development Status**	**Owner**	**Capacity (MW)**	**Foundation Type**	**Commissioning**	**Location**	**Ref.**
Golfe du Lion	Pre-Construction	Caisse des dépôts et consignations (20%) Ocean Winds (80%)	30	Semi-Submersible Platform - Steel	2023	Mediterranean Sea	[68, 23]
Groix & Belle-Île	Consent Authorised	CGN Europe Energy (25.5%) EOLFI (25.5%) Caisse des dépôts et consignations (49%)	28.5	Semi-Submersible Platform - Steel	2022	Atlantic Ocean	[73, 20]
EolMed	Consent Authorised	TotalEnergies (20%) BW Ideol (5%) Qair Marine (75%)	30	Barge - Concrete	2023	Mediterranean Sea	[52, 18]
Provence Grand Large	Pre-Construction	Canada Pension Plan Investment Board (25%) Enbridge Inc. (25%) EDF Energies Nouvelles Group (50%)	25.2	Tension Leg Platform - Steel	2021	Mediterranean Sea	[114, 116]
Floatgen	Fully Commissioned		2	Barge - Ideaol's Damping Pool	2018	English Channel/ Atlantic Ocean	[86]
EOLINK 5 MW Demonstrator	Pre-Construction	EOLINK S.A.S.	5	Semi-Submersible Platform - Steel	2022	English Channel/Atlantic Ocean	[50, 38]
AFLOWT	Concept/ Early Planning		6	Semi-Submersible Platform - Steel		Mediterranean Sea	[3]
EolMed - Ideol & Quadran Commercial Scale Floating Projec	Concept/ Early Planning	Quadran Energies Libres (50%) BW Ideol (50%)	500	Barge - Concrete		Mediterranean Sea	[51]

3. Design of offshore floating substructure

There are currently four different main concepts of floating structure[57] which are illustrated in figure 3.1 and presented in the following.

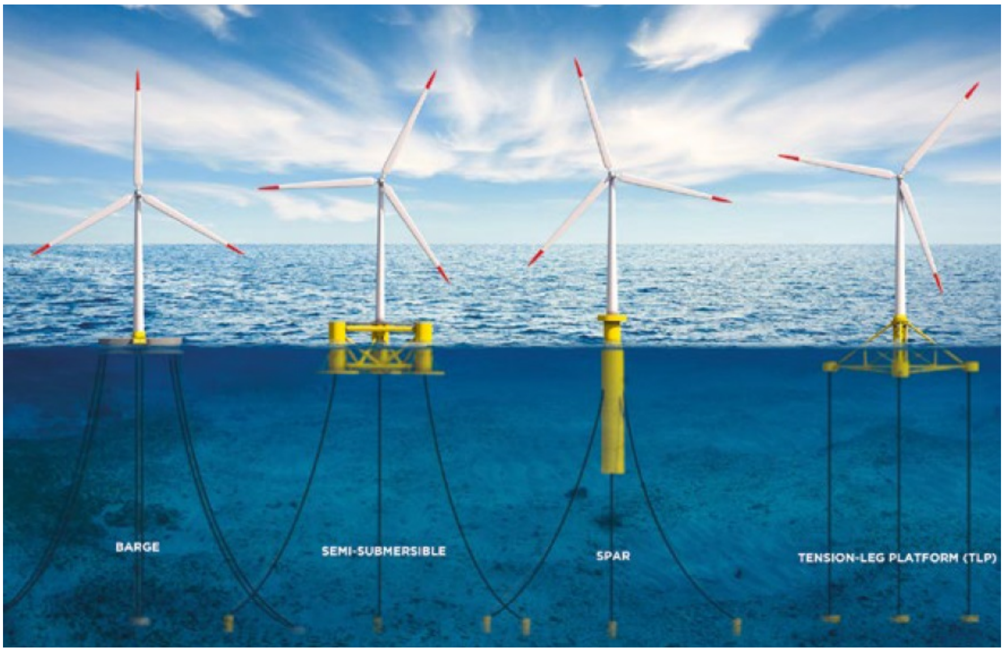


Figure 3.1.: Floating substructure [57]

3.1. Single Point Anchorage (SPAR) buoys

A SPAR-buoy, also called just SPAR, is a cylindrical structure (see figure 3.1) with a relatively small waterplane area. It has a very low centre of gravity because of added ballast to make it stable. Once ballasted, it can have a draught between 70 and 90 m, making it suitable for water depths greater than 100 m. The SPAR is attached with drag anchors and catenary or taut spread mooring to the seabed [119, 147].

3.2. Semi-submersibles

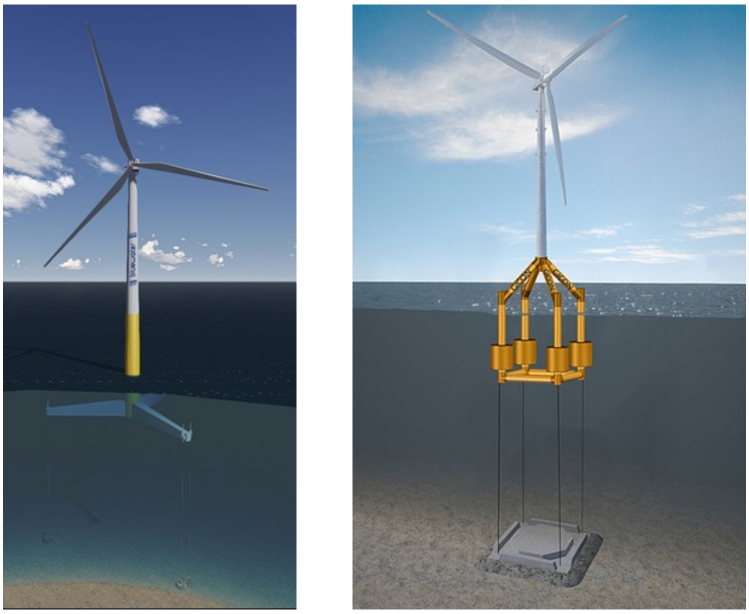
A semi-submersible (semi-sub) usually consists of three columns that are connected. The wind turbine is placed either on one of these columns or in the middle of the structure. Examples for both solutions are illustrated in figure 3.2. The structure is stable by its buoyancy, drag anchors and catenary or taut spread mooring keep the structure in position. Semi-subs have a draught of 15 to 25 m and are suitable for water depths larger than 40 m. [1, 147, 119].

(a) (b)

Figure 3.2.: Semi-submersibles substructure [39]

3.3. Tension Leg Platforms (TLP)

A tension leg platform is a small substructure with a high buoyancy force. The mooring lines are tensioned and provide thereby the required stabilities. Due to its stability, it is sensitive to high-frequency dynamic loads. The draught at installation is between 25 and 35 m, so the minimum required water depth is specified between 40 and 50 m. [7, 56, 57, 59, 119, 147]. Figure 3.3 show two example substructure for TLPs

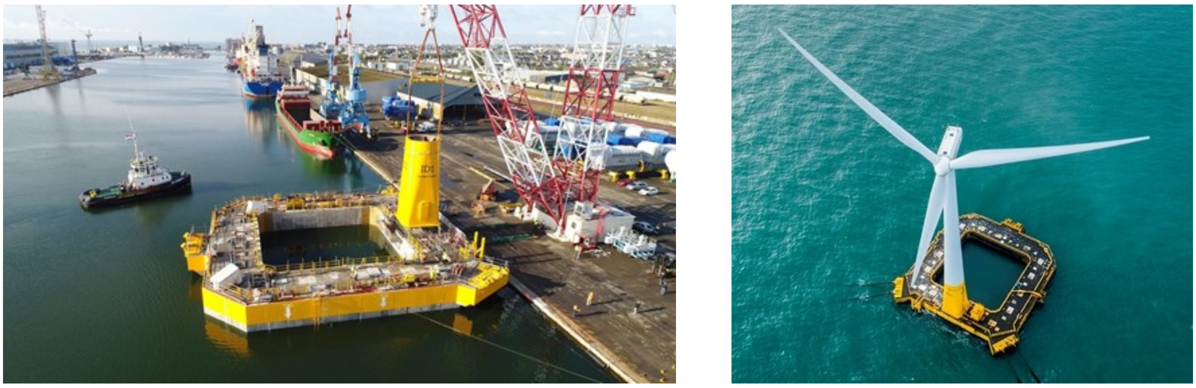


(a) (b)

Figure 3.3.: Tension Leg Platform substructure [39]

3.4. Barges

A barge is a substructure made out of steel or concrete. It is stabilised through its waterplane area and buoyancy. Barges have a low draught, are kept in position with catenary mooring lines, and can be used for water depths larger than 30 m [119, 147]. The company "IDEOL" [81] developed a design with a damping pool in the centre of the barge (see figure 3.4). The pool reduces the motion of the structure by wave loads, and motion [106] resulting in the structure floating more steadily.



(a) (b)

Figure 3.4.: Barge substructure [39]

Summary The table 3.1summarizes the main characteristics of four floater types presented earlier.

Table 3.1.: Summery of main characteristics of the different floating substructurs, Semi-Submersible, Spar, TLP and Barge [1, 59]

Floater Types	**Structure configuration**	**Stability**	**Water depth**	**Station Keeping**	**Turbine installation**	**Transportation and Installation**
Semi - Submersible	complex structure	less stable, problem with wave-induced motion	> 40 m	Catenary mooring	dockside installation	Tug-towing, low draft during transport
Spar	simple desig, large and tall size	Very good stability	>100 m	Catenary mooring	Offshore installation	challenging (size of hull + water depth at site)
TLP	small, light structure	Good stability, except during transportation and installation	> 40 m	Complex mooring due to required tension	dockside installation	Tug-towing
Barge	simple structure	(Very) Good stability	> 30 m	Catenary mooring	dockside installation	Tug-towing

3.5. Assembly and installation

In the section before, different substructure concepts have been presented. In the following, the installation of SPAR and Semi-Sub will be described.
In the case study, it is assumed that the substructures are always available at the site. However, in reality, the substructures need to be produced and towed to the assembly site. Within the Hywind Tampen project, the first parts of the foundation were produced in Stord and then towed to Vindafjord [80]. At Wergeland Base, it is planned to have a dock available where substructures can be produced and towed directly to the assembly quay — having the production facility close to the assembly quay would save a lot of time and uncertainties due to the weather.

3.5.1. SPAR

Generally speaking, a SPAR is fabricated onshore/in a dock, and the turbine is assembled on it in a sheltered place. Not every port can handle a SPAR structure since many ports do not have the required water depth. As indicated in figure 3.5, the structure is towed from the fabrication site to a site where it can be stood up and ballasted. At last, the turbine is mated to the SPAR and towed out to the site where anchors have been pre-installed [87, 36].

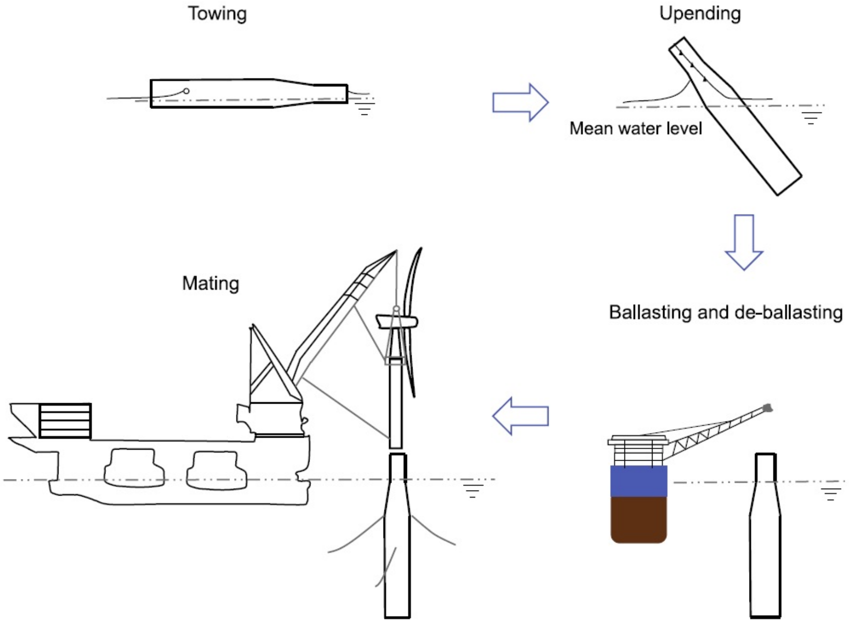


Figure 3.5.: Installation SPAR [87]

Within the Hywind Scotland project, the substructures were produced in Spain. The SPARs were horizontally towed to sheltered coastal waters (Stord, Norway). [36, 90, 78]
For upending the SPAR, water was pumped into the SPARs foundation. Then the structures were ballasted with magnetite while de-ballasting the water to maintain sufficient draft. The pre-assembled wind turbines were mated with the SPAR using a heavy lift vessel. During the installation, it was required that the significant wave height did not exceed 0.5 m and wind speed did not exceed 4 Beaufort. [36, 90]
The pre-assembled wind turbines were then towed from Norway to Scotland one by one. One journey took around four days at a towing speed of 3 knots. As the operation is limited by wave height and wind speed, these parameters have been analysed for the voyage. It was found that the months of April to September give the best operational weather windows for the projects' plans. Therefore the weather depending operations have been scheduled in this period. [55, 90, 98]

For the ongoing project, Hywind Tampen, the first 20 m of the SPAR have been built in a dry dock in Stord. Then the structures were towed to Vindafjord and were continued until a length of 107 m. After completion, the SPARs were dragged to Wergeland Base close to Gulen, where the turbines were assembled in Q2 2022 and towed out. [80]

3.5.2. Semi-Sub

As well as the SPAR, the Semi-Submersible is also constructed onshore. The Semi-Submersible can be built out of two different main materials, steel or concrete. While steel is good established material in the offshore wind industry, the usage of concrete is limited. However, it must be mentioned that the cost of concrete is less than steel, which supports the local supply and does not need specialised equipment like the large-scale welding machines required for steel structures. Nevertheless, steel structures are faster to assemble than concrete as concrete is more weather-sensitive during the construction/drying process. [97] Like the SPAR, the wind turbine is linked to the substructure and combined, they are towed out to the desired location [87]. Figure 3.6 shows how a wind turbine on a semi-sub is towed out in the Celtic Sea [109].

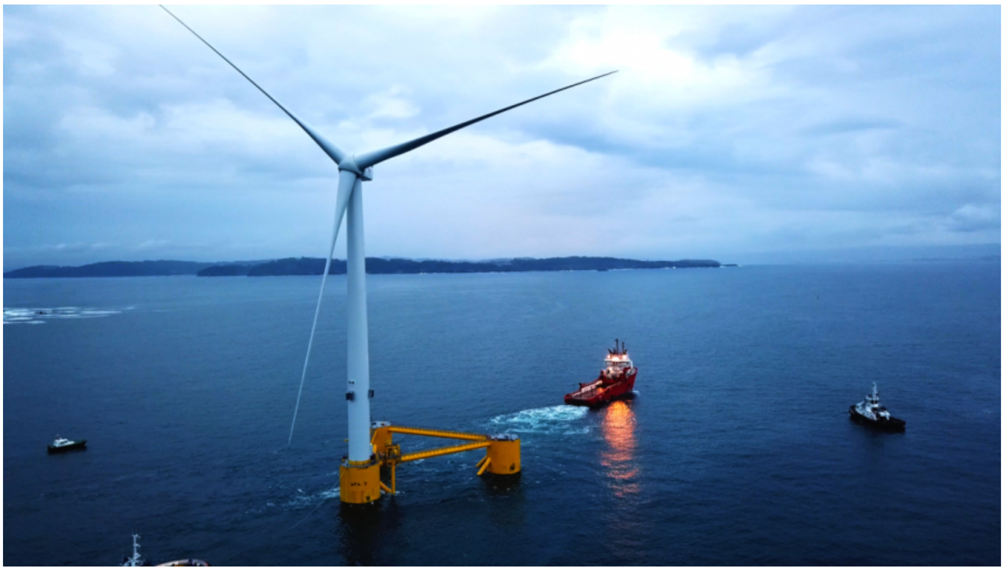


Figure 3.6.: Tow out of a wind turbine on a Semi-Submersible substructure in the Celtic Sea [109]

3.5.3. Assembly

After the substructure is towed to the assembly side, a crane can assemble the wind turbine on the structure. Assuming all components are available, the bottom part of the tower is first connected to the substructure, and depending on the turbine height, more sections are assembled. On top of the tower, the nacelle is allocated to which the blades are connected.
All these operations are weather sensitive. Therefore the operational weather restrictions are limited to a maximum wave height of 0.5 m and a maximum wind speed of 12 meters per second at the height of the hub.

3.5.4. Challenges

All new technologies and inventions come along with new challenges. With time and experience, these challenges can be solved, for example, when using established technologies and experiences from the offshore oil and gas sector. A few challenges offshore floating wind faces will be mentioned in the following.

3.5.4.1. Design and material

The best place to install wind farms are areas with potential high winds. However, this also means installing and operating the turbines in harsh offshore conditions. Those conditions are very demanding for the structure and materials used for offshore wind. Each design mentioned earlier in this section has its advantages and disadvantages, and not every design is the best solution for every place.

One of the key factors for the design is stability, as the turbine is installed at a certain height above sea level and at the same time, the structure has to provide sufficient buoyancy. Furthermore, the structure must be able to counteract the loads from waves and current to be a stable foundation for the wind turbine. However, it was shown that wave-induced loads do not have a significant additional impact due to long cyclic periods in deep water compared to bottom-fixed wind turbines. The different designs have different solutions to fulfil this requirement. [141, 12]

The wind turbines are moored to the ground to maintain their position. Technology and experiences from oil and gas can be used here. However, in offshore floating wind, many single structures are close to each other, and each needs its own mooring. Concepts of shared anchors have been developed to use the installed anchors on the seabed more efficiently and reduce costs. [96, 61]

Another challenge offshore floating wind gives is the connection to the electricity grid. Besides, floating offshore wind is usually further offshore than bottom fixed; it is also in deeper water. Therefore, the length of the required cable and the costs for this cable increase for shore connection. Further, the array of cables raises other challenges. One challenge is that these cables must be very long to be laid on the seabed. Alternatively, buoyancy compounds, so-called floaters, are required to support the array cables, which could result in higher fatigue due to Vortex-induced vibration (VIV) if cables are floating in the water. [96]

3.5.4.2. Manufacturing

As earlier mentioned, there are few experiences with offshore floating wind. Only a few locations have been manufacturing the floating substructures, many of which were prototypes. For manufacturing on a bigger scale, very large port facilities are required; therefore, not every port is suitable. Further modifications like modular construction's ability might help broaden the range of ports; nevertheless, ports should provide relatively deep water close to the quay. [139]

3.5.4.3. Installation and maintenance

Besides that, the construction port requires a large infrastructure; the offshore floating wind turbines are usually assembled in a sheltered area with deep waters close to shore. These criteria limit the variety of ports. Hence the assembled turbines might have to be pulled longer to the designated site.

Conventionally jack-up vessels were used to install bottom-fixed offshore wind turbines, which can not be used due to the increased water depth. Heavy vessels or shore cranes are required for the assembly. The port site requires sufficient water depth for the substructure to use shore cranes for the assembly. A heavy-lift vessel could be used if the quay's water depth is inadequate. However, heavy lift vessels are also required for other operations in the oil and gas industry, affecting the vessel's availability and day rate. Besides the costs and availability of the vessel, the motions between the vessel and the turbine should be considered a risk in operation. For maintenance, it might be reasonable to tow the wind turbine into sheltered water to carry out the maintenance. [102, 139]

4. Scalability

With technological achievements, larger wind turbines and farms are built or are planned to be built. This thesis analyses the scalability of different parameters for the offshore wind base at Wergeland, Gulen.

4.1. Wind turbine

The ongoing projects are planned with wind turbines between 10 and 15 MW (see [1, 115]). IRENA [1] estimated in 2016 that the 10 MW wind turbine will be commercially used in the 2020s and the 15 MW wind turbine in the 2030s. However, projects in Spain show that they already plan projects with 12 MW and 15 MW wind turbines for mid/end of the 2020s (as per section 2.2.2). For this study, a 12 MW turbine has been selected as a basic turbine. Table 4.1 summarizes this study's design parameters of the 12 MW reference turbine. Figure 4.1 shows the power curve of the used turbine.

Table 4.1.: Design summary of a 15 MW and 20 MW wind turbine [2, 37, 82, 63, 135]

Parameter	**Value**		
Nominal power (MW)	12	15	20
Blade Length (m)	107	117	138
Hub Height (m)	136	150	160.2
Weight Tower (t)	781	860	2070
Mass rotor nacelle assembly		1,017	
Mass Nacelle (t)	400		945
Mass 1 Blade (t)		65	259
Mass Hub (t)	298		253
Cut-in wind speed ($\frac{m}{s}$)	3	3	3
Rated wind speed ($\frac{m}{s}$)	11	10.6	10.7
Cut-out wind speed ($\frac{m}{s}$)	25	25	25

Wind turbines with 15 MW, 20 MW or more capacity for future projects are realistic. The leading wind turbine manufacturers are currently developing turbines around 20 MW to establish them in the market in the nearer future [144]. Data like blade length or hub height are already available [122]. The design criteria for a sample 15 and 20 MW turbine are summarized in table 4.1. For the study and simulation, a power curve is required. A power curve from the IEA 15 MW turbine can be found in figure 4.2. However, for a 20 MW, there is currently no power curve available. Therefore a power curve with the following assumptions has been estimated [135]:

- cut-in wind speed of 3 $\frac{m}{s}$
- rated wind speed of 10.7 $\frac{m}{s}$
- cut-out wind speed of 25 $\frac{m}{s}$

The estimated power curve is shown in figure 4.3.

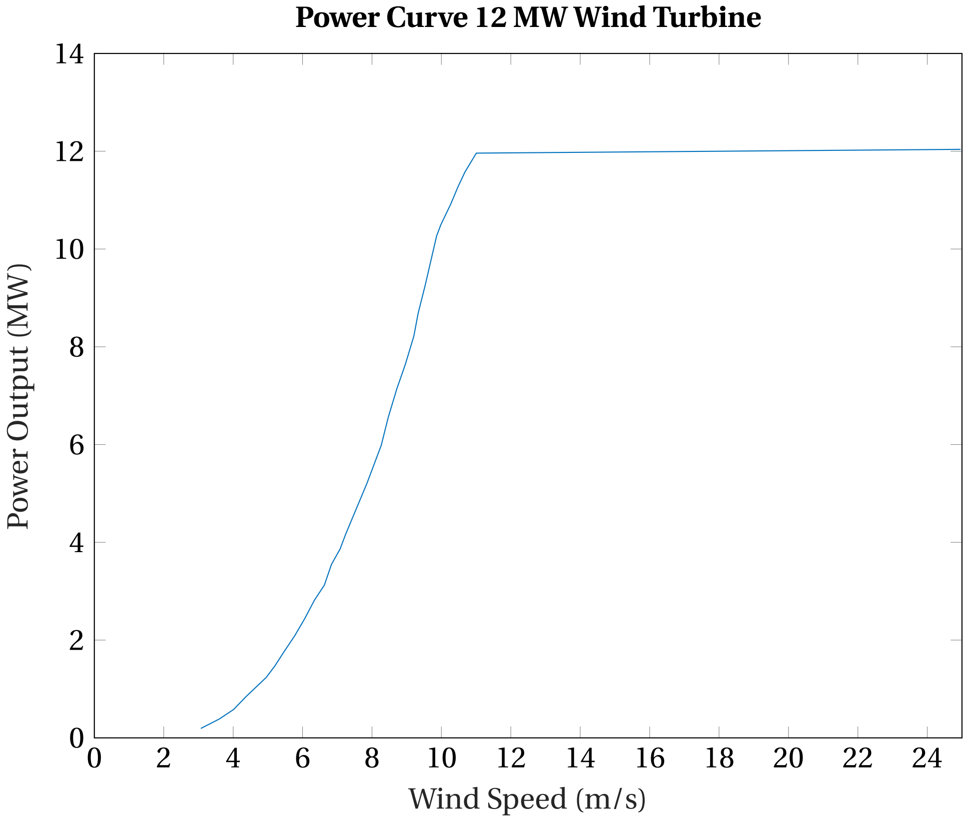


Figure 4.1.: Power Curve of a 12 MW wind turbine [2]

4.2. Infrastructure

Besides the scaling of the wind turbine, the site's infrastructure and logistics are analyzed.

4.2.1. Storage capacity

Other than bottom fixed wind turbines, floating wind turbines are assembled close to shore. When the turbine is assembled, it must be stowed before towing out. For the basic case, it is assumed that up to 10 turbines can be stowed at the base. However, what if the base grows and has more capacity to stow wind turbines before they are towed out will also be analyzed later on.

4.2.2. Vessel

Different vessels are required to install an offshore wind turbine. A floating structure must be attached to the seabed to maintain its position. Therefore mooring lines and anchors are required, which are installed by an anchor vessel (AHV). The mooring system is placed before the pre-assembled wind turbine is towed out. The specifications of the AHV used for this case study are summarized in table 4.2.

The towing speed is significantly less than the general transit speed to avoid damage to the turbine. Further to ensure safe travel, default weather criteria from shoreline [133] is used for the base case. These default criteria include a limiting wave height of 2 m and wind speed of 16 meters per second.

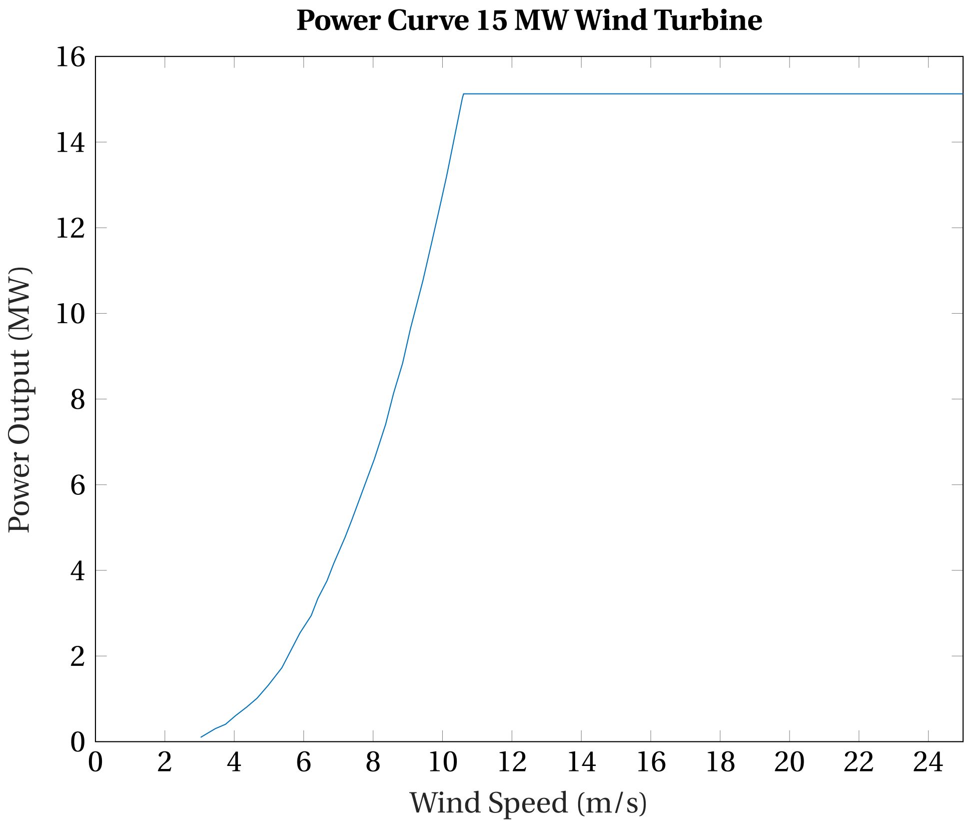


Figure 4.2.: Power Curve of a 15 MW wind turbine [82]

Table 4.2.: Anchor Vessel

Anchor Vessel	1
Mooring line capacity	4
Mooring anchor capacity	4
Transit speed	15 kn
Towing speed	5 kn
Dynamic positioning speed	2 kn
Dynamic positioning activation time	1 h

Table 4.3.: Towing vessel

Set of tug	1
Wind trubine capacity	1
General transit speed	15 kn
Transit while towing	3 kn

The set of tugs is able to tow out one wind turbine at a time. A set of tugs consists of at least two tugs; one drags the turbine while the others assist during manoeuvring. Possible parameters that can be analyzed are the effect of the towing speed on the installation time. Different numbers of sets of tugs and allowed towing speed will be analyzed to find the optimum combination with the shortest waiting times.

Furthermore, a so-called Crew Transfer Vessel (CTV) is required to install a wind turbine in the field. CTVs transfer technicians to the wind turbine who carry out maintenance or, in this case,

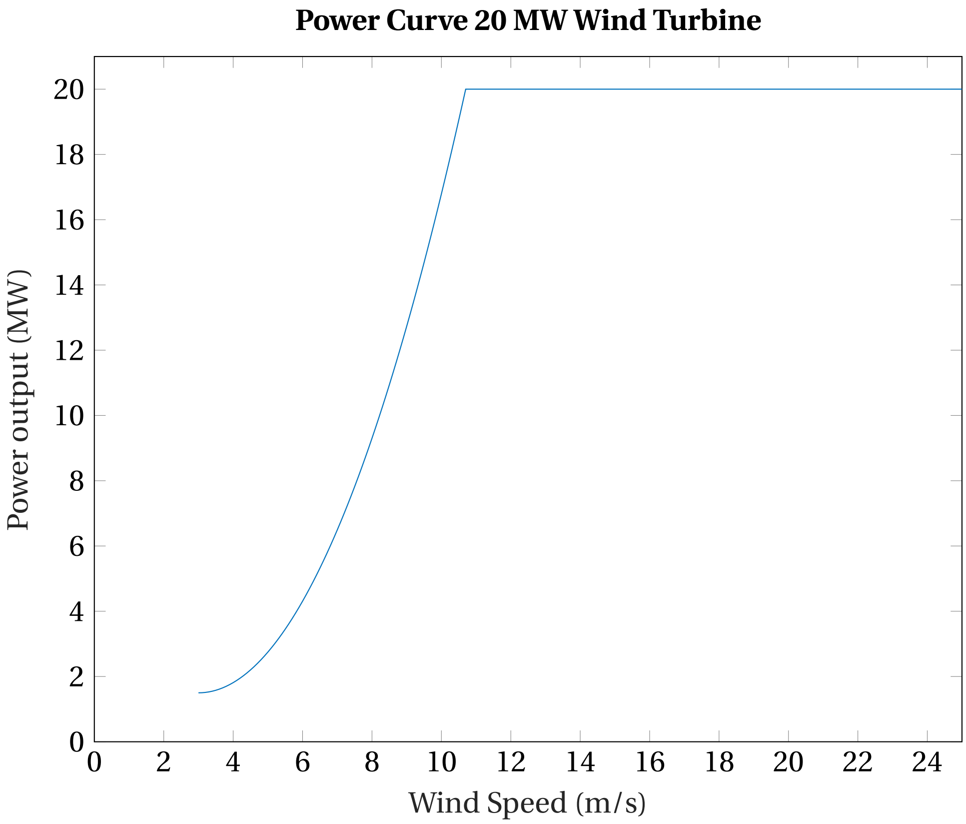


Figure 4.3.: Power Curve of a 20 MW wind turbine

the commissioning. Different limits are applicable depending on the size and design (catamaran/trimaran or conventional hull). The base case is assumed to operate with two CTVs with the specifications as per table 4.4.

Table 4.4.: Crew transfer vessel

Crew transfer vessel	2
Technician capacity	12
Cruising speed	20 kn
Significant wave height access limit	2.25 m

4.2.3. Crane

For the assembly of the wind turbine, a crane is required. Other than for the bottom fixed, the crane can be located ashore for wind turbines on floating substructures. Currently, Wergeland Base is using a Mammoet PTC 200-DS crane to assemble the wind turbines for the Hywind Tampen project. This crane is a so-called ring crane, which can only rotate around itself but not drive along the quayside. The data sheet for this crane can be found in appendix C.2.
Figure 4.4 shows the crane during the assembly of one of the turbines for the Hywind Tampen project in April 2022. The crane configured on behalf of Equinor can lift 1397 t at a radius of 54 m up to a height of 205 m [128]. For a 15 MW turbine assembly, a minimum lifting height of 150 m is required, and for a 20 MW turbine, at least 160 m (compare hub height table 4.1).

Figure 4.4.: Mammoet PTC 200-DS at the heavy lift quay at Wergeland Base, April 2022 [128]

As per table 4.1, a 15 MW turbine could be assembled with this crane. For the 15 MW turbine, the nacelle has an enormous mass of almost 1,017 t. However, the crane cannot assemble the 20 MW turbine based on the information in table 4.1. Hence the mass of the tower is too large. Nevertheless, the tower is not delivered in one piece. Assuming that the tower is delivered in three pieces each piece would have a mass of approximately 690 t, which the crane would be capable to lift.

Wergeland Base has the option of getting a so-called portal Skyhook crane. This crane would be able to travel along the quayside, which results in a larger working radius and more efficient use of the assembly area. The crane can lift 2,600 t up to 135 m high on the main hoist and up to 800 t 190 m on the auxiliary hoist (see also data-sheet in appendix C.1) [117, 128]. Figure 4.5 shows a drawing of how this could look like at Wergeland Base.

For the simulation, it is assumed that the Mammoet PTC 200-DS crane is available at Wergeland Base. The Skyhook crane can lift a larger mass than the Mammoet PTC 200-DS but less heigh. However, the Skyhook crane does not have sufficient capability to assemble a 15 or 20 MW turbine.

Figure 4.5.: Skyhook crane at the heavy lift quay at Wergeland Base [128]

Table 4.5.: Onshore crane at Wergeland Base

Onshore crane	1
Limiting criteria:	
Wave height (m)	0.5
Wind speed ($\frac{m}{s}$)	12
Ref. height (m)	136

4.3. Personal

In the initial case, technicians are available Monday to Sunday from 7 am to 7 pm. Working on weekends causes extra expenses for compensation. Therefore it might be interesting to investigate the effect of shifts on the installation and completion time.

4.4. Project area and port

Different ongoing and planned projects around Europe have been presented in section 2.2. Further in appendix B planned projects with deep water and close multiple installation ports are summarized. The areas with water depth larger than 100 m are considered unique and interesting because, in these areas, a SPAR as substructure is suitable. Another parameter that can be analyzed is the competitiveness of Wergeland Base to other installation ports with view to further future projects. Other than many competitive ports, Wergeland Base has deep water at the quay allowing the installation of wind turbines on a SPAR structure. Further, Wergeland Base is sheltered by the surrounded mountains, which effects the wind speed at the base and reduces the crane downtime during weather-sensitive operations.

5. Simulation

Shoreline is a web-based program to simulate the installation and operation of offshore wind farms. The software has been used to simulate the commissioning of an offshore wind park within this project. Within Shoreline, different concepts can be simulated and compared to simplify decision-making [133]. The following will describe and analyse the basic case and all alternative cases.

5.1. Met-Ocean Data

Shoreline uses historical weather data for weather-restricted operations. Equinor provided this study with weather data from the mast installed at Wergeland Base (Location: 60°50.730'N 5°4.275'E). The data used for the simulation were taken 10 m above ground every 10 minutes for almost two years.

Some modifications need to be made to use this data in Shoreline. The first modification was to calculate an hourly average wind speed. That is since the smallest time step shoreline allows one hour. Another adjustment to be made is the reference height. The wind turbines used in the simulations have reference heights between 136 and 160 m, while the data are taken at 10 m above sea level. The wind power law as per equation 5.1 has been used to estimate the wind velocity at the height of 136 m, 150 m and 160 m. [105]

$$u_{(z)} = u_{ref} \cdot \left(\frac{z}{z_{ref}}\right)^{\alpha} \tag{5.1}$$

Thereby is z_{ref} the reference height, u_{ref} the reference wind velocity and z the height to calculate wind speed. α is the empirical wind shear exponent, which is assumed to be 0.11. u_{ref} is measured wind speed at 10 m height; hence z_{ref} is 10. The wind velocity at a certain height can be estimated. The problem with this method is that the measured wind speed is close to the surface. Due to geographical surroundings, the actual wind speed in higher layers can be different and provoke high uncertainties. Further, $u_{(z)}$ is sensitive to α, which also depends on the atmospheric conditions and surface roughness. This study used a α value of 0.11, representing the power-law exponent's mean value. At least two measurement series in different heights are required for more accurate estimations of α at the site. Because of financial and logistical reasons, such measurements are usually not realised, and estimations must be done with standardised approximated values. [105, 88]

Shoreline has already ERA 5 weather data for the location of Utsira Nord available. It is a 19-year collection of wind speed, wave height, and swell data with a resolution of one hour. ERA 5 is a reanalysis of global weather and climate data. They have an hourly resolution, and the recording of currently used data started in 1979. As they are global measurements, the data has typically a latitude-longitude resolution of 0.25° x 0.25° for the atmosphere and 0.5° x 0.5° for ocean waves. [77] Consequently, it is not possible with ERA 5 data to obtain data for the exact location. The weather data from Utsira Nord is used to simulate the installation of the mooring system and wind turbine at the site.

5.2. Case study

5.2.1. Basic Case / Case 1

The basic case is the reference case with an available input date to which all subsequent cases are compared.
Chief Commercial Officer Tom Erik Sandnes at Wergeland Group shared the information for the installation base used in the base scenario [128]. Table 5.1 summarizes the input data for the base. Further data for the base case are summarised in appendix A.

Table 5.1.: Base input data of Wergeland Base for Base Case

Base			
	Parameters		
	Wergeland Base		
	Location	N 60.847017	E 5.077233
	Number of repair slots	10	Units
	Loadout berth capacity	3	Units
	Capacity		
	Mooring line	200	Units
	Mooring anchor	200	Units
	WTG	10	Units
	Floating WTG	10	Units

At Wergeland Base, it is planned to build and assemble offshore floating wind turbines. The base, located close to Gulen in the north of Bergen (Norway), has over 1250 m quay length and water depths at the quay between 14 to 22 m. Within reach of the crane, the site has spots with water depths larger than 100 m.
In consultation with Wergeland Base, Utsira Nord has been selected as a case site for this study. The location of the sites are illustrated in figure 5.1. The distance between Wergeland Base and Utsira Nord is approximately 203 km.

The Norwegian government plan to install between 500 and 1,000 MW in the area of Utsira Nord [138]. For the basic case, the construction of 50 turbines with each 12 MW is simulated (= 600 MW).

5.2.2. Case 2

At first, it is analysed how the storage capacity influences the completion time and costs of the project. Nine cases have been created in which the storage capacity is scaled up in steps of five, from 10 to 25 wind turbines. Further, the number of sets of tugs has been scaled up together with the storage capacity to find the best and most cost-effective combination.

Figure 5.1.: Map Wergeland Base - Utsira [69]

5.2.3. Case 3

For the third case, the number of cranes available is increased. A 12 MW turbine is used in this case. First, the number of vessels is kept the same as in the basic case. Then, a modification is made, assuming that a second tug is available.

5.2.4. Case 4

This case analyses the effect of tug and anchor handling vessel (AHV) on the installation time and costs. In the base case, the tug is travelling 3 kn during towing. This speed is increased to 4

Table 5.2.: Case 2 scaling-up storage capacity at Wergeland base

Case 2 Scaling up storage capacity

Case 2.1	15 WGT storage capacity
Case 2.2	20 WGT storage capacity
Case 2.3	25 WGT storage capacity
Case 2.4	15 WGT storage capacity, 2 Tug
Case 2.5	20 WGT storage capacity, 2 Tug
Case 2.6	25 WGT storage capacity, 2 Tug
Case 2.7	15 WGT storage capacity, 3 Tug
Case 2.8	20 WGT storage capacity, 3 Tug
Case 2.9	25 WGT storage capacity, 3 Tug

Table 5.3.: Case 3 scaling up number of crane (together with tug)

Case 3 Scaling up number of crane

Case 3.1	2 Crane
Case 3.2	2 Crane, 2 Tug

kn. Based on the data provided by Tom Erik Sandnes, Wergeland assumes a towing speed of 3.5 kn, but, Shoreline does not accept decimals in vessel speed. Therefore the choice of analysing 3 and 4 kn has been made. Further, it is assumed that the speed increase of 1 kn increases the fuel consumption during towing by 16 %.
Besides the towing speed of the tug, the number of AHV and their effect are dissected. Table 5.4 gives an overview of the different combinations that have been investigated.

Table 5.4.: Case 4 influence of tug

Case 4 Tug / AHV

Case 4.1	2 Tug at 3kn
Case 4.2	1 Tug at 4kn
Case 4.3	2 Tug at 4kn
Case 4.4	1 Tug (at 3kn), 2 AHV
Case 4.5	2 Tug (at 3kn), 2 AHV
Case 4.6	1 Tug (at 4kn), 2 AHV
Case 4.7	2 Tug (at 4kn), 2 AHV

5.2.5. Case 5

Within this case, the effect of availability of workers related to the installation and completion time and costs are analysed. In the first case, technicians are available every day of the week in 12 h shifts; as per the table 5.5, eight different shift patterns have been investigated.

5.2.6. Case 6

The logistics behind the installation have been studied of 12 MW turbine, including different time or cost-optimised cases. In the next step, one cost-optimised logistic case is applied to scale up the wind turbine from 12 to 15 and 20 MW. The input data for the two turbines are

Table 5.5.: Case 5 different personnel approaches

Case 5 Personnel amount and/or shifts

Case 5.1	Personnel working only on weekdays
Case 5.2	Personnel working 8h rotation 2 shifts
Case 5.3	Personnel working 8h rotation 2 shifts only weekdays
Case 5.4	Larger shift 36 people
Case 5.5	Larger shift 36 people + extra ctv
Case 5.6	Smaller shift 12 people, only 1 CTV
Case 5.7	Accomodation vessel
Case 5.8	Accomodation vessel full (40 people)

described in section 4.1. The weather criteria for the lifting are unchanged as for the 12 MW turbine; the reference height is increased to 150 and 160 m.

As mentioned in section 4.2.3, the Mammoet PTC 200-DS crane is available at Wergeland base. Because of larger and heavier structures compared to a smaller turbine, the capability of the crane need to be checked. Further, as described in this section, the crane cannot lift the tower as one component. For this reason, it is assumed that the tower is lifted in three pieces and assembled directly on the substructure.

Table 5.6.: Case 6 variation

Case 6 Up-scaling Wind turbine

Case 6.1	40 x 15 MW Wind Turbine reference height 150 m
Case 6.2	30 x 20 MW Wind Turbine reference height 160 m

5.2.7. Case 7

Last, case 7 looks at the competitiveness of Wergeland Base to the port of Cromarty Firth in Scotland for the installation of Utsira Nord in Norway and ScotWind 11 in Scotland.

Cromarty Firth is a large and well-established sport in the Highland. Further, it is more sheltered and has deeper water than other ports in the surroundings. Cromarty Firth is leading for different operations within the oil and gas industry. The geographical location, together with

Table 5.7.: Base input data for port of Cromarty Firth [45]

Base			
	Parameters		
	Cromarty Firth		
	Location	N 57.685735	W 4.180470
	Number of repair slots	10	Units
	Loadout berth capacity	3	Units
	Capacity		
	Mooring line	4	Units
	Mooring anchor	4	Units
	WTG	10	Units
	Floating WTG	10	Units

the already existing facilities at Cromarty Firth, the port is in a good position for different Scottish offshore wind projects, as 15 out of the 17 identified development sites are nearby. [45, 112] Figure 5.7 illustrate how the port site could be used to assemble wind turbines.

The port has up to 14 m water depth at the quayside and up to 30 m at sheltered anchorage [45]. There is not enough water depth for SPAR substructure other than barge or semi-sub. However, for the simulations and to compare the ports, it is assumed that the port could handle a SPAR substructure. The assumptions of the port are stated in table 5.7. For weather-sensitive operation ERA 5 (57.5, -4.0) weather data was used. The installation of two sites is analysed for both bases. The first site is Utsira Nord, and the second is from ScotWind site number 11.

Figure 5.2.: Cromarty Firth [112]

6. Results and Discussion

The results of the cases as described in chapter 5 are now analysed and discussed. Further, an optimised case for cost and installation time will be found.

6.1. Results case 2

Case 2 dealt with the up-scaling of storage capacity and tug.
Figure 6.1 show the completion time relative to the base case. It can be noted that scaling up the capacities without the set of tugs does not significantly influence the completion time (between 3 and 4%). This means that the completion time is sensitive to the number of sets of tug. The completion time reduces by 42 % when using the second set of tugs. Further, there is only a marginal improvement in using three instead of two tugs (less than 1 % difference).
Figure 6.2 shows the influence on the cost per installed MW if the storage capacities and the number of tugs are scaled up. It can be noted that having larger storage capacities saves up to 5 % in costs. This can be explained by the significant (up to 58 %) fewer days having the crane in operation (see figure 6.3). The third set of tugs reduces the crane's operational time most, but the costs increase between 2 and 6 %, while the completion time reduces only by less than 1 % compared to having two sets of tugs. The lowest cost provides case 2.9, having a storage capacity of 25 units and one set of tugs. This can be explained by the relatively low waiting time on the crane due to weather during assembly (see table 6.1); at the same time, the crane does not have to wait for the tugs towing out the wind turbines because of having more storage capacity at the base.

Table 6.1.: Case 2.9 installation vessel \ total waiting on weather time, [h & %] (average from all runs)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tug					285.0	289.9	435.1	252.8	131.9	74.2		
					51.31%	40.38%	58.60%	34.13%	18.39%	15.97	0.00%	
Crane			11.9	56.2	5.8	0.9	5.9	0.9				
			50.59%	7.85%	1.47%	0.34%	2.84%	0.56%	0.00%			
AHV			259.2	503.8	380.0	123.5						
			57.11%	70.13%	51.27%	42.53%						

Concluding from this case, having one set of tugs operating saves more cost than having two to record for the optimum case. A third set is not reasonable unless maybe a second crane would be available. For having more than 15 unit storage capacity, a second tug does not save as much money as just having one, but time reduction is significant.

6.2. Results case 3

Case 3 looked at the effect of using a second crane for assembling turbines.
Figure 6.4 shows the effect of a second crane on the completion time for different unit storage

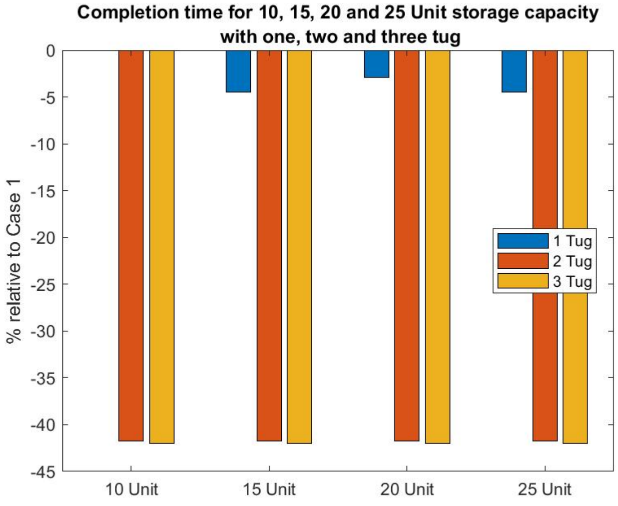


Figure 6.1.: Completion time of case 2

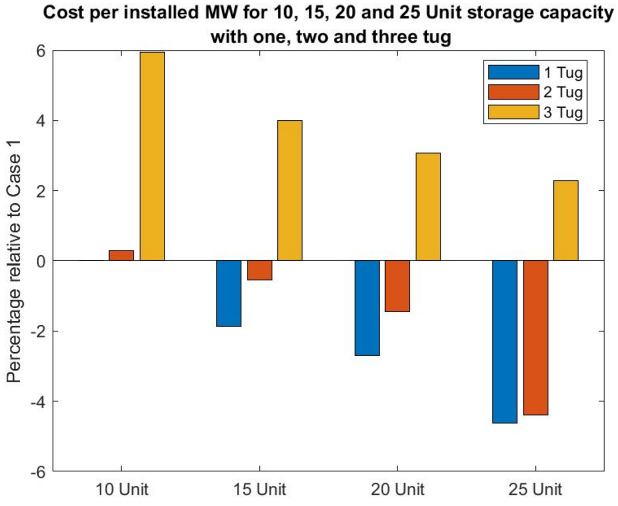


Figure 6.2.: Cost per MW in case 2

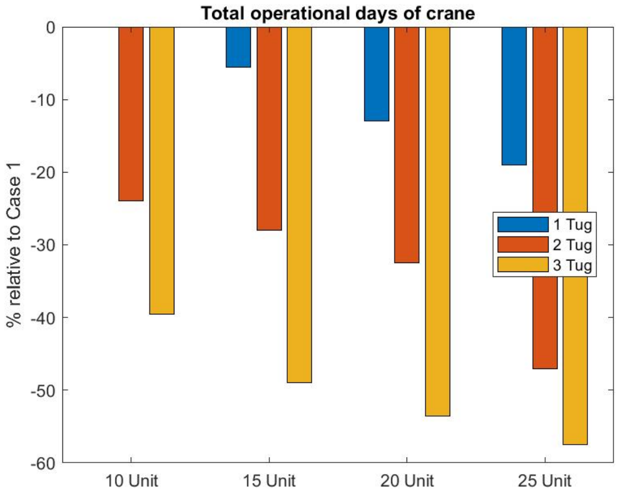


Figure 6.3.: Days crane is operational case 2

capacity and set of tugs available. An improvement of 4% in time can be noted if a second crane is used; if the second set of tugs is used, the time reduction will be up to 42 %. However, there is no significant improvement in time when the third set of tugs is used (less than 1 %). Stowing more units gives the same reduction in time as for ten unit capacity.
Nevertheless, as indicated in figure 6.5 the cost per MW increases between 11 and 20 % if a second crane is used; however, the costs are smaller for larger storage capacity.
It is concluded that overall cases having a second crane is significantly more expensive than having one. More storage capacity improves the cost per MW because the duration of having the crane in operation is reduced, as indicated in figure 6.6. However, the reduction is insufficient to continue with a second crane. Therefore a second crane is not further considered for the optimum case.

6.3. Results case 4

In the previous cases, different numbers of sets of tugs have been analysed together with different variation of the infrastructure. Case 4 evaluates the impact of vessels on the completion time and costs.

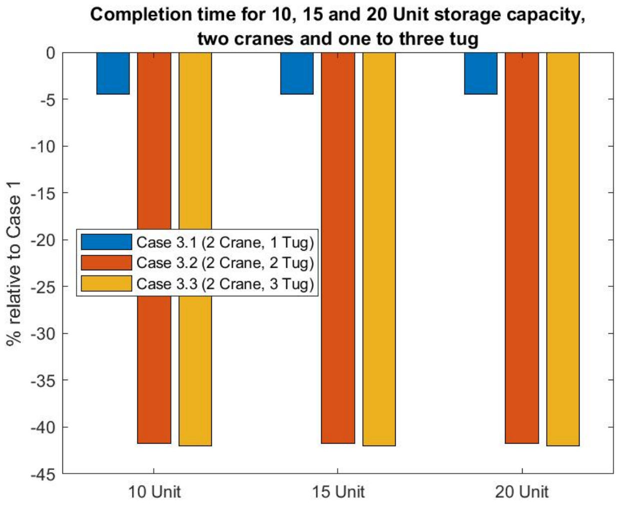


Figure 6.4.: Completion time of case 3

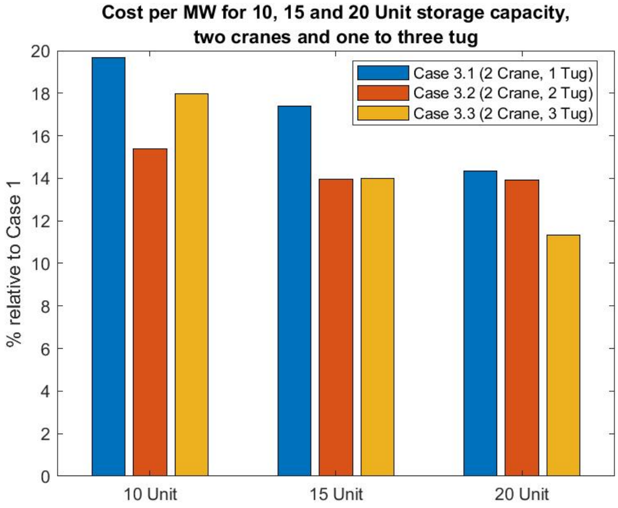


Figure 6.5.: Cost per MW in case 3

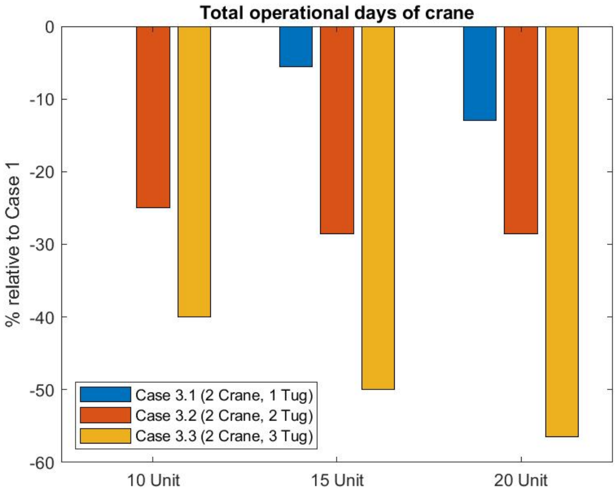


Figure 6.6.: Days crane is operational case 3

Figure 6.7 shows the completion time for the different tug and AHV constellations for ten unit storage capacity. A bigger storage capacity does not effect the installation time. For the reason of understanding, figure 6.7 shows only the completion time for ten units. The analysis of the different numbers of sets of tugs and towing speed show that the completion time can be reduced by nearly 40 % compared to case 1, assuming an increased towing speed. Having a second set of tugs does not improve the completion time. Further, a second AHV was assumed to operate. This gave another 5 % improvement in time compared to the base case (total of approximately 45 %).

The cost per MW for the different cases of case 4 is given in figure 6.8. It shows that having a second AHV increases the cost, while the costs are reduced if the towing speed of the tug is increased. This can be explained by the fact that a higher towing speed leads to a faster completion time and fewer days of the crane being available (see figure 6.9). This compensates for the higher cost due to increased fuel consumption. Further, one tug set as per case 4.1 is approx. 11 % faster and reduces the total costs for the tug by 6.75 % compared to case 1. Having a second set of tugs reduces the working days of tugs and cranes. However, it does not have the same effect as the costs because the day rate and mobilisation for the tugs are doubled. This effect can be reduced if the storage capacity at the site is increased, as the crane can pre-assemble more wind turbines before the tugs tow them out.

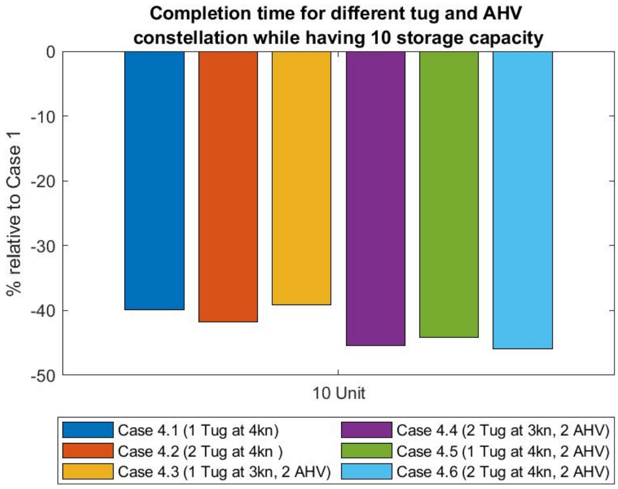


Figure 6.7.: Completion time of case 4

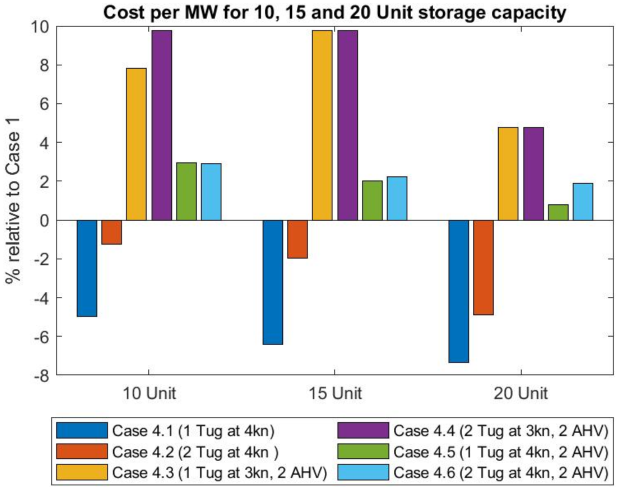


Figure 6.8.: Cost per MW in case 4

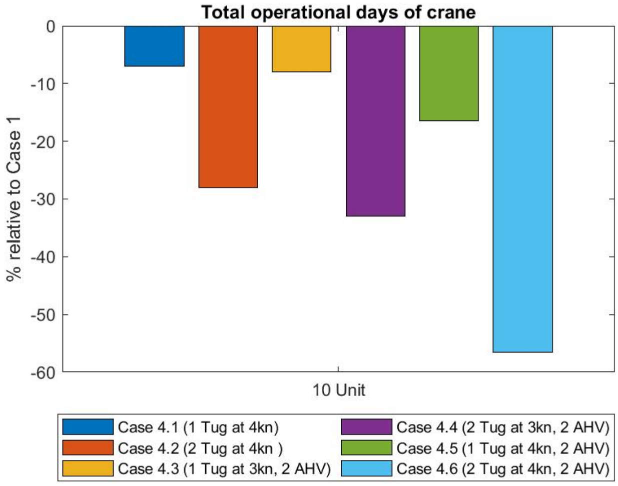


Figure 6.9.: Days crane is operational case 4

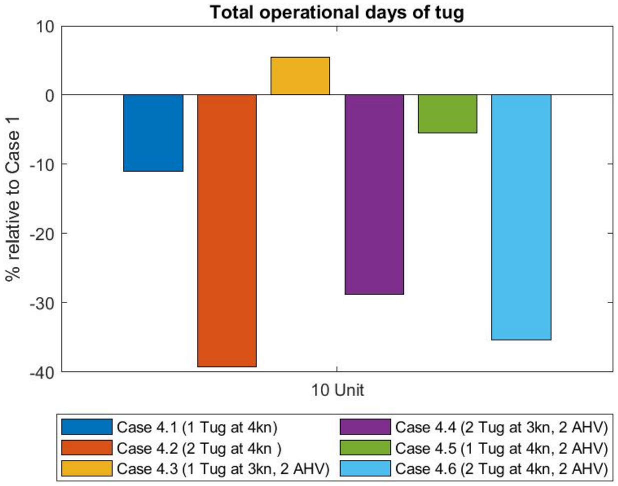


Figure 6.10.: Days tugs are operational case 4

Case 4.1 will be considered for the optimised case as time and costs are reduced. Case 4.2 would have been an option, but the reduction in completion time is insignificant compared to case 4.1 and cost reduction is less than for case 4.1.

6.4. Results case 5

Case 5 compares different approaches to the organisation of technicians. In the base case, it is assumed that 24 technicians are working in 12 h shifts seven days a week. Section 5.2.5 described different approaches which are investigated. Table 5.5 list the different shift models and is copied in below again.
Figure 6.11 contrasts costs and completion time for the different approaches. Having technicians working only on weekdays improves the costs slightly (by 1 %) with little degradation (2 %) of the time performance. Working in shifts prolongs the completion time significantly (more than 100 %) and, therefore, costs up to 43 %. More workers available decreases the completion time by 5 % with a small increase in cost (3 %). Having fewer on-site technicians available for commissioning results in a 19 % longer completion time with no significant impact on the cost per MW (1 %). An accommodation vessel close to the site decreases the completion time significantly by 44 %. At the same time, the costs are increased by almost the same percentage.

Case 5 Personnel amount and/or shifts

Case 5.1	Personnel working only on weekdays
Case 5.2	Personnel working 8h rotation 2 shifts
Case 5.3	Personnel working 8h rotation 2 shifts only weekdays
Case 5.4	Larger shift 36 people
Case 5.5	Larger shift 36 people + extra ctv
Case 5.6	Smaller shift 12 people, only 1 CTV
Case 5.7	Accommodation vessel
Case 5.8	Accommodation vessel full (40 people)

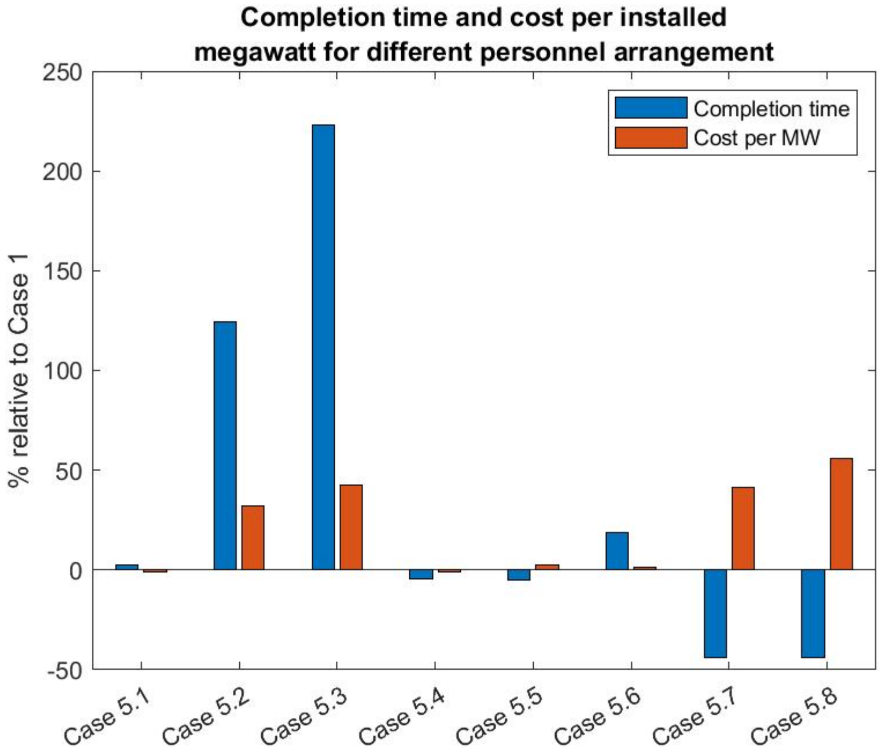


Figure 6.11.: Completion time and cost per MW in case 5

Further investigations showed that if the infrastructure (crane and tugs) is scaled up, case 5.6 reduces the costs with a minimal longer completion time. For this reason, case 5.6 will be considered for the optimum case.

6.5. Cost optimized case

The best results in terms of cost and time from the analysed cases were taken to see how they behave when combining them. Further, these cases were scaled up for storage capacity. In the table 6.2 the different cases are summarized.

All this cases were chosen due to their cost savings in the previous analysis. Figure 6.12 shows the completion time of the different cost-optimised cases for different storage capacities. As expected, the reduction in completion time is more significant with two sets of tugs (39 %),

Table 6.2.: Cost optimized cases input data

Cost 1	2 Tug at 3 kn, 24 technicians
Cost 2	1 Tug at 4 kn, 24 technicians
Cost 3	2 Tug at 3 kn, 12 technicians (1 CTV)
Cost 4	1 Tug at 4 kn, 12 technicians (1 CTV)

respectively, to one set of tugs at a faster-towing speed (37 %), both with a larger shift of technicians available. Having fewer technicians increases the completion time by around 24 %.
As expected from case 2, having two sets of tugs with 24 technicians is almost as costly as the base case (less than 1 % more) when having ten units of storage capacity. However, as expected, when scaling up the storage capacity, the costs are reduced for this case, but not significantly (1 % for 20 unit capacity). Nevertheless, all other three cases provide more cost savings, up to 21 %. Especially one set of tugs towing at 4 kn provides consistent cost savings between 5 and 7 % along with all storage capacities. Remarkable cheap is case cost 3 for 20 unit storage capacity (21 %). This can be explained by a huge reduction of days the crane is used (see figure 6.17). To better understand how this happened, it must be mentioned that Shoreline uses only a single simulation for the economic report. For the completion time, Shoreline calculates probability-weighted timelines from a set of individual timelines from each of the single simulation runs

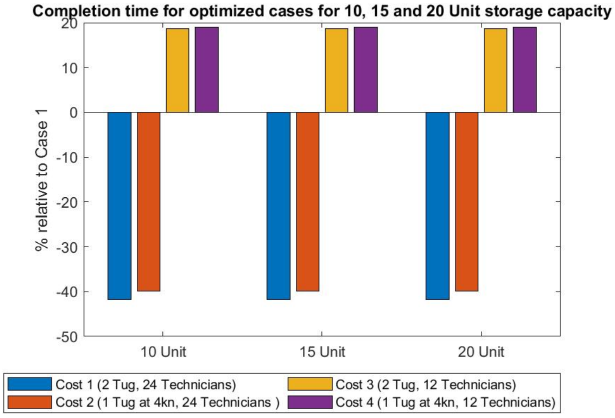


Figure 6.12.: Completion time optimized case

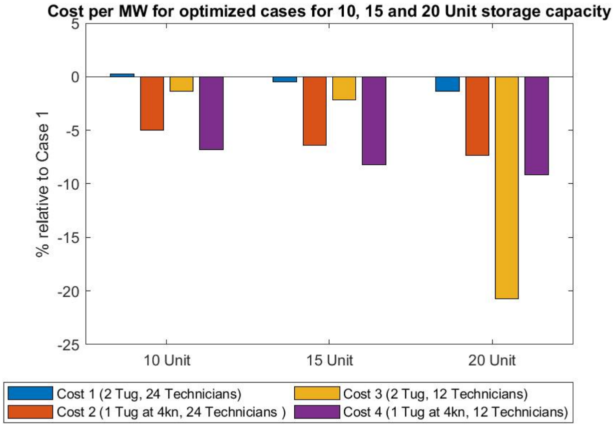


Figure 6.13.: Cost per MW for the optimized case

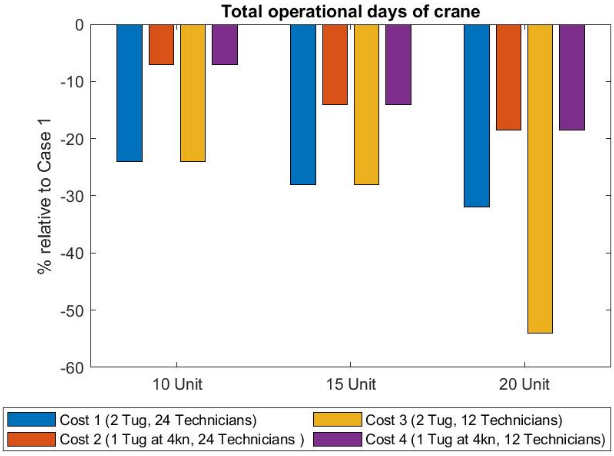


Figure 6.14.: Usage crane optimized cases

[113]. For this study, the average value of P 50 has been used. Nevertheless, for this case, it does not seem adequate to take this value, as Shoreline shows only a single simulation closest to the average along with all simulations for the economic output. Considering the outputs from P 30 to P 60, it shows that the crane usage days are the same as for Cost 1. Further, the average costs per MW of the simulations of P 30, P40 and P 60, the costs are reduced by nearly 7% to the base case; for Cost 1, it is approx. 5%. Hence, the economic output of the P 30 to P 60 is expected to represent the expectations better than P 50.

Having one fast set of tugs operating is constantly saving costs; it is logical to continue with either Cost 2 or 4. Cost 2 does not save as much as cost 4, but therefore Cost 2 is much faster. As fewer turbines need to be installed when scaling up the size, the impact on completion time might be less when using fewer technicians.

6.6. Results case 6

The earlier cases are based on a 12 MW turbine. The installation capacity at the site was assumed to be 600 MW. That resulted in 50 units of 12 MW turbines. In case 6 the size of the turbine is scaled up to 15 and 20 MW, so the number of turbines can be reduced to 40 and 30

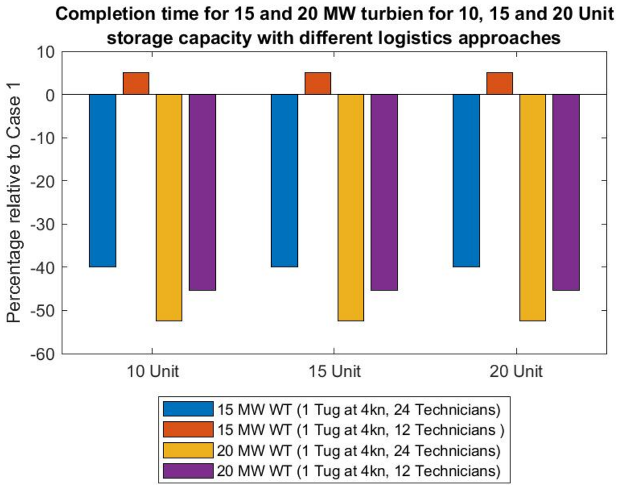


Figure 6.15.: Completion time of case 6

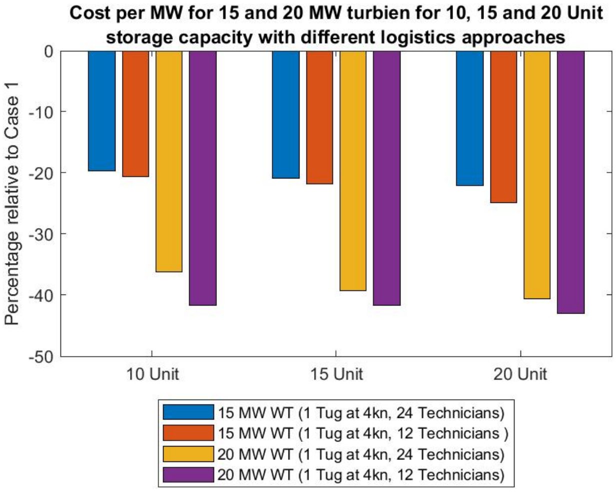


Figure 6.16.: Cost per MW in case 6

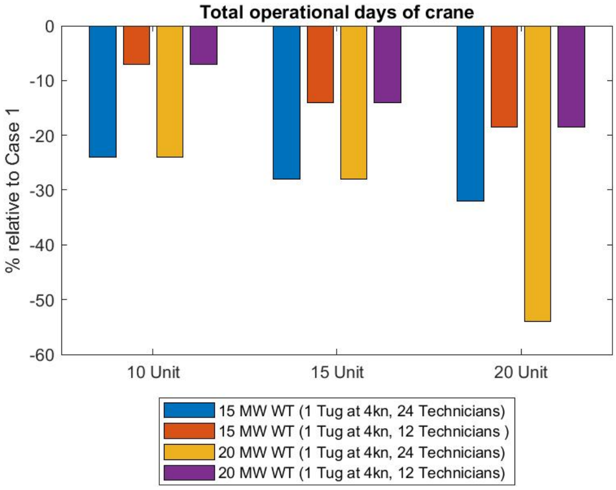


Figure 6.17.: Usage crane case 6

units. The logistical assumption from cost-optimised cases 2 and 4 are used.

The completion time needed for different storage capacities and the two logistical approaches are illustrated in figure 6.15. Scaling up the wind turbine can reduce the installation time by up to 50%. However, a 15 MW turbine with fewer technicians still needs 9% more time to the base case. A good return gives the 20 MW turbine for the smaller shift; the time reduces by 43 %. The number of assets is reduced significantly, and therefore the advantage of having more personnel is reduced. Still, the larger shift is faster (50 % less time to the base case for 20 MW) but less significant for smaller turbines (37 % for 15 MW turbine relative to the base case). Also, scaling up the storage capacity for larger turbines does not influence the completion time.

Figure 6.16 shows how the cost per MW varies with larger turbines, storage unit capacities, and available technicians. As expected, the costs are reduced when scaling up the turbine by up to 43 %. Further, it can be noted that for a 15 MW turbine, the difference between having a smaller or larger shift is 1 % at a ten-unit storage capacity. In comparison, for the 20 MW turbine, the difference is 5 % at the same storage capacity. For more unit storage capacities, the difference in cost between the different shifts harmonises to a reduction of 3 %.

It can be concluded that more technicians are required for turbines until a size of 15 MW, considering completion time and costs. The smaller shift might be an option for larger turbines because the impact of completion time is less important due to fewer units.

6.7. Results case 7

In this case, the installation of two different sites from two different ports is investigated. First, the results for the site of Utsira Nord are analysed, and then for site 11 from ScotWind.

6.7.1. Utsira Nord

This case delves into turbine installation within the Utsira Nord project from Wergeland Base and the Scottish port of Cromarty Firth. The results in figures 6.18 and 6.19 are compared to the reference case, which assumes an installation of 50 12 MW turbines (600 MW capacity) assembled at Wergeland base, using one crane, one AHV, one set of tug and two CTVs with 24 technicians. All costs for both ports are assumed to be the same.

Figure 6.18 shows the required installation time relative to the installation of the 12 MW turbine from Wergeland. It indicates that Cromarty Firth is not competitive with Wergeland if they install the mooring system at the site. The completion time increases by 69 %, and the costs by 20 % compared to the installation from Wergeland with the same infrastructure. However, they become competitive if a port in Norway carries out the installation of the mooring system. The time still increases by more than 60 %, but the costs are reduced by 6 %. If the size of the turbine is scaled up, the costs are reduced by nearly 30 % and the time by 1 %.

As mentioned above, figure 6.19 indicates that scaling up the turbine size reduces the cost per MW. Especially the bars for Wergeland show this expectation clearly. Using a 15 MW does not reduce the time, but costs are reduced by 15 %. For the 20 MW turbine, time is reduced by 21 % and costs even by 33 %.

Table 6.3 to 6.5 show the waiting time on the weather for tugs, AHV and crane for the installation of Utsira Nord from the different port constellations. It can be noted that the downtime for the installation from the Scottish port is less than from the Wergeland. However, it needs to be mentioned that ERA 5 weather data had been used for Cromarty Firth. This data includes high uncertainties as it is a hindcast. For Wergeland, real weather data was available and used.

Further, these tables show that most time and cost driving component is the tug for the installation from Cromarty Firth. Because the tug travels a longer distance, it needs more time to tow out the assembled wind turbines. Consequently, the storage area is not cleared fast enough, which causes idle time for the crane and increases the day rate cost.

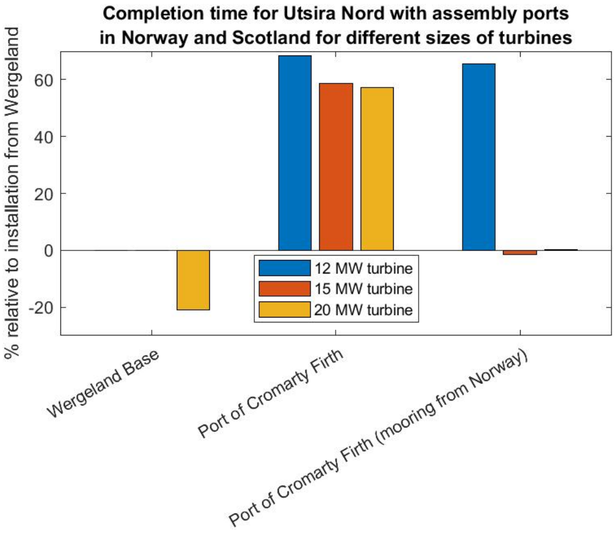


Figure 6.18.: Completion time for Utsira Nord from Wergeland Base vs Port of Cromarty Firth

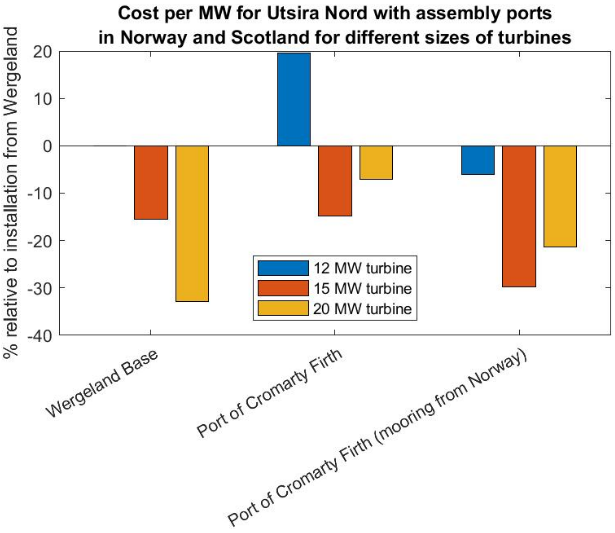


Figure 6.19.: Cost per MW for Utsira Nord from Wergeland Base vs Port of Cromarty Firth

Table 6.3.: Total waiting on weather time, [h & %] (average from all runs) for each vessel for the site of Utsira from Wergeland for 12 MW turbine

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Crane			11.9	56.2	1.7	1.0	8.3	3.4	4.0			
			50.59%	14.12%	0.67%	0.34%	3.67%	1.04%	0.78%	0.00%		
AHV			259.2	503.8	380.0	123.5						
			57.11%	70.11%	51.27%	42.31%						
Tug					303.0	277.3	455.0	268.2	115.7	24.5		
					55.23%	38.64%	61.27%	36.19%	20.25%	5.20%		

6.7.2. ScotWind 11

Next, a site within the ScotWind project has been selected and similar to the case from section 6.7.1 simulated. Site number 11 from the ScotWind project is selected. In section 2.2.3.1 a map of the whole ScotWind project can be found. It is assumed that both ports have the same infrastructure. This includes the same crane and deep water close to site. Cromarty Firth does not have deep water close to shore, but to compare the results they are supposed to have. The following logistics are assumed for both ports:

- 1 Crane
- 2 Tug at 4 kn
- 24 Technicians located at Cromarty Firth with 2 CTV

Table 6.4.: Total waiting on weather time, [h & %] (average from all runs) for each vessel for the site of Utsira from Cromarty Firth for 12 MW turbine

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Crane			2.1	18.6	4.9	3.8	4.5	2.6	15.1	21.6	3.2	0.1
			8.75%	5.05%	2.12%	1.60%	1.80%	1.03%	6.85%	11.41%	5.09%	5.19%
AHV			157.7	167.6	101.4	13.2						
			34.70%	23.37%	14.02%	10.12%						
Tug	275.0	112.3	19.1	7.6	57.3	43.9	27.9	41.4	138.9	209.1	305.1	315.3
	54.55%	50.90%	32.50%	16.42%	8.20%	6.11%	3.76%	5.58%	19.34%	28.14%	42.43%	44.18%

Table 6.5.: Total waiting on weather time, [h & %] (average from all runs) for each vessel for the site of Utsira from Cromarty Firth with mooring from Norway for 12 MW turbine

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Crane			2.1	25.8	5.1	5.0	4.4	3.6	13.8	8.3		
			8.75%	5.05%	2.08%	2.04%	1.76%	1.46%	6.41%	9.44%	0.00%	
AHV			190.4	184.7	7.0							
			42.01%	27.97%	24.47%							
Tug	91.7	35.8		57.8	46.9	40.9	23.6	44.7	137.8	215.9	298.1	265.4
	61.15%	61.00%	0.00%	12.28%	6.32%	5.70%	3.18%	6.02%	19.17%	29.06%	41.86%	50.38%

- 1 AHV operating from Chromarty Firth

Further, it is assumed that all costs are the same for both ports.

Figure 6.20 shows the completion time for the site of ScotWind 11 from the different ports for different turbine sizes. Being closer to the site saves between 52 and 60 % in completion time. As already known from earlier cases, scaling up the turbine size saves time; the best return on completion time has, therefore, the 20 MW turbine. Thus being closer to the project site is an advantage in terms of completion time. Nevertheless, as mentioned earlier, for the installation of Utsira Nord, there are great uncertainties for Cromarty Firth due to a leak of real weather data.

Figure 6.21 shows the cost reduction when scaling up the turbine and having the assembly base closer to the site. Again here, the uncertainties have to be mentioned. As for the completion time, the weather data bring high uncertainties into the simulation because a forecast is used. However, the same costs for both ports are also assumed, which may vary in reality. Using the Scottish port for the assembly reduces the costs by 25 % for the 12 MW turbine and up to 54 % when scaling up the WT. Nevertheless, scaling up the WT gives also a cost reduction of up to 25 % for the installation from Wergeland.

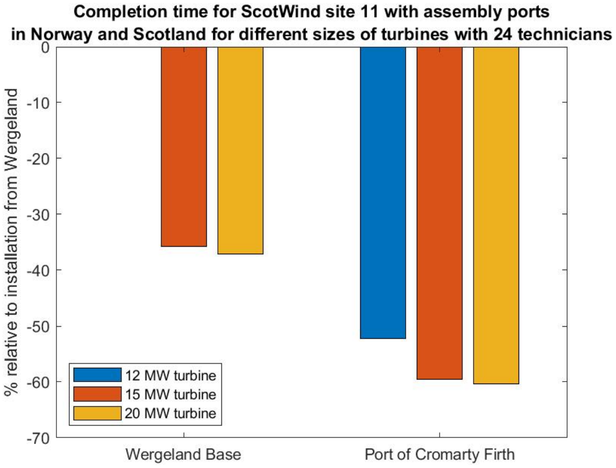


Figure 6.20.: Completion time for ScotWind 11 from Wergeland Base and Port of Cromarty Firth

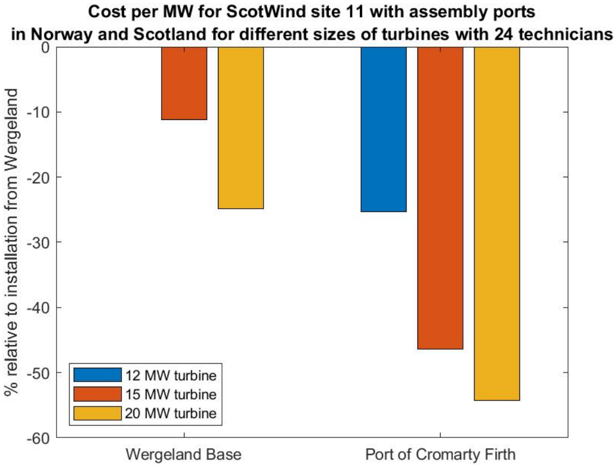


Figure 6.21.: Cost per MW for ScotWind 11 from Wergeland Base and Port of Cromarty Firth

7. Conclusion

The offshore wind grid will need to be expanded to meet the goal of the EU to become net-zero by 2050 [33]. There are many ongoing or planned projects on the European continental shelf. However, many of the projects are located in areas with deep waters. New substructure and logistic solutions must be found for the different locations. This study looked at the Norwegian market with some outlook on the Scottish offshore wind project ScotWind. As a reference site, Utsira Nord in the Norwegian north sea was taken, and the turbines were assembled and installed from the Wergeland base.
From the analysis, the following statements can be concluded.

- If we only increase the on-site storage space of the wind turbine components, this does not significantly affect the completion time; however, it improves the costs per MW because of a better crane utilisation and less waiting time on other vessels by up 5% (case 2.9).

- If two or three sets of tugs are available, the completion time improves by 42% compared to one set of tugs. On the other hand, costs are increased between 2 and 6 % for three sets of tugs. However, for two sets of tugs, the costs reduce between 2 and 5 % for storage capacities larger than 15 units.

- Having an additional assembly crane on-site does not significantly improve completion time (4 %) unless storage capacity and the set of tugs are scaled up appropriately; however, if more sets of tugs are available, the completion time is improved by approximately 42 %, however, the costs are increased between 11 and 19 % for all cases.

- A higher towing speed improves cost between 1 and 7 %, and completion time by approximately 40%. Doubling the number of AHVs improves the completion time between 39 and 46%. Whereas costs are increased between 1 and 10%
    - → The analysis showed that separating the wind turbine assembly port and the port for installing the mooring system could improve costs and completion time if the assembly port is not close to the wind project site. This was true for the simulations that looked at Norway as an assembly for wind projects in Scotland. It may therefore be beneficial to select a port closer to the wind project site that can handle the anchors and mooring line to reduce costs and completion time. Many more ports can handle such operation, and it may be smart to combine this with a specialised assembly site.

- The number of technicians available for commissioning influences significantly the completion time and costs. However,
    - → increasing the number of technicians to 36 reduces completion time by 5%, but this increased the cost by 3 %.

  - → decreasing the number of technicians to 12 increases completion time by 18%, but did not significantly increase the costs when we assume ten units of storage capacity. However, the analysis showed that costs could be reduced between 14 and 28 % when increasing the storage capacity to 15 or 20 units, respectively.
  - → If we include to have an accommodation vessel operating on-site, the technicians are closer to the commissioning site, and the completion time is reduced by 44%. However, costs increased by 41 to 56 %, but this increase in costs could be mitigated by using a local port for the location of the technicians instead of an accommodation vessel.

- An optimised case was selected based on cost-saving combined with reasonable completion times. Our results showed that having 24 technicians with one fast set of tugs or two slow ones reduces costs between 3 and 10 % and completion time around 38 %. However, reducing the number of technicians to 12 saves between 5 and 13 % but has the disadvantage of being 24 % slower in completion time.
  - → Scaling up the size of the wind turbine gave the best return of the optimised cases, which showed that scaling up reduces the costs between 20 and 43 % and reduced the completion time by between 41 and 54 % (considering 24 technicians); however, 12 technicians increases the time only by 2 % for a 15 MW turbine and reduces it by 47 % in the case of a 20 MW turbine.
  - → The best cost-benefit was obtained by the scaling up of the wind turbine size, and this is in line with the future trends of the floating offshore wind industry, which needs to cut costs significantly to be commercially viable.

- When comparing two or more ports with the same infrastructure, the port closest to the installation site has the advantage in terms of installation costs and completion time.

- The simulations in this study have shown that having the components ready on-site is critical for the utilisation of the crane, which is one of the highest costs in the assembly and installation of a floating wind project. This further highlights the importance of optimising the supply chain and logistics, which is critical if Norway is to remain competitive in the offshore wind market in Europe.

7.1. Further work

Due to time limitations and the current capabilities of the Shoreline software, there are several things that could be improved or extended. In the following, some suggestions for future analysis will be made where this work can be continued.

First of all, as mentioned by Tom Eirik Sandnes in the meeting on May 23rd 2022, their main problem is to get the items to the site. Shoreline can simulate the transfer of components to the assembly site for the bottom fixed substructures. However, this function is not yet released for floating substructures. In the near future, this feature should also be available for floating wind simulations so that the cases analysed in this study can be adjusted and reanalysed with additional focus on the effects of the supply chain.

Also, in the same meeting, Tom Eirik Sandnes mentioned that three to four AHVs will be used to install the mooring system for the Hywind Tampen project. In future work, the number, storage capacity, and working cycle of the AHV's could be improved with the experiences from the Hywind Tampen project, which is due for completion by the end of this year. This study assumes only the basic settings from Shoreline for the AHV.

Another aspect is that Wergeland base is preparing to manufacture floating substructures in their dry dock. This study did not deal with the construction on the site, however, future work could consider this in the analysis.

Initially, the information obtained from Wergeland was that the towing speed was assumed to be 3.5 kn. Based on recent experience with the Hywind Tampen project, it turns out that the actual towing speed was 2 kn, and future studies should respect this new towing speed.

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A. Input data

Table A.1.: Input data for the basic case

Base			
	Parameters		
	Wergeland Base		
	Location	N 60.847017	E 5.077233
	Number of repair slots	10	
	Loadout berth capacity	3	
	Capacity		
	Mooring line	200	
	Mooring anchor	200	
	WTG	10	
	Floating WTG	10	
Assets			
	Mooring anchor		
	Loadout port	WB	
	Installation	Regular	
	Mooring line		
	Loadout port	WB	
	Installation	Regular	
	Wind turbine		
	Turbine type	Floating	
	Installation method	Regular	
	Loadout port	WB	
	Rated power	12 MW	
	Nacelle height	136 m	
	Maximum number of technicians in asset	5	
	Completion		
	Completion man hours	50	
	Completion duration	10	
	Completion delay	10	
	Weather window	12	
	Personnel	5 Tech.	
	Vessel	any	
	Commissioning		

Completion man hours	50
Completion duration	10
Completion delay	10
Weather window	12
Personnel	5 Tech.
Vessel	any
Snagging	
Completion man hours	50
Completion duration	10
Completion delay	10
Weather window	12
Personnel	5 Tech.
Vessel	any
Testing	
Test duration	10
Test delay	5

Assembly of Wind turbine	
Pre-assembly port	WB
Assembly arrival rate	1 h

Logistics

Anchor Vessel	1					
Mooring line capacity	4					
Mooring anchor capacity	4					
Performance						
Transit speed	15 kn					
Towing speed	5 kn					
Dynamic positioning speed	2 kn					
Dynamic positioning activation time	1 h					
Cycle	T (h)	Ww (h)	Wh (m)	Ws (m/s)	Ref. H (m)	Cs (m/s)
1 - Mobilising	1					
2.1 - Turbine loadout						
Loadout	0					
2.2 - Mooring anchor loadout						
Loadout	1	2	0	18	100	0
2.3 - Mooring line loadout						
Loadout	1	2	0	18	100	0
2.4 - Cable loadout						
Loadout	0					
3.1 Towing to wind farm						

Prepare towing	1					
Towing		1	2	18	100	0
3.2 Transit to wind farm						
Seafasten assets	2					
Port maoevring	1					
Transit		1	2	18	100	0
4.2 - Mooing anhchor installation						
Installation	3	6	2	16	100	0
4.3 - Mooring line installation						
Installation	3	6	2	16	100	0
5 - Transit from wind farm						
Transit		1	2	18	100	0
Port transit	1					
6 - Arrival at base						
Manoeuvring at base	0					
Tug	1					
Wind trubine capacity	1					
Processes						
General transit speed	15 kn					
Transit while towing	3 kn					
Cycle	T (h)	Ww (h)	Wh (m)	Ws (m/s)	Ref. H (m)	Cs (m/s)
1 - Mobilising	1					
2 - Loadout						
Loadout	2	4	2	16	136	0
3 - Towing to wind farm						
Prepare towing	1					
Towing		2	2	16	136	0
4 - Wind turbine hook up						
Hook up	4	8	2	16	136	0
5 - Transit from wind farm						
Transit		1	2	18	136	0
Port transit	1					
6 - Arrival at base						
Manoeuvring at base	1					
Crew transfere vessel	2					
Technician capacity	12					
Cruising speed	20 kn					
Significant wave height access limit	2.25 m					
Activity Durations						

Connection time	5m
Disconnection time	1m
Personnel transfer time per technician	5m
Equipment transfer time	10m
Mobilising time per port visit	30m
Demobilising time per port visit	30m

Onshore cran	1					
Cycle	T (h)	Ww (h)	Wh (m)	Ws (m/s)	Ref. H (m)	Cs (m/s)
1 - Mobilising	0.5					
2 - Transit to turbine	1					
3.1 - Pre-assembly Wind Turbine						
Connecting	2					
Assembly tower bottom section	2	3	0.5	12	136	0
Disconnecting	1					
Connecting	2					
Assembly tower part	2	3	0.5	12	136	0
Disconnecting	1					
Connecting	2					
Assembly Nacelle	2	3	0.5	12	136	0
Disconnecting	1					
Connecting	2					
Assembly Blades	6	9	0.5	12	136	0
Disconnecting	1					
Transit to commissioning station	3					
Connecting	2					
Assembly finalisation	2	3	0.5	12	136	0
Disconnecting	1					
3.41 - Pre-assembly Mooring Line						
Connecting	1					
Working	1					
Disconnecting	1					
3.41 - Pre-assembly Mooring Anchor						
Connecting	1					
Working	1					
Disconnecting	1					
4 - Transit from turbine						
Post tranist	1					

5 - Arrival at base	
Manoeuvring at basse	0

Personnel

Technician	24
Seasonal availability	1. Mar - 30. Sep
Shift rotation	Weekday
Work hours	7:00 - 19:00

Strategy

Installation package dependencies		
Mooring anchor package	Start date	15.03.2022
Mooring line package	Continous	
Assembly package	Date	01.05.2022
Wind turbine package	Date	01.06.2022

Abbreviations:

WB - Wergeland Base
Tech. - Technican
T - Time
Ww - Weather window
Wh - Wave height
Ws - Wind speed
Ref. H - Ref. height
Cs - Current speed

B. Areas Europe with deep water

Country	Name of the site	Location	Capacity (MW)	Water depth (m)	Substructure	Installation Port	Commissioning	Source
Norway	Utsira nord	4° 16’ 09” E 59° 26’ 53” N 4° 40’ 25” E 59° 28’ 56” N 4° 48’ 44” E 59° 06’ 18” N 4° 24’ 27” E 59° 04’ 10” N	500 - 1000 /10	185 - 280	Spar	Wergeland/ WindWorks Jelsa		[138]
	Sørlige Nordsjø I	3° 02’ 43” E 57° 28’ 13” N 3° 55’ 37” E 57° 35’ 18” N 4° 01’ 21” E 57° 22’ 21” N 3° 08’ 42” E 57° 15’ 03’ N	1000 - 1500/10	50 - 82	Semi-Sub/ Barge	Wergeland/ WindWorks Jelsa		[138]
	Sørlige Nordsjø II	5° 10’ 05” E 57° 05’ 36” N						

		5° 29’ 51” E 56° 44’ 17” N 5° 02’ 01” E 56° 35’ 30” N 4° 38’ 29” E 56° 29’ 02’ N 4° 20’ 48” E 56° 49’ 24’ N	1000 - 2000/10	53 - 70	Semi-Sub/ Barge	Wergeland/ WindWorks Jelsa		[138]
Spain	San Borondón	15° 20’ 23.9" W 27° 50’ 23.9" N	238 /14	72	Semi-Sub	Santa Cruz de Tenerife/ Las Palmas de Gran Canaria	2024	[54, 65, 69, 124, 125]
	Gran Canaria Este	15° 20’ 59.9" W 27° 47’ 23.9" N	144/12	82	Semi-Sub	Santa Cruz de Tenerife/ Las Palmas de Gran Canaria	2000	[54, 65, 69, 72, 71]
	Canarray II	15° 22’ 48" W 27° 46’ 48" N	132/12	74	Semi-Sub	Santa Cruz de Tenerife/ Las Palmas de Gran Canaria	2024	[54, 65, 69, 72, 71]
	Tramuntana I	3° 26’ 23.9" E 42° 11’ 23.9" N	450/15	135	Semi-Sub/ Barge/ Spar	Port-La-Nouvelle	2026	[**ParcTramuntana**, 54, 65, 69, 28]
	Tramuntana II	3° 25’ 11.9" E 42° 5’ 24"	600/15	147	Semi-Sub/ Barge/ Spar	Port-La-Nouvelle	2026	[**ParcTramuntana**, 54, 65, 69, 28]

	Nordes I	8° 30’ 08.9" W 44° 19’ 26.9" N	525		Semi-Sub	A Coruña	2028	[54, 65, 69, 27]
	Nordes II	8° 30’ 50.5" W 44° 00’ 51.0" N	675		Semi-Sub	A Coruña	2028	[54, 65, 69, 27]
	San Cibrao	7° 40’ 11.9" W 43° 58’ 11.9" N	490	173	Semi-Sub/ Barge/ Spar	A Coruña	2027	[54, 65, 69, 127, 31]
	San Brandan	7° 59’ 24" W 43° 57’ 0" N	490	189	Semi-Sub/ Barge/ Spar	A Coruña	2027	[54, 65, 69, 126, 30]
Scotland - ScotWind	2 - SSE Renewables-Marubeni-CIP	0° 57’ 45.4" W 56° 44’ 04.4" N	2610	68	Semi-Sub/ Barge	Port of Nigg/ Port of Cromarty Firth		[54, 65, 69, 40, 130]
	3 - Falck - Bluefloat E1	0° 16’ 50.1" E 56° 51’ 33.2" N	1200	85	Semi-Sub/ Barge	Port of Nigg/ Port of Cromarty Firth		[54, 65, 69, 40, 130]
	4 - CampionWind	0° 12’ 19.4" W 57° 27’ 56.7" N	2000	76	Semi-Sub/ Barge	Port of Nigg/ Port of Cromarty Firth		[54, 65, 69, 40, 130]
	5 - Vattenfall - Fred Olsen E2	0° 33’ 17.2" W 57° 31’ 40.9" N	798	98	Semi-Sub/ Barge	Port of Nigg/ Port of Cromarty Firth		[54, 65, 69, 40, 130]

7 - Cluaran Ear-Thuath	2° 12’ 35.7" W 58° 55’ 23.9" N	1008	81	Semi-Sub/ Barge	Port of Nigg/ Port of Cromarty Firth	[54, 65, 69, 40, 130]
8 - Falck - Bluefloat - Ørsted NE3	2° 15’ 47.2" W 58° 31’ 12.9" N	1000	75	Semi-Sub/ Barge	Port of Nigg/ Port of Cromarty Firth	[54, 65, 69, 40, 130]
10 - Falck - Bluefloat NE6	1° 57’ 35.7" W 58° 10’ 18.5" N	500	72	Semi-Sub/ Barge	Port of Nigg/ Port of Cromarty Firth	[54, 65, 69, 40, 130]
11 - MaramWind	0° 04’ 34.3"W 58° 10’ 40.2" N	3000	130	Semi-Sub/Barge/Spar	Port of Nigg/ Port of Cromarty Firth	[54, 65, 69, 40, 130]
12 - Floating Energy Allyance NE8	0° 43’ 26.4" W 58° 27’ 57.4" N	960	125	Semi-Sub/ Barge/ Spar	Port of Nigg/ Port of Cromarty Firth	[54, 65, 69, 40, 130]
14 - Northland Power N2	5° 28’ 35.9" W 58° 54’ 25.6" N	1500	90	Semi-Sub/ Barge	Stornoway Port/ Kishorn Port/ Port of Nigg/ Port of Cromarty Firth	[54, 65, 69, 40, 130]

	15 - Magnora - Technip N3	6° 25’ 38.2" W 58° 50’ 45.8" N	495	122	Semi-Sub/ Barge/ Spar	Stornoway Port/ Kishorn Port/ Port of Nigg/ Port of Cromarty Firth		[54, 65, 69, 40, 130]
Wales	Llyr 1	5° 27’ 0" W 51° 20’ 24" N	100	70	Semi-Sub/Barge	Port Talbot/ Pembroke Port	2026	[54, 65, 69, 91, 24]
	Llyr 2	5° 16’ 11.9" W 51° 20’ 24" N	100	68	Semi-Sub/Barge	Port Talbot/ Pembroke Port	2026	[54, 65, 69, 91, 24]
	Llywelyn	5° 47’ 59.9" W 51° 6’ 35.9"	300	85	Semi-Sub/Barge	Port Talbot/ Pembroke Port	2029	[54, 65, 69, 91, 24]
	Gwynt Glas	5° 44’ 24" W 51° 11’ 23.9" N	300	85	Semi-Sub/Barge	Port Talbot/ Pembroke Port	2026	[54, 65, 69, 91, 24]
	Erebus (commercial)	5° 35’ 59.9" W 51° 22’ 48" N	600	72	Semi-Sub/Barge	Port Talbot/ Pembroke Port		[54, 65, 69, 91, 24]
	Valourous	5° 42’ 35.9" W 51° 21’ 35.9" N	300	81	Semi-Sub/Barge	Port Talbot/ Pembroke Port	2026	[54, 65, 69, 91, 24]

	North Wales	5° 08’ 31.7" W 52° 39’ 29.6" N	300 - 1000	80	Semi-Sub/Barge	Port Talbot/ Pembroke Port		[54, 65, 69, 91, 24]
	South Wales	5° 44’ 05.7" W 51° 49’ 44.0"	300 - 1000	115	Semi-Sub/Barge	Port Talbot/ Pembroke Port		[54, 65, 69, 91, 24]
England	Petroc	5° 29’ 24" W 50° 56’ 23.9" N	300	62	Semi-Sub/Barge	Port Talbot/ Pembroke Port	2029	[54, 65, 69, 110, 111]
	White Cross	5° 27’ 10.9" W 51° 06’ 52.5" N	100	59	Semi-Sub/Barge	Port Talbot/ Pembroke Port	2026/27	[54, 65, 69, 145, 146]
Ireland	Inis Ealga Marine Energy Park	7° 49’ 49.1" W 51° 39’ 37.9" N	1000/14	82	Semi-Sub/ Barge	Port Talbot/ Pembroke Port/ Cork	2030	[54, 65, 69, 84, 83]
	Emerald	8° 12’ 04.7" W 51° 28’ 53.9" N	1000/25	90	Semi-Sub	Port Talbot/ Pembroke Port/ Cork	2027/28	[54, 65, 69, 48, 47]
	SSE Renewables Celtic Sea	7° 07’ 48.8" W 51° 52’ 48.4" N	800	72	Semi-Sub /Barge	Port Talbot/ Pembroke Port/ Cork	2027	[54, 65, 69, 137, 34]
	Blackwater	6° 30’ 34.3" W 51° 47’ 51.2" N	1500	61	Semi-Sub/ Barge	Port Talbot/ Pembroke Port/ Cork	2027	[54, 65, 69, 10, 9]

	ANIAR Offshore Array - phase 2	9° 04' 10.5" W 54° 35' 02.4" N	500	75	Semi-Sub/ Barge	Galway		[54, 65, 69, 5]
	Moneypoint Offshore Two	10° 31' 03.4" W 52° 32' 30.9" N	1100	105	Semi-Sub/ Barge	Galway	2028	[54, 65, 69, 100]
	Urban Sea	10° 04' 06.2" W 51° 27' 12.8" N	4000	73	Semi-Sub/ Barge	Port Talbot/ Pembroke Port/ Cork		[54, 65, 69, 142]
France	EolMed - Ideol & Quadran Commercial Scale Floating Project	3° 23' 40.9" E 42° 51' 54.6" N	500	88	Barge	Port-La-Nouvelle		[51, 65, 54]
Portugal	Viana do Castelo (1)	9° 06' W 41° 54' N 9° 06' W 41° 42' N 9° 00' W 41° 42' N 9° 00' W 41° 54' N	909	100	Semi-Sub/ Barge/ Spar			[41]
	Viana do Castelo (2)	9° 18' W 41° 48' N 9° 12' W 41° 48' N 9° 12' W 41° 36' N	527	150	Semi-Sub/ Barge/ Spar			[41]
	Povoa de Varzim	9° 12' W 41° 30' N 9° 06' W 41° 24' N	449	100	Semi-Sub/ Barge/ Spar		[41]	

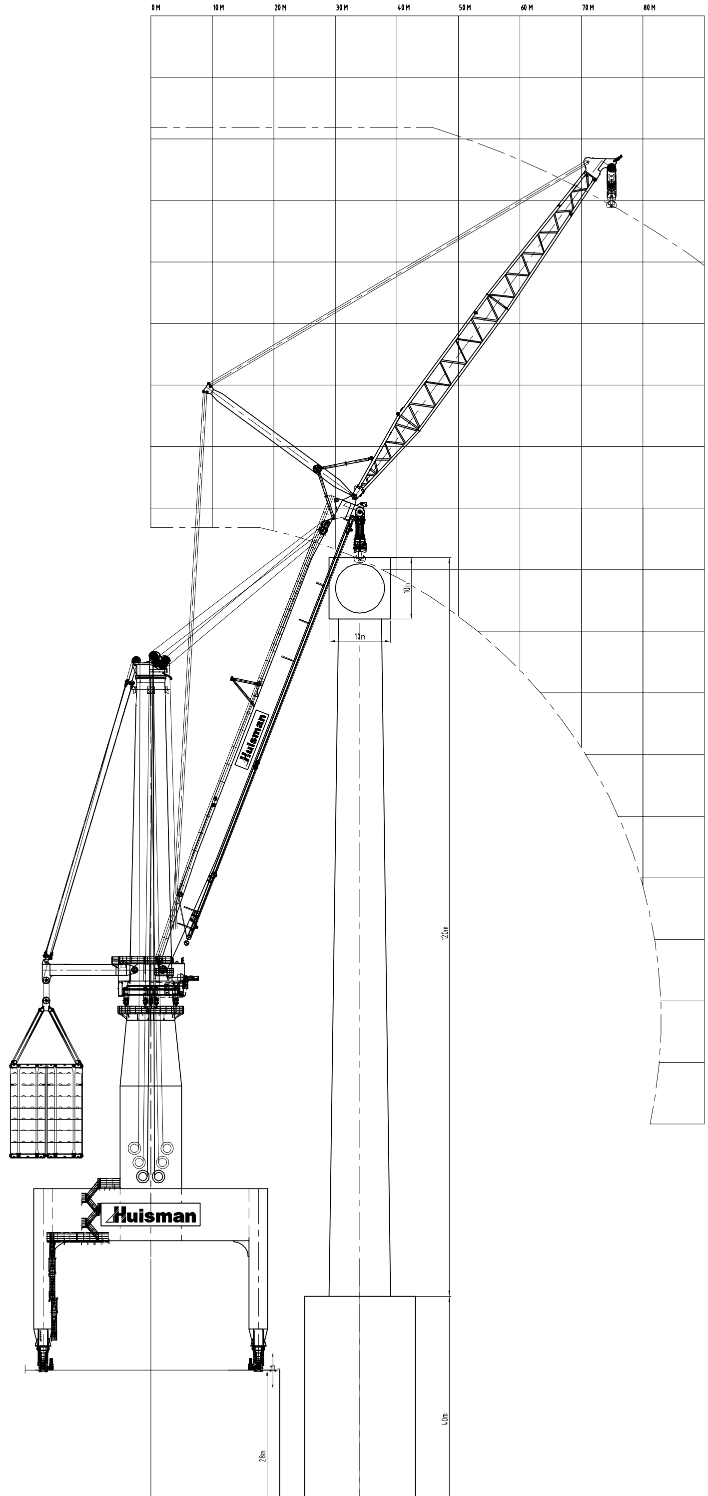
	9° 00’ W 41° 24’ N 9° 06’ W 41° 30’ N				
Porto	9° 12’ W 41° 12’ N 9° 12’ W 41° 12’ N 9° 06’ W 41° 06’ N 9° 18’ W 41° 06’ N	780	150	Semi-Sub/ Barge/ Spar	[41]
Figueira da Foz	9° 30’ W 40° 24’ N 9° 24’ W 40° 24’ N 9° 30’ W 40° 12’ N 9° 36’ W 40° 12’ N	700	150	Semi-Sub/ Barge/ Spar	[41]
Albufeira	8° 24’ W 36° 54’ N 8° 18’ W 36° 54’ N 8° 12’ W 36° 48’ N 7° 12’ W 36° 54’ N	460	100	Semi-Sub/ Barge/ Spar	[41]
Faro	7° 42’ W 36° 54’ N 7° 42’ W 36° 48’ N	444	600	Semi-Sub/ Barge/ Spar	[41]

7° 30’ W 36° 54’ N
7° 30’ W 36° 54’ N

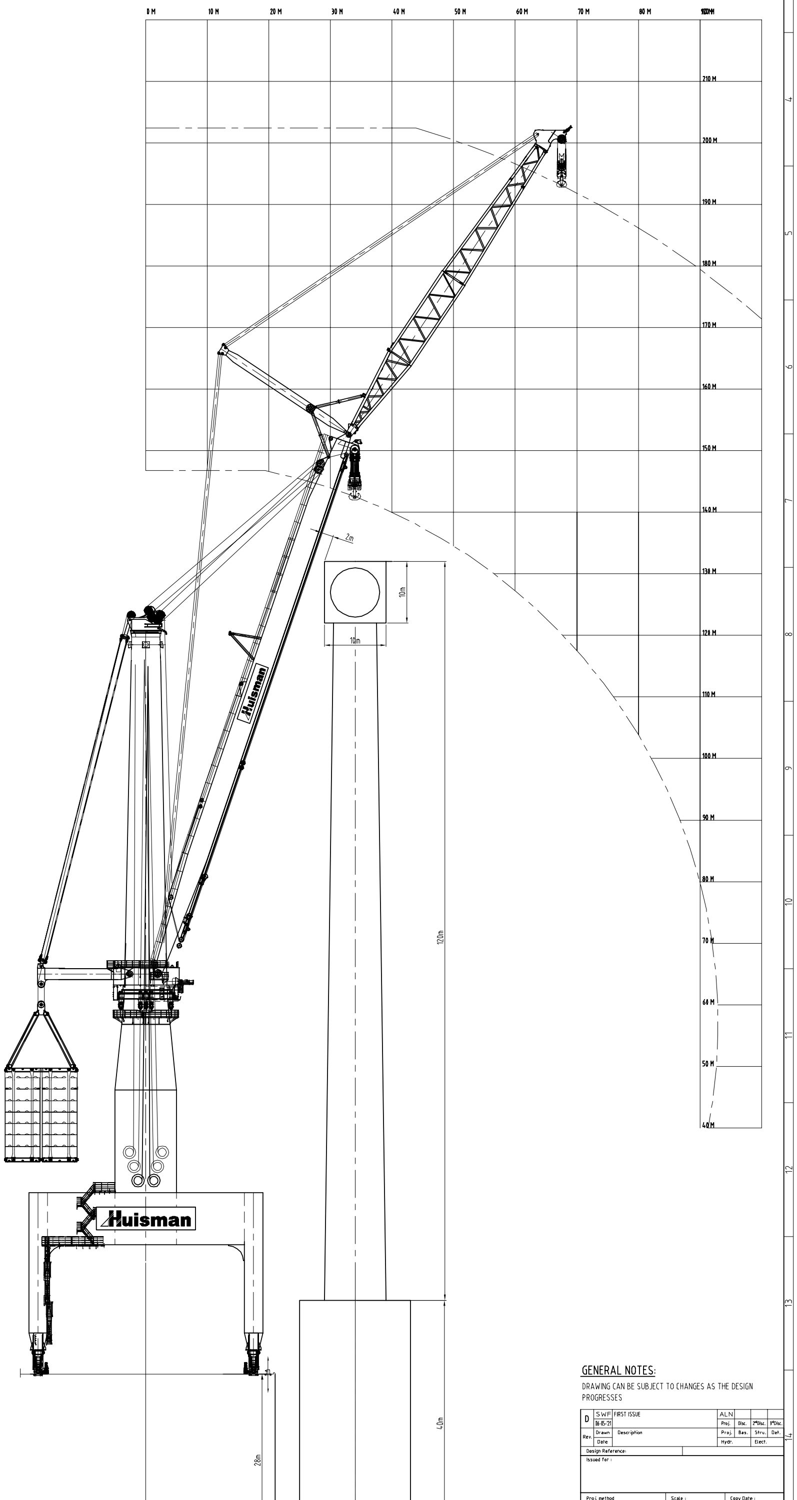
C. Quayside Crane

C.1. 2,600MT Skyhook

SKYHOOK MC ACC. REVISION D2



SKYHOOK MC WITH 91m BOOM



GENERAL NOTES:

DRAWING CAN BE SUBJECT TO CHANGES AS THE DESIGN PROGRESSES

D	SWF 06-05-'21	FIRST ISSUE	ALN			
			Proj.	Disc.	2nd Disc.	3rd Disc.
Rev.	Drawn Date	Description	Proj. Hydr.	Bas.	Stru. Elect.	Det.

Design Reference:

Issued for :

Proj. method

Scale : 1:300

Copy Date : 06-05-2021

Notation	According	Tolerances	According
Dimensions	ISO 129-1	Welding	ISO 13920-AE
Geometrics	ISO 1101 + Ⓔ	Cutting	ISO 9013-431
Roughness	ISO 1302	Machining	ISO 2768-mK
		Plate Thickness	EN 10029-AN
		Castings	ISO 8062-DCTG11

Client : WERGELAND

Project : 2600mt SKYHOOK MC

Title : TURBINE ASSEMBLY WITH MAIN HOIST
QUAYSIDE CRANE

Huisman

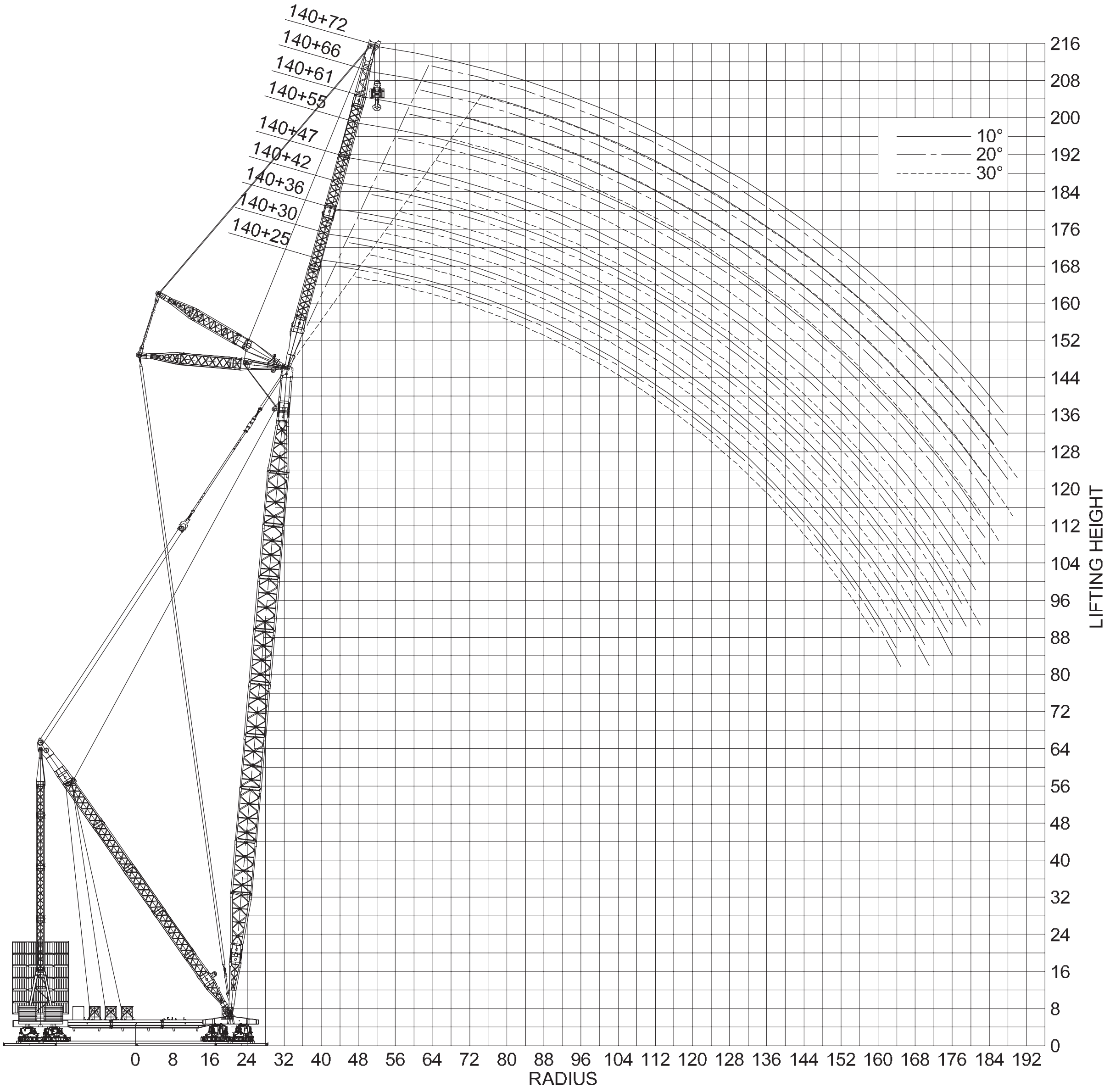
Huisman Equipment B.V.
Admiraal Trompstraat 2
3115 HH Schiedam, The Netherlands
Telephone : +31(0)88 070 22 22
Telefax : +31(0)88 070 22 20

Format	Order No.	Drawingno.	Rev.
A0	A20-11170	A20-11170-10-05	D

C.2. Mammoet PTC 200-DS

MAMMOET PTC 200-DS

RADIUS DIAGRAM FOR SFSL



Dimensions are in meters.

Version 1, 2015-11-06, SAP No. 4000098140

MAMMOET PTC 200-DS

LOAD TABLE FOR SFSL

Boom length (m)	Jib length (m)	Radius (m)																										
		35	38	42	46	50	54	58	62	66	70	74	78	82	86	90	94	98	106	114	122	132	142	152	162	172	182	192
111	25		3200	3087	2887	2703	2534	2381	2240	2111	1990	1960	1856	1752	1580	1440	1313	1198	994	818	661	485						
	30			3030	2828	2645	2479	2327	2188	2059	1940	1830	1813	1711	1615	1462	1337	1223	1022	849	697	527	370					
	36			2972	2780	2597	2432	2282	2143	2016	1900	1790	1713	1674	1581	1474	1354	1244	1048	878	729	564	413					
	42			2784	2704	2542	2378	2240	2102	1977	1859	1754	1654	1630	1549	1463	1374	1262	1067	900	753	593	449	314				
	47				2485	2431	2315	2185	2061	1944	1829	1722	1625	1534	1523	1439	1364	1278	1088	925	783	623	482	352				
	55				2227	2189	2150	2075	1964	1859	1761	1668	1579	1492	1408	1394	1323	1251	1096	937	797	646	507	386	269			
	61					2014	1980	1945	1885	1789	1699	1613	1531	1454	1381	1345	1300	1233	1101	951	814	663	528	411	302			
	66					1829	1798	1767	1735	1704	1633	1554	1479	1407	1338	1272	1241	1204	1086	954	818	676	549	430	325	223		
	72					1668	1640	1612	1490	1466	1441	1417	1393	1359	1294	1233	1175	1170	1061	960	831	685	557	452	345	249	156	
	78						1493	1446	1400	1356	1313	1272	1232	1194	1158	1122	1089	1057	996	937	848	702	575	463	363	270	181	
	84						1291	1245	1200	1158	1117	1078	1041	1006	973	941	910	881	828	778	733	682	589	479	379	288	204	120
117	25		3106	2903	2717	2544	2387	2240	2105	1977	1862	1780	1739	1638	1545	1448	1324	1211	1011	838	686	516	357					
	30			2839	2650	2482	2325	2188	2055	1932	1816	1710	1660	1599	1507	1421	1339	1232	1035	865	717	552	401					
	36			2773	2591	2427	2269	2137	2010	1892	1779	1675	1578	1565	1477	1393	1313	1239	1056	891	744	585	438	305				
	42				2536	2373	2225	2089	1964	1849	1742	1640	1545	1500	1445	1365	1288	1216	1077	914	771	614	473	340				
	47				2442	2319	2175	2042	1921	1808	1704	1607	1517	1433	1389	1337	1264	1195	1065	932	792	639	499	377	258			
	55				2203	2163	2088	1969	1856	1749	1648	1554	1467	1386	1309	1273	1224	1157	1035	924	803	653	523	402	292	1817		
	61					1994	1959	1893	1792	1696	1606	1520	1438	1359	1285	1215	1202	1138	1018	911	814	670	542	426	319	217		
	66					1811	1780	1749	1717	1634	1550	1471	1396	1324	1256	1190	1127	1117	1001	897	802	682	555	443	339	241	146	
	72					1687	1650	1613	1572	1539	1493	1420	1350	1283	1220	1159	1101	1072	985	883	791	686	575	462	362	265	175	
	78						1487	1448	1404	1361	1320	1279	1241	1204	1168	1123	1069	1017	958	863	775	675	578	475	376	283	196	112
	84						1293	1248	1205	1163	1124	1086	1050	1015	982	951	921	893	840	791	746	663	576	482	385	302	216	136
123	25			2750	2558	2386	2229	2087	1956	1833	1721	1617	1592	1504	1414	1330	1250	1174	1020	850	702	538	387					
	30			2698	2512	2340	2184	2042	1912	1792	1682	1580	1484	1469	1382	1299	1222	1149	1014	875	730	569	426	290				
	36			2638	2460	2298	2145	2004	1888	1758	1650	1549	1456	1412	1356	1275	1199	1128	997	879	762	602	462	332				
	42				2403	2245	2101	1968	1842	1725	1618	1519	1427	1342	1330	1251	1178	1109	981	866	762	626	488	364	245			
	47				2348	2194	2054	1922	1808	1698	1592	1494	1404	1320	1241	1231	1159	1091	967	856	755	641	513	392	278			
	55					2097	1971	1854	1745	1642	1541	1443	1353	1273	1205	1136	1128	1062	941	834	737	626	525	410	304	202		
	61					1976	1895	1787	1686	1591	1502	1419	1340	1266	1191	1121	1087	1046	930	824	730	623	528	430	328	229	137	
	66					1821	1780	1716	1623	1536	1453	1374	1300	1230	1164	1102	1040	1009	918	814	721	617	524	439	348	252	163	
	72						1633	1588	1558	1478	1402	1329	1260	1195	1132	1072	1016	962	905	805	714	612	521	440	362	273	188	101
	78						1477	1450	1407	1365	1326	1280	1216	1155	1097	1041	987	937	885	794	706	605	517	436	364	289	205	123
	84						1295	1251	1209	1169	1130	1093	1058	1024	991	961	931	903	842	777	697	601	514	436	365	297	223	145
128	25			2582	2397	2231	2080	1943	1816	1701	1593	1493	1423	1381	1295	1216	1140	1068	934	814	704	555	411	276				
	30			2542	2357	2191	2041	1902	1778	1663	1558	1460	1369	1325	1267	1189	1116	1046	918	802	696	574	445	316				
	36			2508	2322	2156	2007	1871	1748	1634	1530	1434	1343	1259	1244	1167	1095	1029	904	792	690	574	468	350	233			
	42				2281	2123	1975	1840	1717	1605	1502	1408	1319	1237	1198	1148	1078	1012	889	780	682	570	469	376	264			
	47				2225	2079	1943	1814	1695	1581	1479	1385	1299	1218	1143	1107	1062	997	878	772	676	568	470	380	294	190		
	55					1954	1818	1706	1608	1516	1430	1349	1264	1185	1112	1043	1011	970	858	753	659	556	463	378	300	220	124	
	61					1907	1792	1682	1575	1475	1381	1294	1212	1142	1080	1022	966	957	846	745	655	553	463	381	306	234	155	
	66					1789	1721	1624	1531	1444	1362	1283	1206	1133	1064	1000	939	881	819	732	647	547	460	380	307	239	174	87
	72						1607	1556	1473	1393	1318	1246	1178	1113	1052	994	937	882	819	724	636	543	458	380	308	244	182	117
	78						1462	1436	1402	1336	1267	1201	1138	1078	1020	966	913	864	812	721	635	539	454	378	309	245	187	129
	84						1297	1254	1213	1174	1136	1100	1065	1032	988	937	888	841	753	709	630	536	451	377	310	249	192	138
134	25			2433	2253	2092	1945	1813	1691	1579	1476	1380	1290	1268	1191	1115	1043	973	847	732	627	507	397	293				
	30			2382	2213	2054	1907	1775	1656	1545	1443	1350	1262	1221	1166	1091	1021	955	832	722	622	507	402	304	211			
	36				2166	2016	1876	1745	1627	1520	1418	1324	1239	1159	1120	1072	1003	939	820	714	617	506	406	313	228			
	42				2120	1973	1839	1715	1598	1492	1392	1301	1217	1139	1066	1054	987	925	807	704	610	504	408	319	239	161		
	47				2078	1934	1805	1683	1574	1468	1370	1281	1198	1121	1049	982	973	911	798	697	605	502	410	325	249	173		
	55					1872	1745	1630	1524	1426	1335	1247	1165	1090	1020	955	894	886	776	679	591	491	404	323	250	180	115	
	61					1813	1698	1591	1493	1399	1311	1226	1145	1075	1007	943	883	854	768	673	587	490	404	327	254	189	123	
	66						1638	1538	1445	1359	1277	1202	1130	1061	993	929	870	814	758	664	580	486	402	327	258	192	134	76
	72						1572	1482	1397	1316	1240	1168	1100	1036	976	919	860	805	750	658	575	483	401	327	259	198	139	87
	78						1449	1416	1343	1269	1198	1131	1068	1007	950	896	844	795	720	650	568	477	397	325	260	199	145	91
	84							1254	1214	1176	1139	1092	1033	977	924	872	824	777	689	644	564	475	396	325	262	202	150	98
140	25			2256	2094	1947	1814	1692	1577	1469	1369	1276	1191	1151	1096	1023	953	889	767	658	560	446	342	246	153			
	30			2211	2051	1904	1773	1653	1542	1438	1340	1249	1165	1087	1074	1002	935	871	756	650	555	446	348	257	169			
	36				2011	1868	1739	1621	1513	1413	1315	1226	1144	1067	997	985	919	858	745	644	551	447	352	266	184	108		
	42				1972	1831	1704	1588	1482	1384	1292	1206	1125	1050	980	947	904	844	734	635	545	445	355	270	195	121		
	47				1937	1798	1673	1559	1454	1358	1270	1186	1107	1034	965	901	872	834	726	629	541	444	357	278	204	134		
	55					1747	1624	1513	1411	1318	1231	1151	1076	1007	938	876	817	789	706	612	528	434	350	275	204	140	76	
	61					1714	1595	1486	1386	1295	1210	1132	1059	992	926	864	807	753	698	608	526	434	352	277	210	146	82	
	66						1552	1453	1360	1271	1188	1111	1040	974	912	852	795	743	689	599	519	429	352	276	217	152	93	
	72						1499	1408	1321	1240	1164	1093	1023	959	898	841	785	733	661	594	515	427	349	278	215	156	100	
	78						1435	1355	1276	1201	1130	1062	999	939	882	827	775	723	630	586	509	423	346	276	215	159	103	
	84							1254	1215	1158	1093	1030	971	915	861	810	762	716	624	581	505	419	344	278	217	161	111	

t = metric tons.

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