Winning solution of foundations-structural supports in locations 30-50 m

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Promoteur(s) : 14971
Faculté : Faculté des Sciences appliquées
Diplôme : Master : ingénieur civil mécanicien, à finalité spécialisée en "Advanced Ship Design"
Année académique : 2020-2021
URI/URL : http://hdl.handle.net/2268.2/13264

Winning Solution of Foundations-Structural Supports in Locations 30-50 m

Submitted on 25th August, 2021

by

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ABSTRACT

The study begins with the exhibition and analysis of the state of the art of the offshore wind turbine foundations-structural supports in general. The suitability of each type of foundation-support (monopile, gravity-based and jacket) will be analyzed for the different conditions that can be found in locations with a draft of 30-50 m. Some of the most important considerations such as metocean loads, geotechnics, economic aspects, manufacturing, transportation, installation, operation and decommissioning, local content, etc. will be taken into account. Then, it continues with the establishment of a methodology for the decision making of the most suitable offshore wind turbine foundation. TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), a widely used multi-criteria decision-making method that allows for both quantitative and qualitative criteria to be considered in the decision-making process, will be employed.

This methodology is divided in three phases. The first phase consists of the weighting factors to be considered for the possible influence and the degree of importance of each criteria in the foundation selection. The second phase consists of the rating factors to make decision about selection depending on the characteristics of the wind farm. The final phase is to use the TOPSIS approach for evaluating the best solution based on their degree of adequacy. This strategy is currently being utilized to identify solutions that are as close to an ideal solution as feasible while taking into account a certain distance, and the resulting solutions are referred to as compromises.

It has been verified in this document that the proposed methodology allows the decision of offshore wind turbine foundation according to the conditioning factors, enabling not only technical and financial feasibility of the offshore wind farm to be achieved, but also respect for the environmental impacts. The results of this study show the importance of all types of weighting factors to take into consideration in decision method, as well as the requirements to consider all issues in a comprehensive perspective, since this has a significant influence not only on the financial profitability of the facility, but also on the compatibility with the environment. In addition to this, learning and progressing knowledge in this field is slow due to the high level of confidentiality surrounding the use of information from offshore wind farm operations.

ACKNOWLEDGEMENTS

First and foremost, a debt of heartfelt gratitude is owed to EMSHIP Program for providing me the financial support to complete the research of this master thesis. I wish to extend my immense gratitude to Professor Philippe Rigo (Head Coordinator) at EMSHIP Program for giving me a learning opportunity, invaluable support and assistance.

The completion of this thesis could not have been accomplished without the expertise of Dr. José Santos López Gutiérrez and Dr. Dolores Esteban Pérez, my beloved thesis supervisors. Their sincere support, prompt, useful advice and guidance during my dissertation as well as overall insights in this offshore renewable field have made this an inspiring experience, diligence and erudition for me.

Most importantly, I would also like to say a special thank you to my parents and my family as a whole for their continuous support and understanding during the compilation of this dissertation. It is my privilege to thank my beloved Ko Ko for his constant encouragement throughout my dissertation.

Last but not least, with this achievement, I would like to honour the fallen heroes of Myanmar, and their sacrifices to achieve the Justice, Democracy, Freedom and Human Rights against the Abhorrent Tyranny of Military Regime during the Spring Revolution, Myanmar 2021.

Declaration of Authorship

I declare that this thesis and the work presented in it are my own and have been generated by me as the result of my own original research.

Where I have consulted the published work of others, this is always clearly attributed.

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This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma.

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1. INTRODUCTION

1.1. Concept Analysis

In this study each type of offshore foundation is described so that the strengths and disadvantages of each type can be investigated. According to the offshore wind in Europe - key trends and statistics of 2019 regarding monopiles remains the most widely deployed base, with 4,258 units (81%) installed to date, including grid-connected and non-grid-connected foundations. The jackets share (8.9%) increased with the installations at Beatrice 2 and gravity base (5.7%) follow the cumulative share [1]. Figure 1 shows the annual offshore wind installation by country in Europe and has a total installed offshore wind capacity of 22,072 MW.

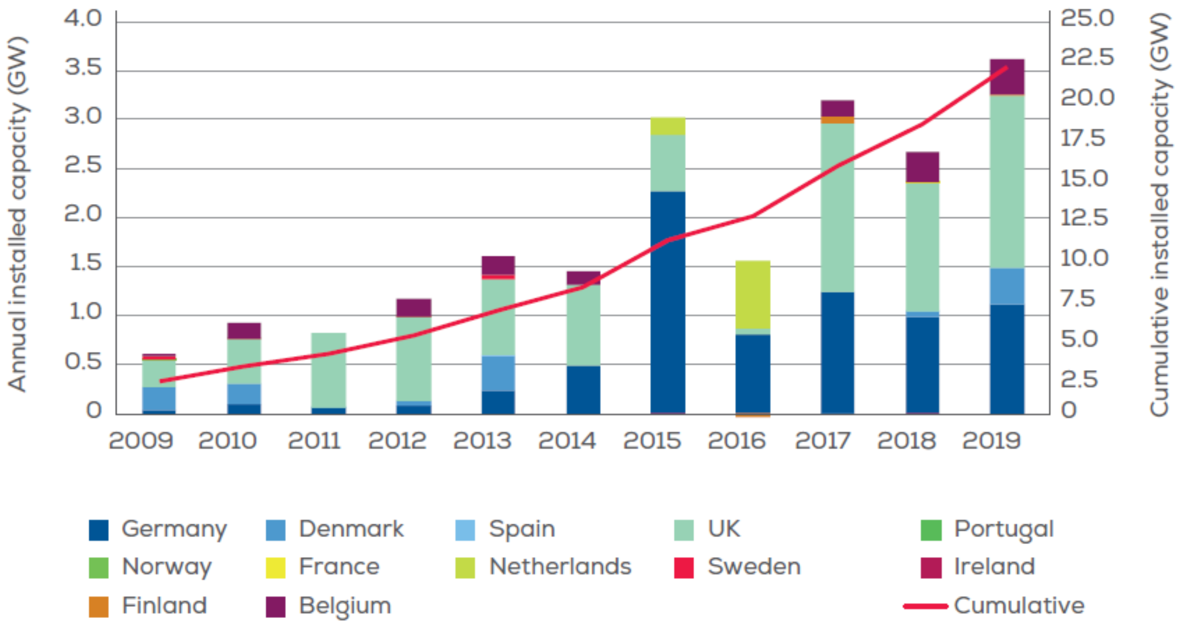

Figure 1. Annual Offshore wind installation and cumulative capacity [1]

1.2. Offshore Wind Industry Trend

Offshore wind farms are moving farther and into deeper waters. It can usually be used in a few specific locations. The range of applications for this type of installation is limited by two factors:

1) The depth of the seabed: higher expenses and the usage of more complicated and specialized technologies are associated with greater depths, which is reflected in the wind farm's final

investment, while decreasing its profitability. Closed seas, which are found within continental platforms, have a far significantly lower depth than oceans and open seas, making them more suitable for this project.

2) The distance to shore: To improve wind and less impact on the landscape and the coast, it is sought to locate these types of facilities quite far away from the coastline as feasible, since this allows for the use of turbines of greater nominal size and power. However, this usually leads to an increase in depth.

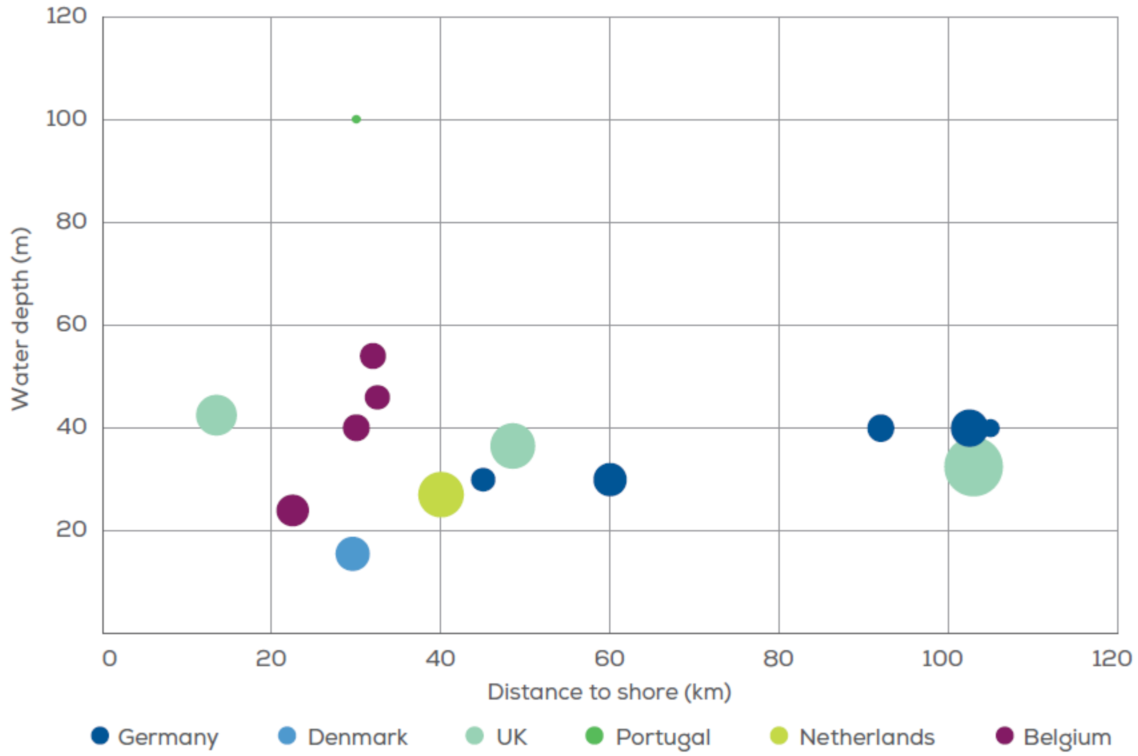

Figure 2. Water depth and distance to shore of offshore wind farms under construction during 2019 [1]

Figure 2 shows result of both factors which are better stable wind resources and the depletion of near-shore locations. New offshore wind farms under construction and with permits are moving farther away. Figure 3 and Figure 4 show that the rolling averages of both water depth and distance to shore have a strong growing pattern by European Wind Energy Association. The total water depth of offshore wind farms under construction in 2019 was 33 meters, up from 30 meters in 2018, and the average distance to shore was 59 kilometers, a significant improvement over average of 2018.

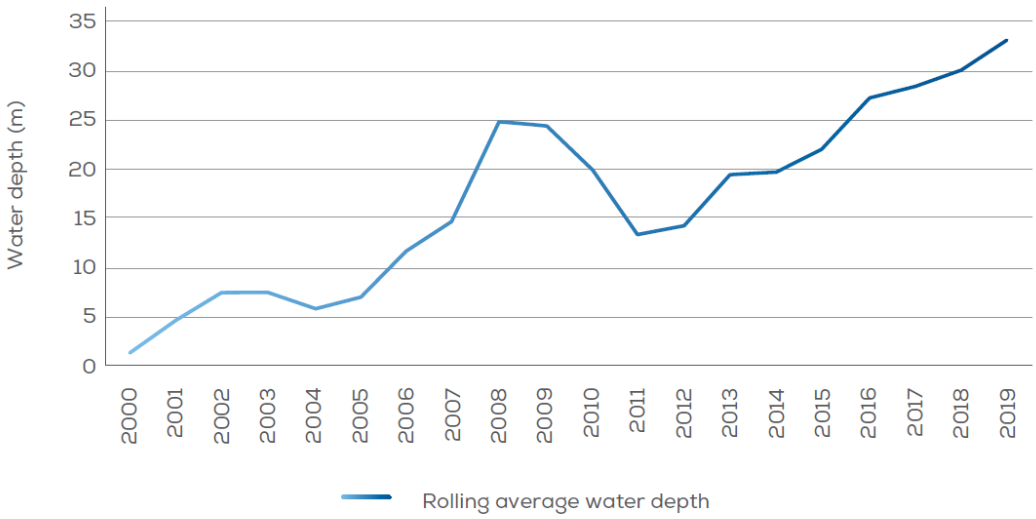

Figure 3. Rolling average water depth of offshore wind farms [1]

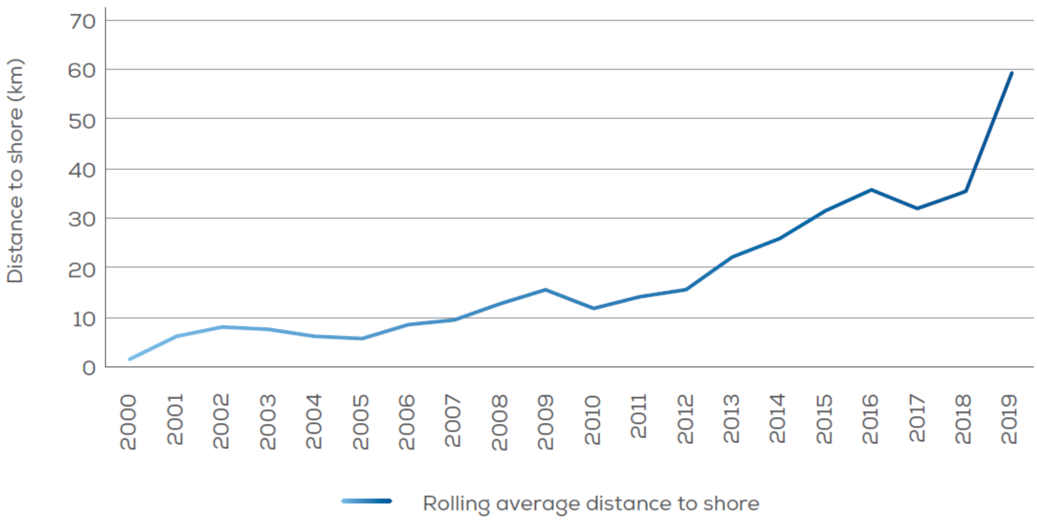

Figure 4. Rolling average distance to shore of offshore wind farms [1]

1.3. Typologies of Structural Foundation for Offshore Wind Turbines

Offshore wind turbines are attached to the seabed via foundations by strong support structures. They must sustain the wind turbines while also absorbing all forces and loads and providing a strong and stable base. Foundations is one of the main elements of structure in offshore wind farms because they are located in such a complex and extremely powerful element as the sea. According to inventory data, structural foundations account for approximately 20–30 % of the total cost of a typical offshore wind power output [2]. Hence, winning solution of a suitable foundation type for offshore wind turbines is key to exploitation of offshore wind energy.

Several factors, such as the nature of the foundations, substructures, and support structures, need to be changed. In offshore wind farms, wind turbines are installed above sea level with various foundations depending on the water depth as one of the factors for the foundation selection in offshore wind farms. In this study, the suitability of each type of dominant support structures are used for fixed offshore wind turbines. Monopile foundation, gravity-based foundation (GBF), and jacket foundation will be analyzed for the different conditions that can be found in certain locations with a water depth of 30 to 50 meters. Figure 5 shows schematic of support structures of bottom-fixed offshore wind turbine.

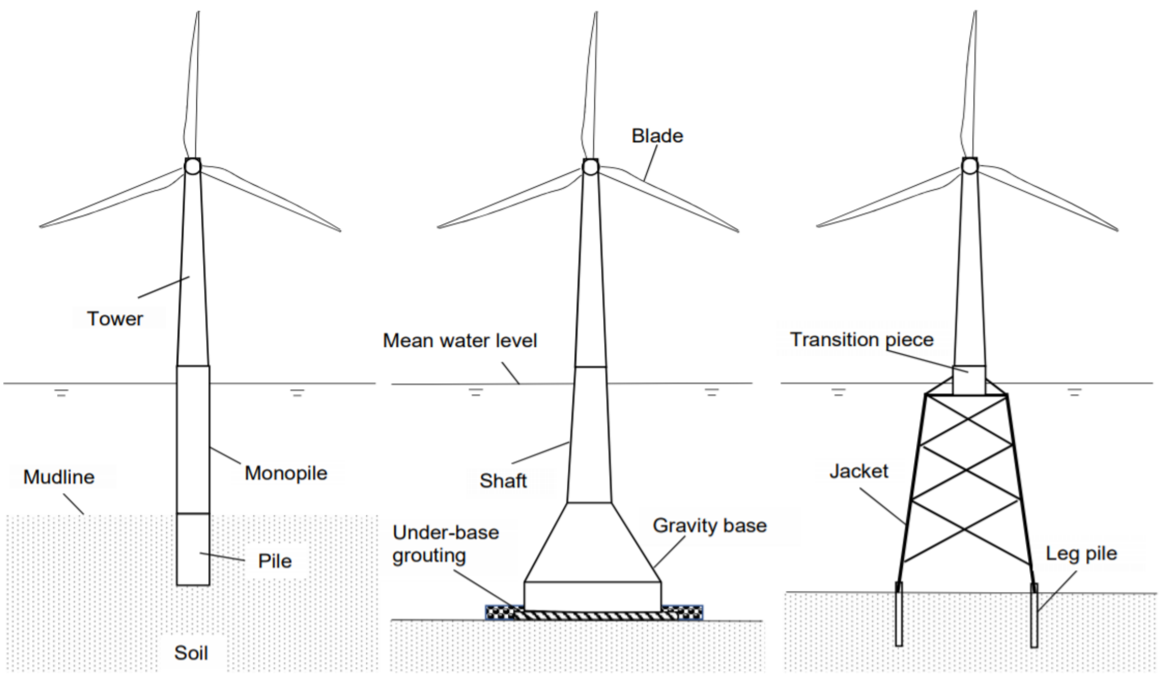

Figure 5. Schematic of support structures of bottom-fixed offshore wind turbine
(from left to right: Monopile, Gravity-based and jacket foundations) [3]

1.4. Aims and Objectives

This research focuses on offshore foundations, with the goal of determining the most favorable and unfavorable characteristics of each of the current foundation types. It is therefore necessary to investigate the conditions of each foundation. Several condition aspects will be studied in this analysis in order to balance the sustainable sector for socio-economic operations. Not only the technical aspects, economic profitability of the installation and its management are considered, but also its compatibility with the environment are taken into consideration. Some of which are, soil conditions, metocean loads, underwater noises and so on that will lead the way to this investigation and will be described in detail afterwards.

Once the comparative analysis has been carried out, there will be a methodology for the foundation selection of offshore wind farms in which all the variables that influence the development of these projects are taken into account. On the other hand, the specific conditions ought to be studied, in order to define what qualities and features are required by the specific place and its conditions. The environmental conditions study will also take place in a specific wind farm area. Additionally, another important aim of this research is the reduction of costs and environmental impacts. It is critical to improve the economic efficiency of an industry by selecting the optimal offshore wind turbine support structures. To sum up, the chosen foundation will have to support the offshore wind farm and minimize costs and environmental impact at the same time.

This study intends to give an analytical technique for selecting the most proper foundation from the three most commonly used support structure configurations - monopile, gravity-based, and jacket in water depths of 30-50 meters. Based on this purpose, a decision tool that is appropriate for the problem and incorporates the established criteria, will be developed and structured. Several condition aspects will be studied in this analysis in order to balance the sustainable sector for socio-economic operations.

1.5. Methodology

The first step in this study is to confirm the requirements for a methodology of selecting the proper offshore wind turbine foundation for a wind farm. An extensive research and critical analysis of information relating to metocean data, geotechnical engineering, and, in particular, foundation systems and support structures will be analyzed for this purpose. Once these requirements have been confirmed, the analysis of each existing foundation will be performed in order to find out about their advantages and disadvantages when developing an offshore wind farm project and determine how it affects the environment.

According to the bibliographic review carried out to confirm the need, established information must be expanded from what has been exposed and discussed in various specialized forums such as Conferences, National and International Congresses, and Work Seminars, as well as by consulting various articles of Congresses and proceedings of conferences, journals, books and technical reports, research projects, Webpages of public bodies responsible for the development of these facilities, Websites of various wind farms in operation, under construction, or in the process, and so on.

The methodological proposal presented in this study is general and based on a balanced treatment of all of the aspects involved, rather than claiming to be a specific and detailed critique of any of them. As a result, many of the points made in this study will need to be expanded upon in other texts, many of which will be referenced in this one as bibliographic references, and many of them will need to be investigated in future. Once the characteristics that can influence an offshore wind farm in some way have been identified, they will be reflected in a logical order that provides for a clear visual representation of the entire project. Following that, the potential influences of each of them on foundation systems will be analyzed.

Based on the above, a methodology proposal for the selection of offshore wind turbine foundations will be produced, in which all considerations that may influence the technical feasibility, profitability, and environmental compatibility of the installation will be considered.

Then, as a last step, in order to complete this work, the proposed method must be verified and validated, for which the procedure to be followed will have to be defined. It is highly important to know the features and characteristics of the location of the current offshore wind farm, which has been chosen for the foundation installation.

2. FOUNDATION SYSTEMS AND SUPPORT STRUCTURES

This section provides a state of the art of the various types of foundations and structural configurations of offshore wind turbine support structures. It also discusses how foundation structures are chosen in general.

2.1. Different Types of Offshore Wind Turbine Foundations

Almost all currently operating offshore wind farms, the major dominant choices for offshore wind turbine foundations can be isolated into four distinctive underwater structures which are classified according to the water depths as can be seen in the following Figure 6.

1) Monopiles
2) Gravity-based structures (with skirts)
3) Jackets or tripods (pre-piled or with suction buckets)
4) Floating foundations (technically viable with water depths from 50 m and deeper waters)

Fixed base offshore wind turbines are generally considered technically feasible in waters less than 50 meters deep. Due to the fact that this research will be focused on locations with water depths of 30 to 50 meters, only three forms of foundations will be considered.

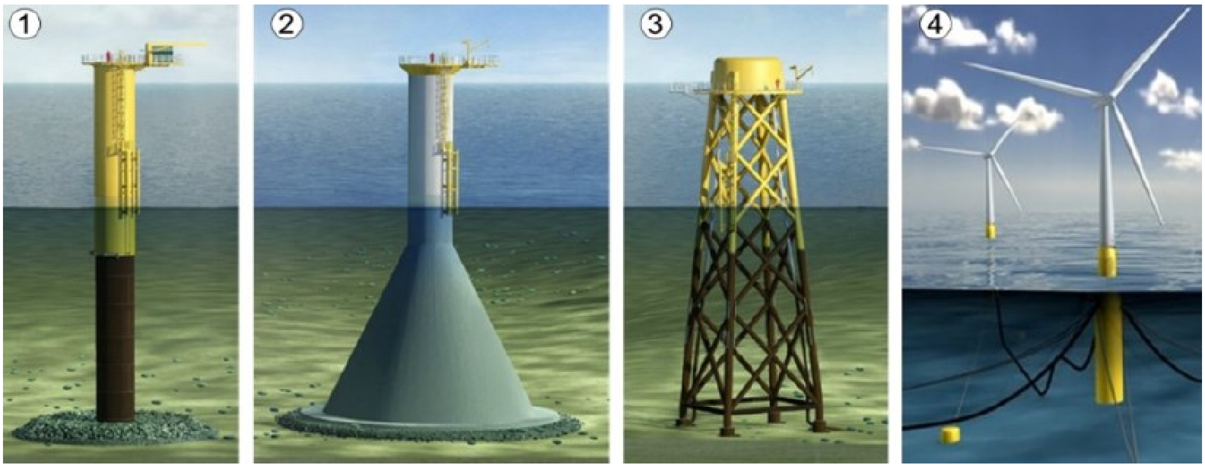

Figure 6. Four different types of offshore wind turbine foundation [Illustrations: Ramboll and Equinor]

The tower is closely similar for all types of foundations. Nevertheless, the response of combined tower and foundation system may differ respectively.

2.1.1. Monopile Foundation

Monopile used in offshore wind facilities is the simplest structure, which consist of a pile linked to a transition piece (transitional section between tower and monopile). It generally consists of a single long steel tubular structure with a large diameter between 3 and 8 meters that is hammered or vibratory driven into the seabed with clay, sand, or chalk stratigraphy and for a rocky seabed, drilling and bored pile methods are commonly adopted. Its elegant and simple design makes it cost effective solution for shallow to intermediate water depth. However, the monopile must be longer, wider and thicker to maintain a strong and stiff structure with heavier turbines and deeper waters. The monopile support structure is the combination of tower and substructure. The substructure is connected to the tower through an annulus transition piece attached by grout, and the foundation begins at mudline or seabed line, while the substructure begins at the sea level. It is shown particularly in details in the following Figure 7.

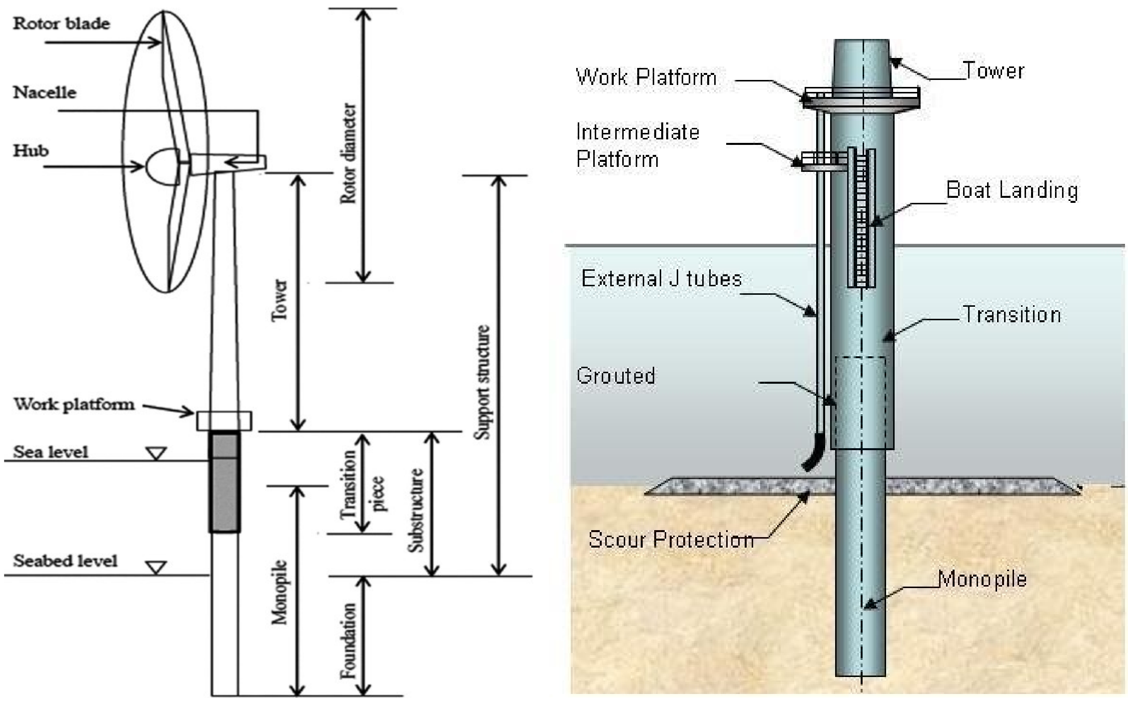

Figure 7. Model representing the components of monopile foundation [4-5]

Up to 1,000 tonnes in mass, which transfers the applied vertical and larger lateral loading into the seabed foundation. The installation process consists of pile driving, mounting and grouting of the transition piece, which can be usually achieved in 24 hours [6]. Due to its ease of manufacture, low cost, manageable construction and safely installed, the monopile has been utilized worldwide for offshore wind turbine foundations. Moreover, due to the fact that minimal seabed preparation requirements, resistance seabed movement, scour damage and inexpensive production costs, monopiles are one of the most commonly and widely used foundation type and currently remain the most installed foundations at the top of its popularity in 2019. In order to extend their feasibility to larger wind turbines and greater water depths, so called "XL-monopiles" (extra-long monopiles), with diameters up to 11 meters, are currently developed [7]. Monopiles are currently located in water depth, ranging between 35 and 40 meters (latest solutions) and depending on the site climate conditions. The standard monopiles without lateral support are mainly used in shallow water depth up to 25 m, while monopiles with lateral support braces are suitable for depth from 35 m to 40 m.

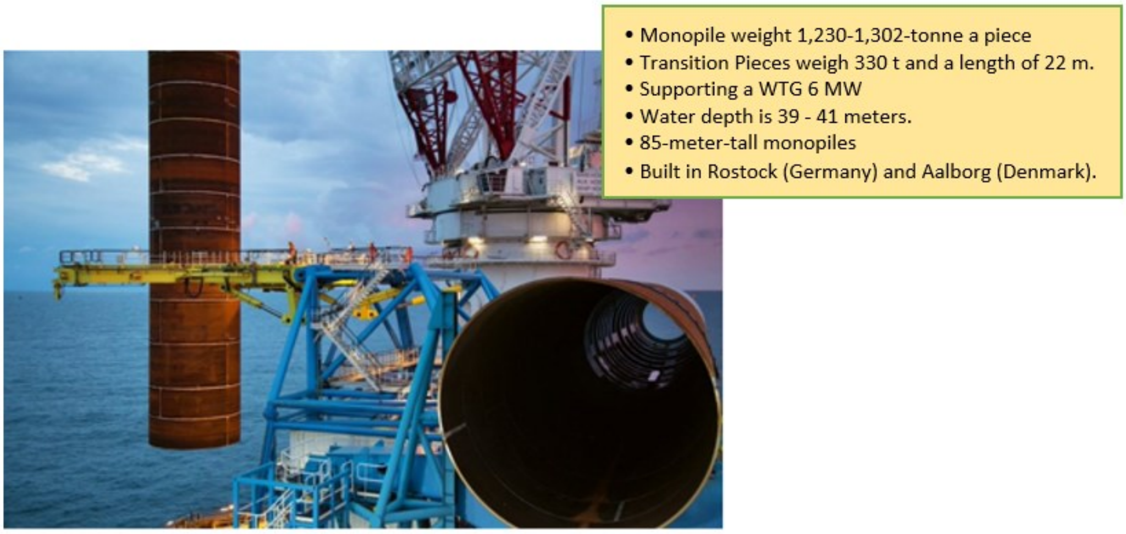

Figure 8. Veja Mate offshore wind farm [8]

Figure 9. Walney Extension offshore wind farm [9]

2.1.2. Gravity-Based Foundation

Gravity based structures used in offshore wind farms, are normally built of reinforced concrete (concrete with reinforcing steel or rebar) and a steel bar or mesh of steel wires. This type of foundation is relatively heavy compared to the monopile as it is usually made out of concrete materials. This also has a transition piece for the wind turbine made out of steel or concrete shaft. As a result, they can be divided into three main parts: a relatively thin concrete slab in the lower portion, a conical form in the lower part, and a vertical shaft in the upper part. Gravity-based foundations are divided into three types that correspond to the first, second, and third generations [10].

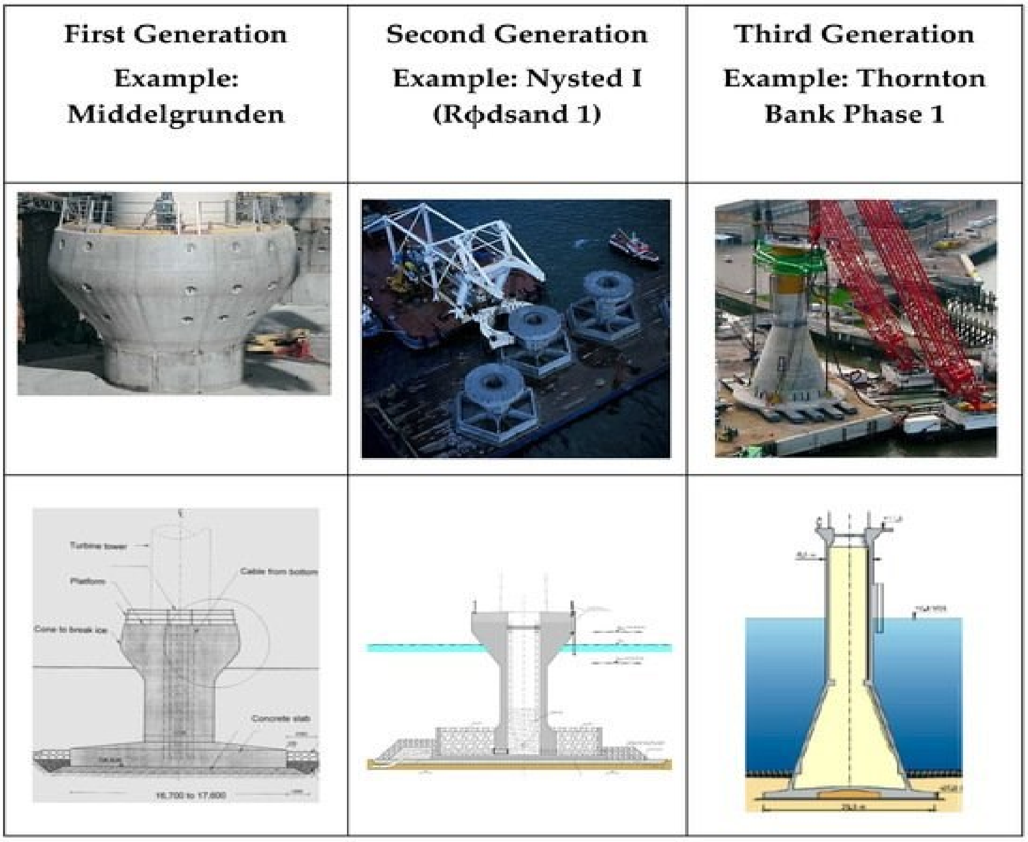

Figure 10. The classification proposed for the GBS concepts used in offshore wind farms [10]

First of all, the first-generation foundations are solid concrete structures, without cells or holes. Next, the second generation include holes or cells in the slab or lower part of the structure with a hexagonal shape, which reduces their weight for transport and installation and moreover, that hollow shaft has a constant diameter and on the top of the foundation has a conical shape to reduce the ice loads. Once the gravity-based structure is installed, the holes or cells are filled with ballast, achieving the final design weight that supports the design loads. Furthermore, the only example of a third-generation structure is Thornton Bank in Belgium. This concept has a conical hollow shape, not only in the slab or lower part, as in the second-generations that provides buoyancy to the structure during the tow-out phase. The top part of the structure consists of a steel column which is connected to the concrete part. This type of structure decreases the weight of the foundation and reduces the lifting requirements. This structure is designed with a big flat base primarily to provide enough friction and distribute the loads on the seabed according to their self-weight to resist the extreme overturning moments, leaving support structures standing upright on the seabed and to reduce the horizontal surface to decrease the horizontal loads.

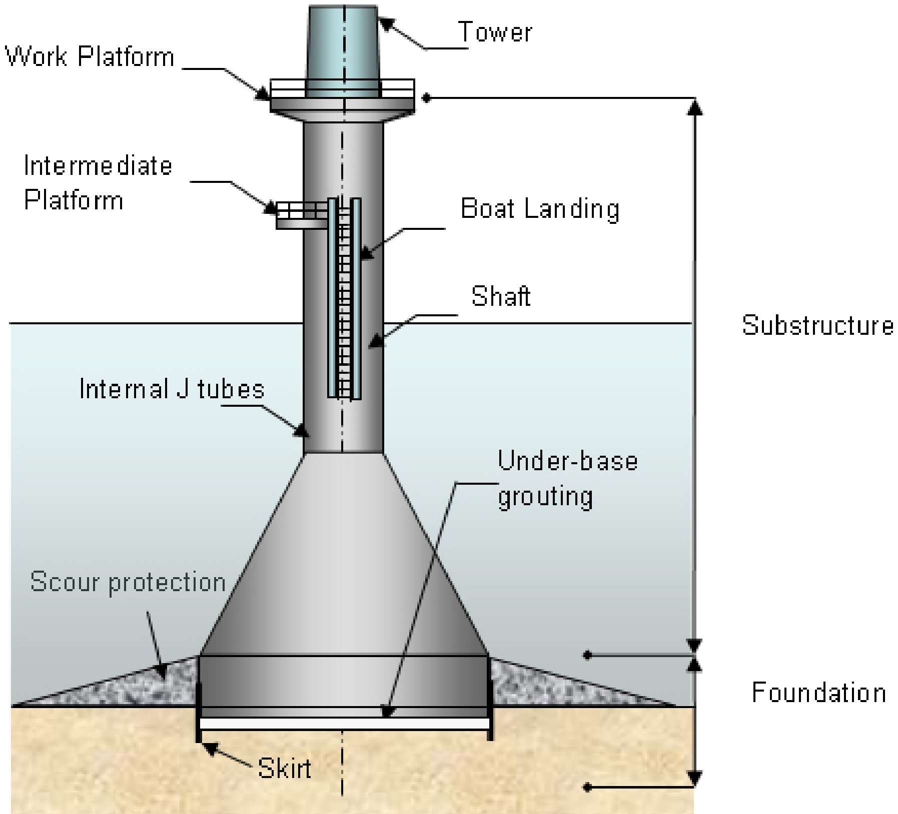

Figure 11. Main components of third-generation gravity-based foundation [wind-energy-the-facts.org]

Permanent Ballast Installation is necessary to ensure stability during design life. After lowering the structure onto the seabed by flooding the internal volume, the interior hole is ballasted by filling the hollow concrete base with sand, iron ore or rock to provide the structure with additional stability. Sand is the most frequently used ballast material. However, depending on stability requirements, high density material such as olivine or iron ore is required. During lowering to seabed, controlled water ballasting is required. Structure is divided in several caissons and filling can be done by an external pump installed in an assisting vessel. Water ballast ensures sufficient submerged weight until solid (permanent ballast) is installed.

Figure 12. Multi-purpose barge Thornton I depicted in permanent ballasting and backfilling [11]

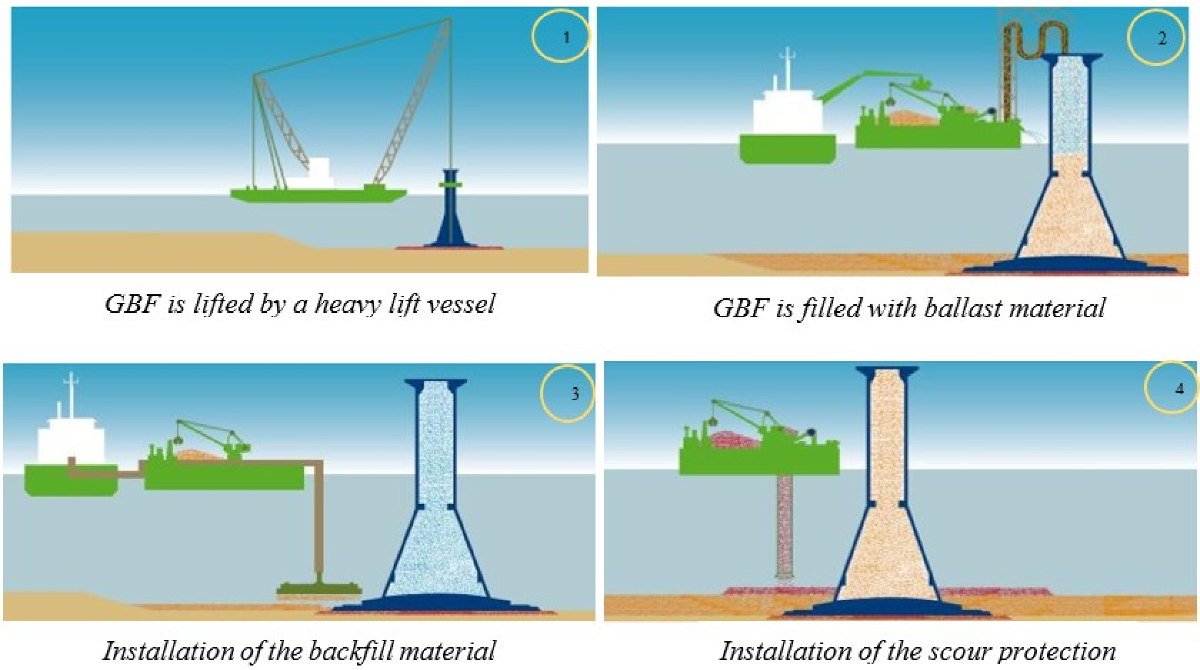

Figure 13. Foundation Installation (DEME Group)

Ballast can be performed by different methods such as hydraulic pumps as can be seen in Thorton Bank (third generation caisson), fall pipe as can be seen in Kårehamn Wind Park (first generation caisson) and different types of vessels (jack ups, dredgers, and special equipped barges). Furthermore, they are more appropriate for seabed's composed of compacted clay, sandy soil, and rock. However, it requires the seabed to be prepared in advance and the toe of the structure to be protected against scour. Backfill operations around the gravity based structures are usually performed with sands dredged from the nearby disposal areas, which originated from the dredging of the foundation pits. Scour protection typically consist of a filter layer installed over the backfilled material and an armour layer installed on top of the filter layer. Similar vessels to the ones used for the permanent ballast installation (Fall Pipe Vessels) are used for the scour protection installation. Side Stone Dumping Vessels can be hired specifically for these operations.

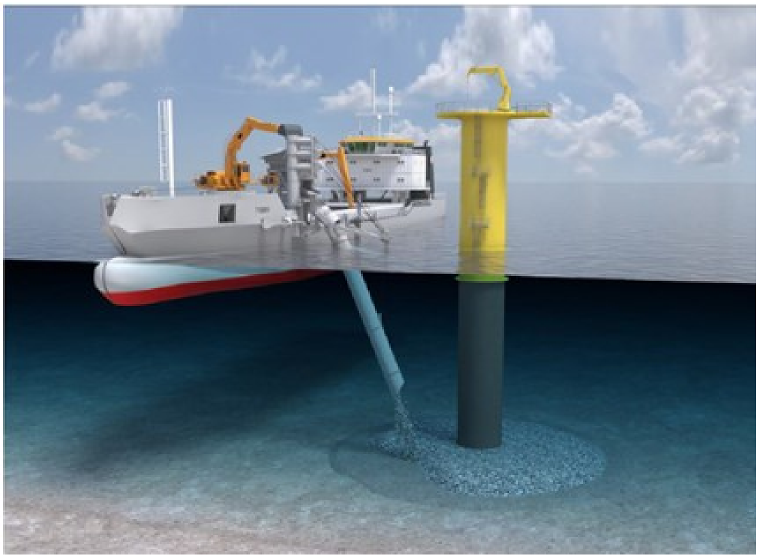

Figure 14. Scour protection installation [12]

The gravity base is a type of reinforced concrete caisson structure that is easy to build and has a low load bearing capacity. It needs adequate load bearing capacity to accommodate the self-weight of foundation structures, service loads, and environmental loads. The benefit is that the fabrication process can rapidly be executed as an onshore activity, in ports close to the wind farm site, minimizing the need for offshore operations. Construction methods such as dry dock, floating pontoon and quayside are intimated link to the transport method and installation method. However, because of their size and weight, they are difficult to transport and mount, restricting their use in deep water. These systems would also necessitate a large amount of port capacity. Gravity-based foundations are normally restricted to a water depth of about 25 to 30 meters (latest solutions) and depending on site environment conditions due to the widespread use of concrete in this form of construction.

Figure 15. Shallow water concept: Nysted I offshore wind farm foundations [13]

Figure 16. Shallow water concept: Middelgrundenoffshore wind farm foundations [14]

Figure 17. Deep water concept: Thornton Bank [11]

2.1.3. Jacket Foundation

The number of legs on the jacket base varies, with three or four legged structures being the most common in the offshore wind industry. Regardless, the traditional jacket structure is a space frame structure made up of interconnected corner steel tubular piles connected by bracings to form a lattice tower in the center. When comparing the monopile and jacket foundations, the jacket foundation requires three or four pilings, while the monopile foundation only requires one piling on a larger scale. The stiffness of the jacket, on the other hand, helps it to settle massive wind turbines. In addition, when jacket piling is done during jacket installation, a less efficient and therefore quieter hammer is used.

Figure 18. Jacket foundation for four legs with tubular steel piles [15]

Figure 19. Jacket foundation for three legs with tubular steel piles [16]

The structural ability to survive overturning is aided by the foundation's large base. On one hand, the legged piles are driven into the soil, and on the other, they are driven into the pile sleeve. For ease of manufacture, these parts are simple and regular, and this type of construction necessitates a transition piece between the main jacket and the wind turbine tower. Loads are transferred axially across the various sections, such as the truss structure. Since this foundation is stiffer than a monopile foundation, it is less influenced by wave and current loads. Seabed preparation is usually not required for this form of foundation. Furthermore, this concept does not need any scour protection and it has already been installed in four wind farms [17]. Nowadays, jacket foundations have been widely used to be suitable for large turbines in intermediate water depths ranging from 35 to 40 m.

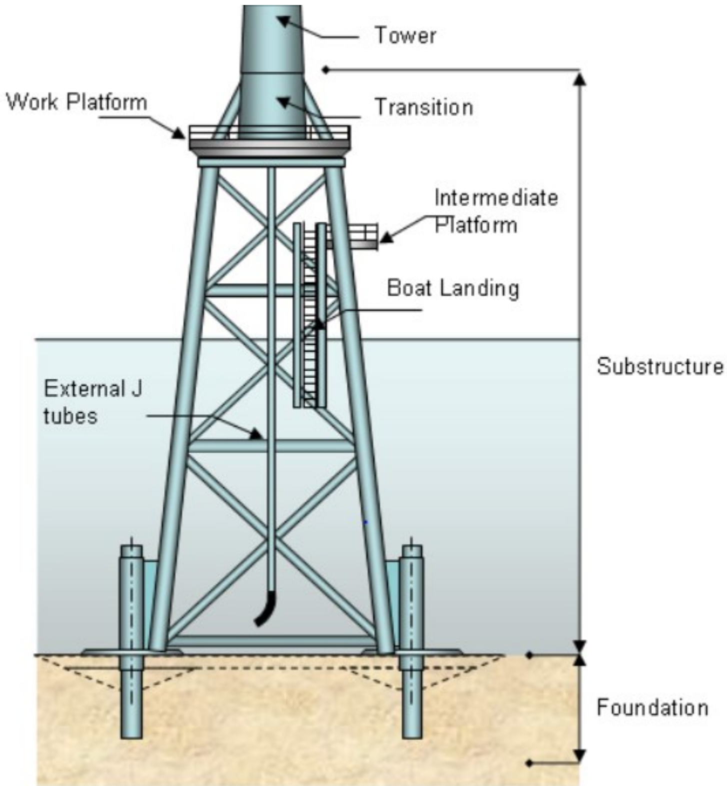

Figure 20. Main components and geometry of Jacket foundation [wind-energy-the-facts.org]

The jacket is normally manufactured on land and then transported to the site, where it is piled into the seabed. Additionally, they are comparatively cost-effective in terms of steel consumption; this substructure is thought to be distinguished by its environmentally sustainable fabrication and efficient installation, but storage, logistics, construction, installation and maintenance cost can be expensive, substantially raising the overall cost [18]. Furthermore, due to the difficulty in removing numerous piles and their lack of resistance to ice flow damage, transportation is neither extremely simple nor moderately difficult, as shown in Figure 21.

Figure 21. Transportation of jacket structure from land [19]

Jackets may also be anchored to the seabed using suction caissons, a type of watertight retaining structure. Suction caissons are similar to large-diameter pipe piles, but instead of being hammered or vibrated into position, they are forced below the seabed by reducing the pressure within the caisson and leveraging the pressure of the ocean to force the caissons into the soil. The suction caissons transfer the loads to the seabed soils similarly to piles, but the caissons are larger in diameter and shorter in length. In this study, jackets with pile foundations will be considered for further details.

2.1.4. Tripod and Tripile Foundation

A tripod foundation has some of the characteristics of a jacket foundation and some of the characteristics of a monopile foundation. It has three-legged structure (Figure 22), which is supported by three medium diameter steel pipe piles arranged in an equilateral triangle, the apex of which supports the upper tripod truss structure. A tripod truss will bear upper loads applied to the tower and deliver stresses and moments to the three steel piles as a precast unit. The tripod foundation is stable, light, and can be used in water depths of 10–35 meters. Examples include Alpha Ventus, Germany [20] and Nogersund, Sweden [21].

The tripile foundation is a variation of tripod-like concept and it also consists of a three-legged structure at the lowest part, which is assembled to the monopile (Figure 23) but smaller diameter. Its installation starts with the three legs being driven into the soil. A vibratory hammer is used first, followed by a hydraulic hammer to complete the introduction. This concept is suitable for water depths of 25 to 50 meters according to the manufacturing data they are less expensive and lighter than other support structures. It also provides better lateral stability than monopiles. Despite the fact that the diameter of these piles is smaller than that of monopiles, tripod requires three piles driving. The three legs distribute the loads over a larger footprint, similar to the base of a tripod foundation. On the other hand, its transport process is still considered as hard.

Figure 22. Tripod foundation [22]

Figure 23. Tripile foundation [23]

2.2. Summary of Foundation Systems Used For Offshore Wind Turbines

Although the selection option of foundation would be site-specific, the relative advantages and disadvantages of the most used fixed foundation-support structures systems are summarized. In the previous section, several types of structures have been described. However, Tables 1-3 refer to only monopile, gravity-based, and jacket foundations for the reason of analyzing these three common fixed offshore foundations in this study.

Table 1. Advantages and Disadvantages of Monopiles

Types of foundation system	Monopiles
Advantages	- Most commonly installed - Simplest structural design - Simple and quick installation process - Minimal seabed preparation - Due to its relatively deep penetration, it is less vulnerable to seabed mobility and scour impact. - Low cost per ton of steel - High serial production
Disadvantages	- Environmental impact for noises and vibrations generated during the pile driving installation process - Fatigue affects the pile and the surrounding soil during installation - Failure of the grouted connections between the monopile and the transition piece - Require large scour protection - Difficult to remove after design life

Table 2. Advantages and Disadvantages of Gravity-based structures

Types of foundation system	Gravity-based structures
Advantages	- Simple installation but no transition piece installation - Low environmental impact due to the absence of piling during the installation - Permanent ballast (e.g., heavy density materials and sand) is necessary to ensure the required stability. - Transfer loads extremely well - Structure can be floated to avoid costly installation vessels

Disadvantages	- Requires massive quayside space & onshore crane - Difficult to transport due to heavy size and weight - Not suitable on soft seabed surfaces - Require seabed preparation: increase installation time - High production cost - Requires special operations on deep waters - Large footprint at seafloor

Table 3. Advantages and Disadvantages of Jackets

Types of foundation system	Jackets
Advantages	- Lightweight and stiff structure - Minimal seabed preparation. - Good response to wave and current loads - Due to its relatively deep penetration, it is less vulnerable to seabed mobility and scour impact - Economically viable on transitional/deep waters - Cost-effective in terms of steel consumption
Disadvantages	- Complexity of fabrication - Complex connection to transition pieces - Large number of joints required - Moderately difficult for transportation due to width - Expensive cost for installation and maintenance - Requires piling, which has environmental noise concerns

3. CONDITIONING ASPECTS FOR THE DECISION

This section exhibits how to choose an optimum foundation system for offshore wind turbines based on the most important factors. In fact, there are several factors to be considered when deciding the most suitable foundation for a wind turbine plant. The selection of an optimum foundation system is not an easy process because it is influenced by a number of considerations, including geotechnical, geological and geophysical site conditions, water depth, metocean loads, economic impacts, and environmental aspects.

3.1. Water Depth

The water depth is the most essential factor for the viability of offshore wind farms because the cost for foundations increases dramatically with depth. The water depth is generally classified in the offshore wind industry into three classes: shallow waters (0–30 m), transitional waters (30–50 m), and deep waters (50–200 m) [24, 25]. It is also vital when selecting an appropriate foundation structure because the dynamic response of a conventional wind turbine is determined by the stiffness of the support structure, which is inversely proportional to the free standing height of the turbine (or water depth). The height of the foundation system rises to hold the wind tower and turbine above the water surface. As a result, variations in water depth will alter the size and nature of the stresses that are applied to the foundation system. Each foundation system is typically most suited for a particular range of water depths based on performance and expense, which can vary based on several geological and environmental factors. Table 4 includes some of the most accepted criteria [26, 27].

Table 4. Range of water depth where the foundation systems are feasible

Foundation Systems	Ashuri and Zaaijer, 2007	DNV, 2013	Iberdrola, 2017	Latest solution
Gravity-based	0 – 10 m	0 – 25 m	0 – 30 m	25 – 30 m
Monopile	0 – 30 m	0 – 25 m	0 – 15 m	35 – 40 m
Jacket	> 20 m	20 – 50 m	>30 m	35 – 40 m
Floating	> 50 m	> 50 m	> 50 m	> 50 m

3.2. Metocean Loadings

The role of offshore wind foundations is to support the wind turbine and in the case of support structures for wind turbines, it is necessary to ensure that the wave loads are as minimal as possible and that the waves are as transparent as possible, with the goal of minimizing the cost of the system. For this reason, metocean loads should be taken into account when deciding on a foundation system. Offshore metocean loads influencing wind farm design, such as site-specific meteorological and oceanographic measurements in the region, should be characterized for proposed wind farm sites for about a year prior to construction.

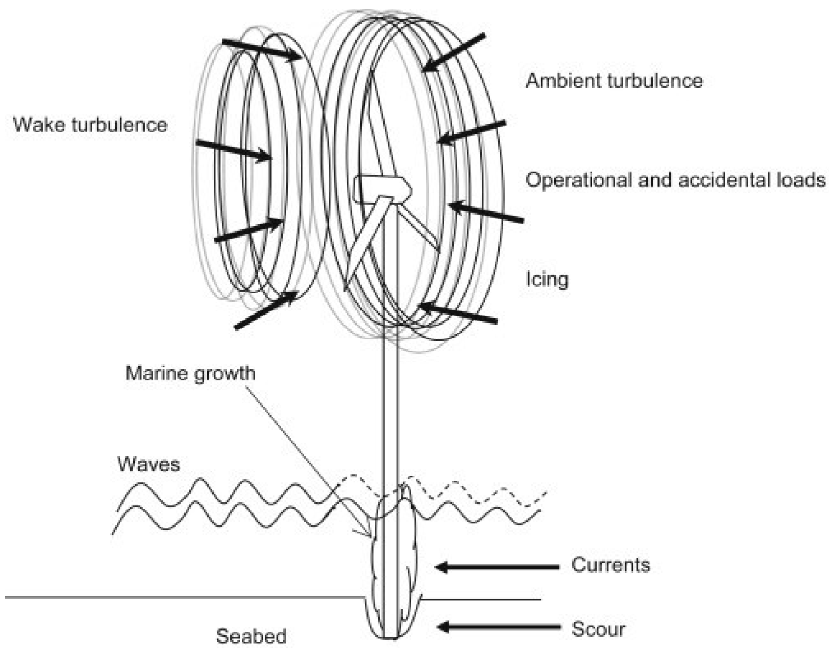

Figure 24. Sources of loading on offshore wind turbines [28]

Metocean loads such as wind, wave, current, tide, ice and earthquake as shown in Figure 24 are affected by a variety of factors, including the location of the project and water depth. These loads are time dependent, covering a wide range of time periods. Under various design conditions, these loads act on the wind tower in various load combinations and directions, which are then resolved into an axial force, horizontal base shear, an overturning moment, and a torsional moment that must be resisted by the foundation. Gravity-based foundations, for example, are unlikely to be considered if the foundation structure is exposed to comparatively high tensile, overturning moments, and/or lateral loads for the installation, especially during the seabed preparation.

3.2.1. Wave Loading

The substructure and foundation are also affected by the wave loads acting on an offshore wind turbine structure. The significant wave height, (Hs) and the spectral peak wave period (Tp), are the two key parameters that can be used to reflect wave loads. The significant wave height is an indicator of the wave climate intensity that takes into account wave height variability. It can be described as four times the standard deviation of the sea elevation process (i.e. four times the area under the wave spectrum, H_{m0}) [29], or as the mean height of the 1/3 highest wave, $H_{1/3}$. The frequency content of a sea state is defined by the wave spectrum, which is usually based on a Pierson-Moskowitz spectrum for a well-developed sea state or a JONSWAP spectrum for a small fetch and sea state duration. Theoretical predictions and model or full-scale measurements can be used to estimate hydrodynamic loads. The amount of each is carried out is determined by the degree of uncertainty in the predictions. If the waves cover a sufficient period of time, wave statistics may be used to estimate these parameters. When using data from a nearby location, variations in water depth and seafloor topography should be considered.

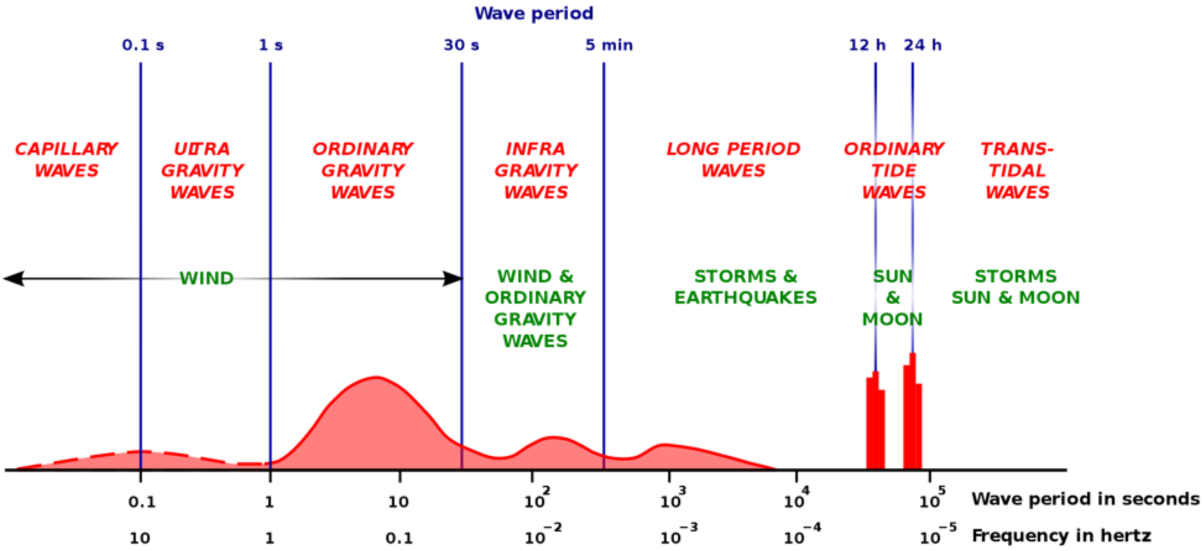

Figure 25.Wave period distribution [30]

3.2.2. Current and Tidal Loading

Sea currents consist of wind-generated currents and tidal currents. Density currents, currents caused by storm surge and atmospheric pressure changes, and near-shore, wave-induced surf currents running parallel to the coast are examples of such current components which are other than the wind generated and tidal currents. In shallow water, sea currents caused by tidal wave propagation are characterized by a velocity range that is nearly horizontal. Their intensity gradually diminishes as the depth is increased. In the absence of site-specific measurements, the following equations can be used to compute the vertical profile of the current (IEC 6 1400-3.2005).

$$V(z) = V_{wind}(z) + V_{tide}(z) \qquad \text{Eq. 1}$$

$$V_{wind}(z) = V_{wind\ 0}\left(\frac{h_0+z}{h_0}\right) \quad (\text{For} -d_0 \leq z \leq 0) \qquad \text{Eq. 2}$$

$$V_{tide}(z) = V_{tide\ 0}\left(\frac{h_0+z}{h_0}\right)^{1/7} \quad (\text{For } z \leq 0) \qquad \text{Eq. 3}$$

Where z denotes the elevation above sea level. The current velocities on the surface, V_{tide} and V_{wind}, are tide and wind induced. And h_0 is a depth guide (which typically is assumed of 20 meters).

Concrete GBF are the unfavorable foundations in terms of physical obstruction to waves and tidal currents. In the offshore windfarm industry, there is now a substantial evidence base indicating that conical gravity base structures have the greatest potential effect [31]. This is due to the fact that these structures take up a significant portion of the water column as a solid mass (as opposed to an open lattice of slender columns and cross-members, like jackets, or a single slender column like a monopile). As a result, they have the potential to influence wave propagation and near-surface tidal currents in ways that other foundation types do not.

3.2.3. Ice Loading

Ice loading is one of the important dynamic loads for offshore wind turbine (OWT). In winter-climate waters, ice loading is a severe and decisive load case. Winter temperatures in Northern Europe are rising by several degrees as a result of climate change. As a matter of fact, the ice in the Baltic Sea is melting [32]. However, as this situation has not yet been stabilized, the foundations must be prepared for the possibility of ice formation. Moving ice can create significant loads on foundation-support structures, tends to result in catastrophic failures of offshore wind turbines.

3.2.4. Seismic Loading

When performing desktop studies and site investigations, the level of seismicity should be determined. If the level of seismicity is found to be high, and the wind turbines will be affected. Foundations can experience partial to full loss of bearing or sliding support, unmitigated differential movements or post-earthquake reduction in soil strength. Additionally, structural members may undergo repetitive loading which in turn can weaken structural connections, to the detriment of the foundation. Seismic loads can shake the structure in two directions in the horizontal plane and in the vertical plane (up or down), simultaneously. Also, inertial loads from displaced water need to be accounted for in the foundation design. Seismic foundation design must also consider the amount of damage that a foundation may take while remaining operational. In many cases, high quality seismic data can be used for preliminary assessment of suitable types of foundations and required pile embedment length or effect of changed wind farm layout, see Figure 26.

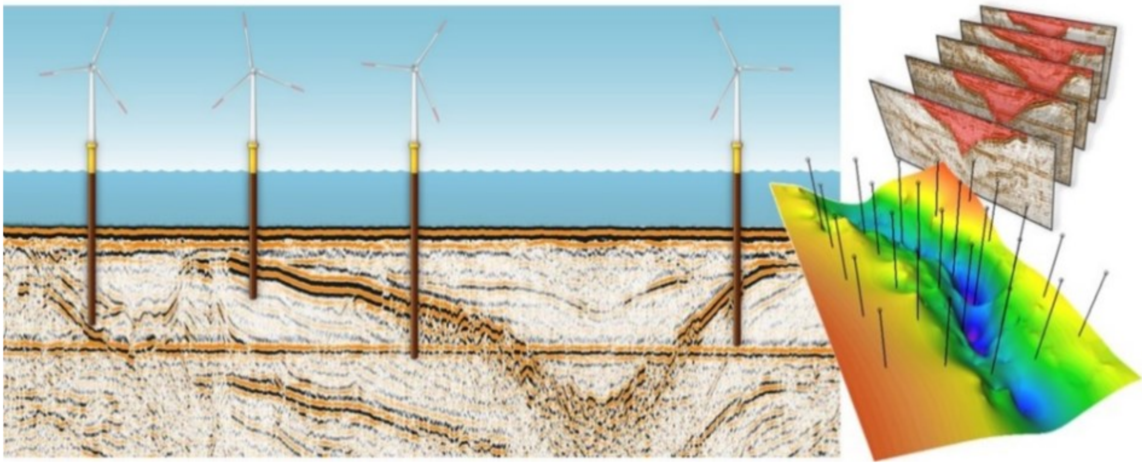

Figure 26. Preliminary pile design based on multichannel high resolution seismic profiles (Illustrations Fraunhofer Institute for Wind Energy Systems)

Seismic implications come from liquefaction of the soil, seismically induced settlement, horizontal earthquake loads, and horizontal tsunami loads. For liquefaction to occur, the soil must be loose, sandy or silty, and of low plasticity, and there must be a quick load applied, such as an earthquake. Liquefaction causes significant reduction in the strength and stiffness of soil, and may cause bearing failure, settlement localized differential movements, and ground loss or subsidence. However, regardless of where the wind farm is proposed, the risk of liquefaction which results from cyclic loads, has to be assessed in seismic and/or strong swell zones.

The effect of an earthquake on a wind turbine structure can be summarized as follows:

1) Loose to medium dense sandy soil around the foundation may liquefy which will affect the behavior of the foundation. If a monopile foundation is not sufficiently embedded in non-liquefiable soil beneath the liquefiable soil, it may settle, causing tilting or, in the worst-case scenario, bearing collapse. Due to liquefaction, the time period of the wind turbine structure will lengthen, and the structure will shift away from the dominant frequency of the earthquake, generating larger nacelle displacement.
2) Clay soils may soften depending on the layering/ground profile and the earthquake type. It may either dampen or amplify the motion experienced by the structure.
3) Behavior of intermediate soils, i.e., sandy silt or silty sand, or silty clay under seismic loading is difficult to predict and sophisticated element tests and characterization are required. Cyclic tri-axial tests can be carried out to assess the liquefaction potential of the soils.

3.3. Environmental Impacts

Environmental regulations can have an effect on the chosen foundation type. A developer must first secure an environmental permit before beginning construction. It contains a number of terms and conditions designed to reduce or mitigate the environmental impacts of the wind farm project. Regardless of the chosen type of foundation, it will also have an impact on the environment. The influence of offshore wind turbine foundations on the environment is probably confined to the surrounding regions of the foundations and the windfarm site area. The majority of physical processes, such as hydrodynamic and sedimentary processes, may be impacted, however the magnitude of the effects will vary based on the types of foundations. Activities such as dredging for site preparation of gravity-based foundations, or reverse-circular drilling for certain monopiles, are likely to have greater seabed disturbance compared to methods that require low levels of bottom disturbance. Similarly, smaller footprint foundations, such as jacket foundations, are likely to have smaller seabed disturbance than larger footprint foundations, such as gravity foundations. Some of the most important impacts will be presented in this section as major negative effects and main positive effect which is that the foundations may act as artificial reefs.

3.3.1. Underwater Noise and Vibration

Offshore wind farms can cause increased noise levels in the marine environment, which could be harmful. Noises from offshore turbines during operation can reach the water in two ways: either through the air as airborne noise or through the tower and foundation as structural noise. In fact, the structural noise from towers and foundations causes the majority of underwater noise which has two components such as vibration and pressure. The level of underwater noise and frequency is determined by the way the tower is constructed and by the choice of foundation type and material which is steel for monopile and jacket or concrete for gravity-based foundation.

The short-term effects of installing monopile foundations are seen during the pile driving process as a result of the hydraulic offshore hammer used as this activity generates loud underwater noises. The noisy activity will have an effect on animals present in the area, and particular focus is paid to marine mammals. During construction, fish, marine mammals and invertebrates can die or be injured as a result of noises levels and pressure waves, especially caused by foundation installation activities.

Pile driving during the installation of certain monopile and jacket foundations is expected to have similar acoustic effects and it creates the largest effects and other installation methods or activities, effects from reverse circular drilling or vibratory pile driving would likely be smaller than pile driving. Less noise and pressure waves are emitted from dredging site preparation of gravity-based foundation compared to pile driving. In contrast, monopile foundations have been criticized for environmental damage during pile driving installation phase for producing excessive underwater noises and sound pressure level.

3.3.2. Sediment Deposition and Mobility

Discharging dredge material is usually prohibited or controlled to minimize negative effects of direct sediment deposition onto the seafloor. Sediment deposition can also occur during installation if dredged materials from bottom preparation are discharged into the water column or directly onto the seafloor. Such spoil mounds consisting of waste material could persist for many years if they are composed of large particles. Due to the massive amount of waste disposed, dredged material disposal is another important concern. A significant portion of this material is silt, which, if suspended, can locally increase turbidity. Another part consists of fine sand whose displacement changes the bathymetry and sediment composition around the disposal site.

Therefore, gravity-based foundations are also not free of environmental issues, since they usually necessitate comprehensive seabed preparation, and dredging of the seabed disturbs the benthos, potentially affecting the entire ecosystem. For monopile foundations, as the area of bottom disturbance increases with pile diameter, the potential to elevate suspended sediment concentrations and deposition rates may also increase. Additionally, if a monopile is installed with drilling by reverse circulation methods, it can produce relatively larger releases of fine sediments. The largest effects are expected for gravity-based foundations that require more extensive seabed preparation than for other foundation types because dredging is conducted to level the seabed in the footprint before paving the area with gravel or stone for the foundation to sit on top of. Jacket foundations may use piles that are driven through sleeves or legs that would minimize sediment effects due to lower scour potential and smaller wake effects.

3.3.3. Coastal Dynamics

Currents, waves, and winds all have an impact on the land's margins near bodies of water. These processes vary depending on the type of coast and climate. Coasts are comprised of a variety of materials, such as sand, rocky sediments, mud, and biological materials. Coastal habitats are ever-changing. Natural forces shape the shape of a coast, and in many places it responds strongly to changing environmental conditions. Humans also play a role in coastal areas. They settle in coastal areas, farm them, and extract resources. The interaction between such interventions and geological and biological processes can produce a wide range of outcomes. Coasts react differently to natural forces acting on them as a result of these variations. In fact, the history of humanity is closely connected to coastal dynamics.

3.3.4. Artificial Reefs

The seabed around the base of the foundations will often be protected against erosion or scouring by placing rocks and boulders around the foundation. The foundation and the scour protection will constitute a new substratum on the seabed, and mussels and algae will often colonise these new habitats. One of the main environmental impacts from the foundation itself is therefore considered to be the introduction of new habitats and the development of related vegetation and fauna, which again can serve as a food resource for instance birds and fish.

The "reef" effect of the offshore wind turbine foundations is likely to provide a small positive effect, although one which would not be significant in terms of commercial stocks. As a possible attraction effect, the gravel bed around foundations, on the other hand, could be used to create artificial reefs and provide new life, which can be beneficial to the environment. There are potentially beneficial effects from offshore wind project installation and operations due to the creation of habitat in the water column and introduction of hard surfaces by foundations and scour protection.

Compared to monopiles, these potential beneficial effects could be larger with a jacket foundation which can provide the most habitat for species to colonize and become established due to much greater surface area of its lattice and monopile structure would produce the lowest increase in biodiversity. The quantity of scour protection employed would also contribute to the magnitude of an artificial reef effect, hence the amount of scour protection applied for gravity-based and monopile foundations would be the maximum, and relatively smallest for jacket foundations.

3.4. Geotechnical Considerations

Geotechnical investigations are of particular importance because foundation construction costs can grow rapidly when unexpected soil conditions are encountered. The project performance will be assessed by a thorough understanding of the seabed features, as well as descriptions of the various types of soil and rock, their physical and mechanical properties, and their expected behaviors during both the installation and the operation of the turbine. Classification systems are useful to anticipate the range of variability for properties and to plan the geotechnical survey. The geotechnical prospection includes (Figure 27):

1) Preliminary desktop job: bibliography, nearby public works, etc.
2) Regional surveys (usually geophysics)
3) Geotechnical survey (in-situ testing plus sampling and laboratory testing)

Preliminary jobs are based on the geological history of the area, and it serves as a foundation for the scope and method of the geotechnical site investigation when combined with the type, size, and significance of the wind turbine structure. It aims at performing a study of the lithology and tectonic structures in the project area as well as the bedding conditions of the soil.

After a desk study gathering all available information it was decided to perform an extensive site investigation program which consisted of geophysical and geotechnical surveys. Geophysical survey determines seabed topography, morphology and bathymetry, and identifies possible hazards. Echo sounding techniques are used to assess seabed bathymetry and topography, while conventional sonars and magnetometers are used to determine seabed morphology. The geotechnical study must provide soil characterization and properties that will be used in calculation. The material properties, classification and description, shear strength and deformation properties of the soils and rocks are characterized by the geotechnical site investigation. In order to obtain quality in situ test results and quality samples for a wide range of soil conditions, offshore site investigations involve a wide range of equipment and techniques.

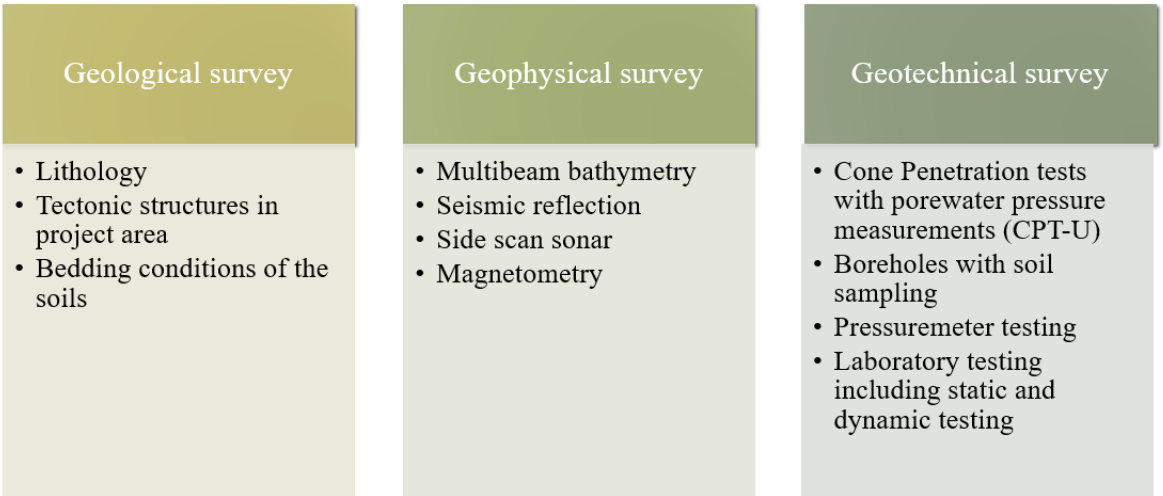

Figure 27. Geotechnical prospection

3.4.1. Soil Classifications

Before constructing any project, the first stage of the procedure is to conduct a soil investigation in order to determine the parameters of the soil as well as to comprehend the behavior of the subsoil. Soils are classified as cohesive or cohesionless. A cohesive soil attracts particles of the same type, origin, and nature. As a result, cohesive soils are soils that stick together. Silts and clays, as well as fine-grained soils, are examples of cohesive soils. A cohesionless soil does not adhere to each other and relies on particle friction (measured by the friction angle). Sands and gravels, often known as coarse-grained soils, are examples of these soils. When it comes to erosion and storm water runoff, cohesive soils are less likely to erode or are more difficult to erode because they do not cling together. As a result, cohesive soils can have a variety of grain sizes, but cohesionless soils can be coarser. It is important to know what kind of soils have on the site to better understand how the soils will react. Figure 28 shows the soil classification system according to the grain size distribution in mm for cohesive soils and cohesionless soils.

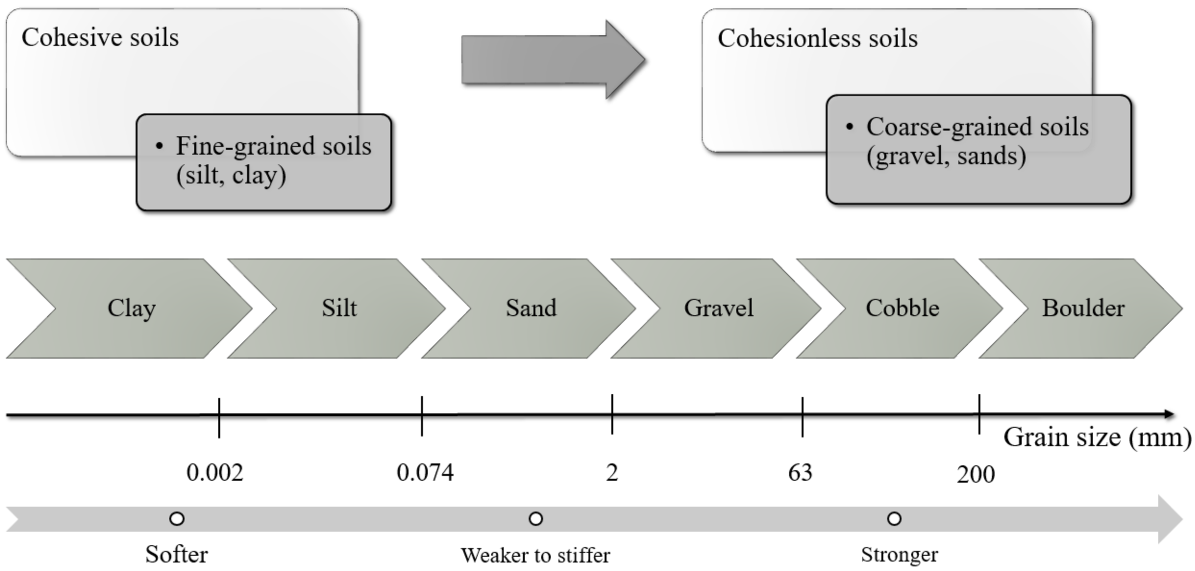

Figure 28. Classification of soil

The rocks are distinguished by the type of rocks and rock mass classification index (RMR, Q-system, GSI, etc). The coarse-grained soils are distinguished sands from gravels by sieving (particle size distribution), and further classified as grading. According to ESCS (European Soil Classification System) based on principles set out in EN ISO 14688-2:2018, the soil is classified as coarse-grained if more than 50% of the total quantity of dry sample remains on sieve size 0.074 mm (Figure 28). The fine-grained soils are distinguished by consistency limits (sedimentation analysis) and additionally classified according to plasticity. The plasticity diagram is used for classifying soil into clay and silt.

It can be seen the differences between fined-grained soils and coarse-grained soils in Table 5. In addition, soil characterizations and properties that will be used in calculation will be shown in Table 6.

Table 5. Differences between cohesionless and cohesive soils

Soil Type	Index Property
Cohesionless soil (Coarse-grained)	▪ Particle size distribution ▪ Shapes of particles ▪ Grading ▪ Relative density
Cohesive soil (Fine-grained)	▪ Consistency limits ▪ Water content ▪ Plasticity ▪ Atterberg limits

Table 6. Soil Characterizations and Properties that will be used in calculation

'Soil'	Note	Strength properties	Deformation properties
Rocks	- Properties depend on the rock and the rock mass index	Hoek-Brown criterion	E, ν (elastic parameters)
Coarse-grained soils	- Almost linear behavior upon failure. - Always drained (except in case of earthquakes or very fast loading)	Mohr-Coulomb criterion φ': friction angle	E, ν (elastic parameters)
Fine-grained soils	- Non-linear behavior. - Much more deformable. - Undrained or drained behavior (depending on the time scale)	Mohr-Coulomb criterion *Drained strength (long-term)* c': cohesion φ': friction angle *Undrained strength (short-term):* S_u: undrained shear strength	- Compression index: Cc, Cs (how much the soil will deform) - Consolidation index: Cv (How long it will take)

The difference between short-term (undrained) and long-term (drained) behavior, depends on the soil (mainly permeability and deformability) and the dimensions of the problem. In the case of fine-grained soils, this time framework can be comparable and even longer than construction time. The soils are complex, variable and uncontrolled materials so that reliability is assessed through factors of safety or more advanced reliability assessment techniques.

In general, soils have various characteristics at different depths. Therefore, in situ tests such as the cone penetration test (CPT) and the standard penetration test (SPT) can be used to predict numerous properties of soils across depth. Standard Penetration Test is the traditional and destructive way of obtaining the soil profile of the tested location in order to determine the parameter and characteristic of the soil. Table 7 describes consistency and relative density of the soil related to the SPT value and therefore, the soil condition of the specific wind farm site can easily be obtained.

Table 7. N SPT value and degree of impact for cohesive and cohesionless soils [33]

Cohesive soils		Cohesionless soils	
N SPT value	Consistency	N SPT value	Relative density
< 2	Very soft	< 4	Very loose
2 - 4	Soft	4 - 10	Loose
4 - 8	Medium	10 - 30	Medium
8 -15	Stiff	30 - 50	Dense
15 - 30	Very stiff	> 50	Very dense
> 30	Hard		

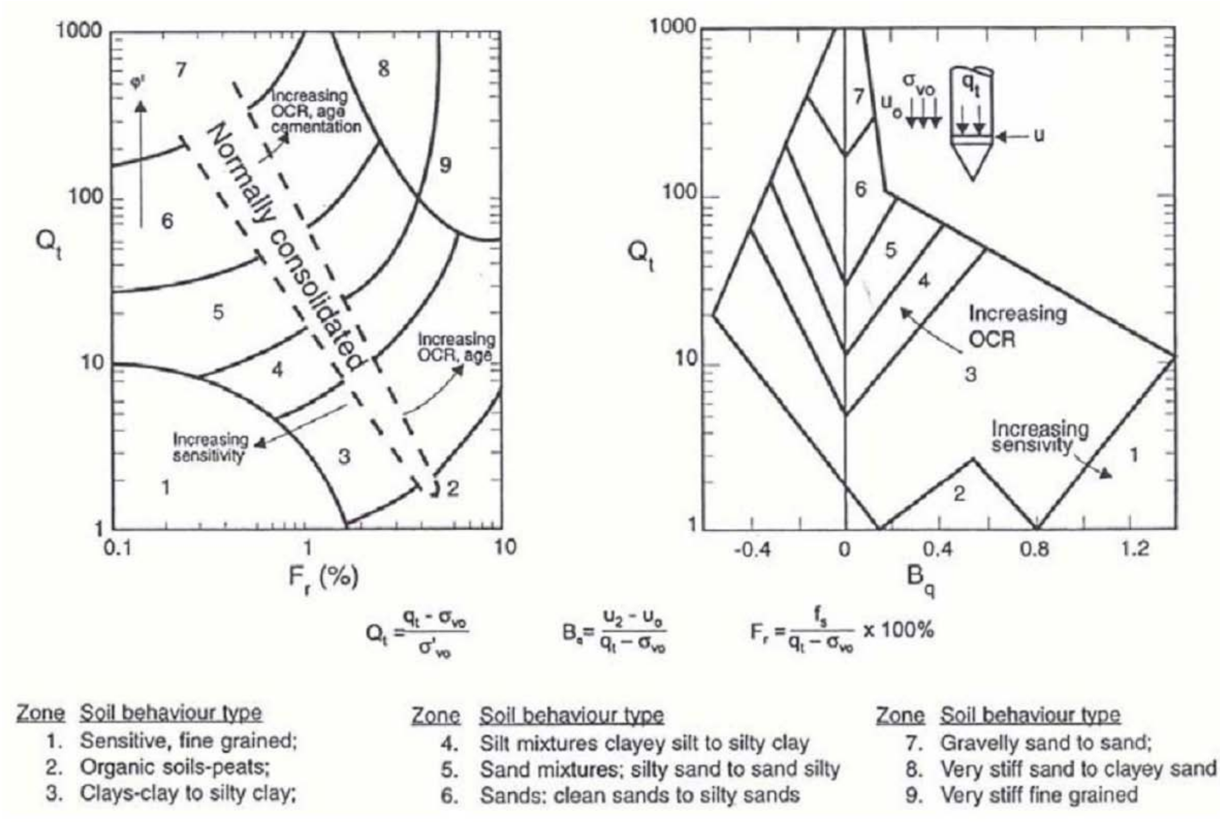

Figure 29. Soil behavior type classification chart [34]

Bearing resistance, friction resistance, and pore water pressure can all be determined using the CPT. All three measurements are used to classify the soil in the classification charts displayed in Figure 29. If only basic CPT data is available, the chart on the left should be used (i.e., q_c and f_s). If pore water pressures are measured, the soil type should be determined using the chart on the right. The tip resistance (q_c) is high in sands and low in clays, whereas the friction ratio (R_f = fs/q_c) is low in sands and high in clays for the most commonly encountered soil types. Clays have usually higher pore pressures than sands.

3.4.2. Soil Conditions

Soil conditions at the foundation play a vital role and at a project site will generally drive the method of installation and constructability aspects. The soil type and properties will influence the location of the structure and it is important for optimizing the cost and to avoid from overdesigning of the foundation. Soil conditions are different at every site.

Monopile installation with pile-driving hammers or vibratory methods is best for marine sediments that are predominantly composed of sands and clays. Monopiles are less practicable and may not be a cost-effective foundation option where there is shallow bedrock or strata with boulders, cobbles, or coarse gravel that prevent the pile from reaching its design depth during driving. Monopiles that are driven are the most flexible to a wide range of soil conditions. In stiff soils, it may be necessary to clear the pile plug or to drill pilot holes to assist driving. In rocky soils, monopiles can be drilled instead of driven. Drilled and grouted piles may be the only feasible foundation option for seabed composed of weak rock or carbonite soils. Special seabed templates and drilling rigs are then required, see in Figure 30. When compared to traditional pile driving, installation activities are frequently more time consuming and costly.

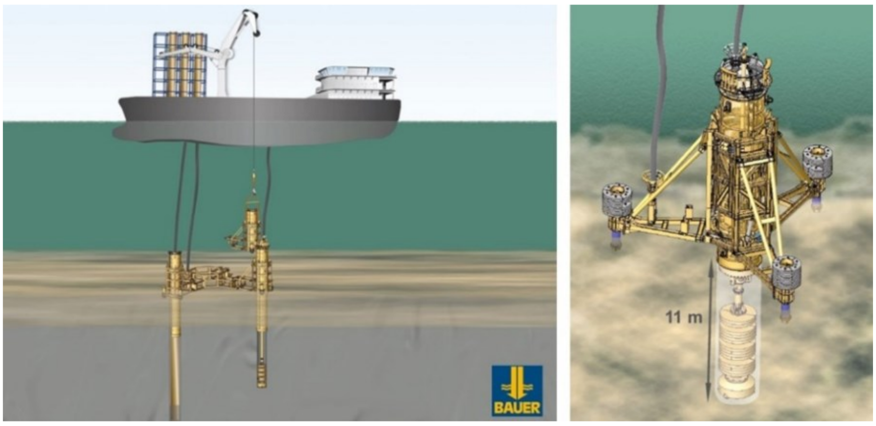

Figure 30. Seabed templates and drilling rigs for drilled and grouted piles (Bauer Renewables)

Therefore, in stiff soils and soft rocks, special attention should be paid to the hazards of premature refusal, potential damage to the pile top at hard levels, and the possibility of pile collapse owing to structural instability and steel fatigue caused by a large number of impacts. A pile drivability analysis should be performed to ensure that the foundation can be installed to the desired depth given the local soil conditions, as well as to assess the impact on soil properties compared to in-situ and laboratory testing performance. Drivability analyses may also aid in determining the type of installation equipment needed.

Jacket foundations are particularly well suited to stiff clays and medium-to-dense sands, which can aid in generating the required friction along the length of the driven piles. They also work well in softer soils, such as silts and clay, but may require longer lengths to develop enough friction resistance. These piles are also effective where very soft sediments overlay stiffer soils or bedrock, provided the piles can develop sufficient tensile resistance. Piles are not well suited for locations with boulders. Soil reactions under the base, due to monotonic and cyclic loads, must be accounted for in gravity-based foundation. These reactions can be quite powerful in stiff soils or soils with very heterometric particle sizes.

For seabed with sand at the surface and strong currents, the possibility of scour formation and the need for scour protection must be considered (often tidal).Significant scour around seabed foundations can develop quickly, represents a major threat on the dynamic behavior and stability of foundations. Other conditions that must be investigated is the seabed topography (sand dunes, etc.) and the presence of embedded boulders.

Table 8. Site Conditions For Different Types of Foundations

Foundations	Water Depth	Soil Conditions
Monopiles	35 – 40 m	- Can be installed in a wide range of soil conditions including weak to stiff fine-grained sediments and loose to dense coarse-grained materials. - Sand and clay preferred. - Not suitable for shallow bedrock or strata with boulders, cobbles, or coarse gravel.

Jacket	35 – 40 m	- Stiff clay and medium to dense sand preferred. - Possible in softer silt and clay, and in very soft sediments overlying stiffer soils or bedrock. - Less well suited for locations with many boulders.
Gravity-based	25 – 30 m	- Flat, featureless seabed - May not be suitable for very soft soil or weak clay. - Rock outcrops, dense sand, medium to stiff clay, bedrock, and strata with cobbles, boulders, or coarse gravel. - Weak near surface marine sediments.

3.4.3. Wake and Scour Effects

Wake effects can vary among the foundation types due to differences in diameter of foundation structures and the volume of impervious structure within the water column and near seabed. Gravity foundations have a wider diameter at the sea floor, for instance, 25 to 30 m compared to 10 m diameter monopiles and would likely result in a larger wake effect at depth, but they typically taper toward the surface, where currents are often stronger, therefore the cumulative wake effect may be similar to monopiles. Wake effects of jacket foundations are expected to be smaller because each individual leg that has a smaller diameter compared to some monopile diameters. However the structures have multiple legs. Compared to monopiles, jacket foundations have a more open structure and may relatively displace a smaller volume of the water column, overall wake effects of jacket foundation types are expected to be weaker than monopile foundations. Due to the lattice structural design, they may have more, smaller-scale turbulence wakes that reduce more rapidly.

The movement of seafloor sediments caused by currents or waves is known as scour which is resulting from the fluid-structure-soil interaction and is a mixture of hydrodynamic and geotechnical processes. Scour can occur immediately after the foundation is installed in the seabed (Figure 31). If the scour happens on gravel or sand, the sediments will most likely form local deposits; otherwise, if the scour occurs in a silty or clay seabed, the eroded material will be taken away in suspension, leaving a depression.

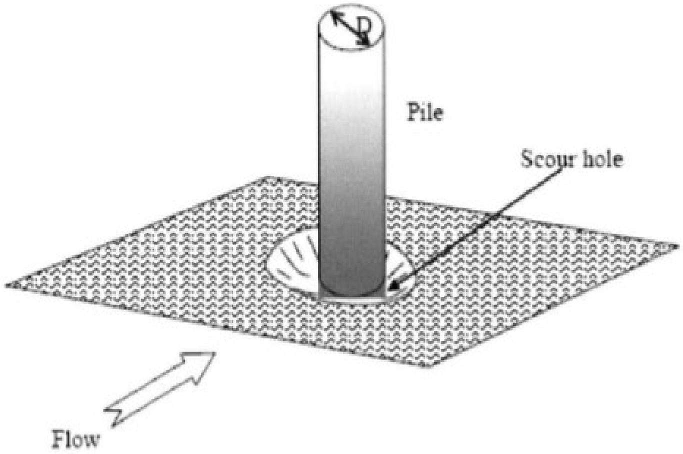

Figure 31. Scour Around a Vertical Pile [DNV-OS-J101, 2004]

The scour effects are specific to the foundation type around which it occurs. The extent of a foundation near the sea floor, which is a combination of the lower foundation diameter and the amount of scour protection used, will affect scour effects. The most significant obstructions near the sea floor are gravity-based foundations, followed by monopile foundations, and jacket foundations. Therefore, larger scour effects would be expected at gravity-based foundations compared to monopiles, due to the wider foundation diameter near the seabed and larger scour protection. The legs of a jacket foundation have smaller leg diameters, less scour protection, and open, lattice-like formations, all of which reduce scour impacts.

Furthermore, scour has an impact on bearing capacity of the pile foundation, the dynamic behavior of the offshore wind turbine system, and may even cause structural instability. Moreover, pile foundation suffers a total loss of lateral and axial resistance down to the depth of scour below the seafloor, as well as a decrease in effective overburden stress, lowering the resistance of the lower soil layers while gravity-based foundations may lose soil from beneath the foundation, resulting in bearing capacity reduction, settlement, or overstressing of the foundation elements. Scour can be minimized with scour mats or site improvements. Scour mats are concrete or crushed rock masses placed around the base of the foundation. They work by preventing the current from moving the soil. Alternatively, the soil around the foundation could be improved and strengthened so that it is not susceptible to scour.

3.4.4. Seafloor Mudslides

Mudslides can occur on any slope on the seafloor, and they can be local or global. Waves or earthquakes can cause mudslides, which can damage foundations. Flowing soil can cause excessive loads on turbine foundations. Also, if the soil around the foundation moves, a loss of capacity can occur, and the foundation can even be undermined. Finally, submarine mudslides can damage seafloor cables. While it is hard to design for these loads, efforts should be taken to account for additional loads and diminished capacities when designing wind turbine foundations.

3.5. Economic Impact

Although the support structure plays an important role in defining the system's reliability and performance characteristics, it also affects costs associated with operation and maintenance (O&M). One of the most essential concerns to answer for offshore wind development is which support structure to use, and this is a problem that must be solved in a multidisciplinary framework that includes both the technical aspects of structural design and the economic aspects of overall cost.

The cost of production and marine operations in general, installation processes, and maintenance of the foundation system in particular, are significant factors which will vary greatly depending on the location of a project. Hence, when selecting the foundation system to pursue, a developer should consider the total initial and lifecycle costs associated with each foundation system. Nonetheless, certain site-specific conditions can necessitate the use of multiple foundation systems in various areas of the wind farm.

The operational expenditures depend only on the site location and not on the substructure type. The cost of maintenance is also a factor in the overall economics of a wind farm and should be considered early on in the development process. Offshore maintenance and operations typically represent a big part of the total costs (e.g. 25–30% of the total lifecycle costs for offshore wind farms). This is nearly as much as the cost of the wind turbines, as well as the costs of construction and installation. The high cost of operation and maintenance is one of the major impediments to the utilization of offshore wind energy. Due to the more irregular and severe nature of the sea conditions, a higher level of technical practice is required, stronger security criteria must be satisfied, and lengthier transit times are necessary. Because of higher average wind speeds and thus better wind energy generation, large wind farms farther off the coast have high expectations (in terms of megawatts per capital).

Maintenance is categorized into preventive and corrective maintenance. Preventive maintenance entails scheduled turbine maintenance at 4 to 6 month intervals, according to a set maintenance schedule. When a malfunction occurs, corrective maintenance is required. In some circumstances, the problem can be resolved remotely. In such situations, a trip to the turbine is necessary. Individual offshore wind turbines now require roughly five site visits per year: one for routine maintenance and three to four for breakdowns. The employees doing the repairs must climb onto the turbines during operation and maintenance (O&M) visits, which are carried out by boat or helicopter. Therefore, the costs of maintaining the turbines can add up over their design life and should be considered in the initial financial rate of return analyses. Distance from the port, availability of boats, weather, and insurance premiums are all important factors to consider when estimating operational maintenance costs.

3.5.1. Potential Impacts during Construction

During the construction phase of the offshore wind farm, there is potential for foundation installation activities to cause water and sediment disturbance effects, potentially resulting in changes in water quality, suspended sediment concentrations and/or sea bed or shoreline levels due to deposition or erosion. These potential impacts include:

- Changes in suspended sediment concentrations and associated water quality due to foundation installation;
- Changes in sea bed levels due to foundation installation;
- Changes in water quality associated with re-suspension of nutrients due to foundation installation; and
- Changes in water quality associated with use of construction materials.

The damage to the soil caused by pile driving activities is another installation loading factor. The cumulative fatigue damage in a piled foundation is derived during the installation phase and also cyclic soil damage that occurs during the operating process.

3.5.2. Local Content

The global offshore wind energy sector has undergone a significant transformation process over the past decade. Today, the value chain for offshore wind is more "global" than "local" with manufacturing of turbines, foundations and main components produced all over the world and shipped to their final destinations. As global energy buyers are pushing for lower prices, there is added pressure on energy companies and offshore wind turbine manufacturers to reduce costs, which spills over to the supply chain. At the same time, there is also a growing "counter-push" from energy buyers and host governments to link the continued expansion of green energy with more local jobs. This means that the demand for local content during the planning, manufacturing, installation, and operation of offshore wind farms is growing louder in many offshore wind markets. As an example, in the U.K., the world's largest offshore wind market, local content is an issue of high political concern. The country's new Sector Deal from 2019 sets out a non-binding proposal to gradually build up the proportion of local content going into U.K. offshore wind farms from a target of 50 percent today to 60 percent by 2030 [35]. In other offshore wind markets such as Taiwan, local content has turned into hard law with offshore wind developers being required to use Taiwanese registered vessels for installation and service of offshore wind farms. Across the board, when tendering for new contracts, offshore wind companies increasingly must balance between buyer and policy demands for low costs vs. high local content.

One of the main opportunities for linking the expansion of offshore wind energy with the creation of local jobs and value-added for host nations is during the installation and O&M of an offshore wind farm. For countries which unlike Denmark, do not have local manufacturing capacity in offshore wind, the installation and O&M phase, by default, becomes the main driver of local economic benefits. Since the production stage of an offshore wind project is the most labor-intensive, it is frequently the focus of local content issues. The combined installation and operation and maintenance stages of an offshore windfarm account for more than a third of the total (direct) manhours required. Further, installation and O&M also comes with several "localized" opportunities for domestic ports and the hinterland of local suppliers, including dock workers, seafarers, transport and logistics workers, technicians, and engineers. Since many of these opportunities often accrue in coastal communities outside of a country's conventional economic centers, these jobs are often of interest to host nations and governments.

3.6. Decommissioning and Dismantling

The decommissioning phase will occur several decades after the beginning of the project and the design criteria phase. When decommissioning there are many things to consider; a few major ones are the foundation type, the specialized equipment and vessels available, the distance to ports, the water depth and the weather conditions. The essential thing is to move every structure as large as possible and then deconstruct on land. This not only saves time, but it also makes the process safer and less risky by removing factors like strong winds and rough waves.

The operations carried out will mostly be determined by the foundation type. Due to the massive lifting necessary as a result of the foundations' considerable weight, specialized vessels are required. Internal access to the foundation is usually acquired once the J-tubes have been removed. The external J-tubes are then removed using a cutting method, and the foundation is cut where specified in the decommissioning program, allowing lifting [36]. There are two proposed removal methods: complete foundation removal or cutting from a certain depth below the mud line and leaving the rest in situ, so that it will not disturb the site's activities [37]. Cutting and leaving the rest in place is usually the preferred method since it eliminates risks, is more cost-effective, and causes less disruption to the site. To hide the hole left once the foundation is completely removed, landfilling will be required. While partial removal does not necessitate this expense, cutting the foundations is usually fairly costly. Depending on the type of foundation, the removal operations will be quite different. If the foundation has scour protection, it must be removed to allow access for the cutting process.

Due to the extreme size of the monopiles, the depth of penetration into the seabed, and the weight of the structure, removing the entire structure is extremely difficult, having significant risks to personnel and significant environmental impact due to deeper excavation and disturbance. Furthermore, specialized equipment is required over longer periods of time, making it a more expensive and less practical option than cutting [38]. The deeper the monopile is cut into the seabed, the more expensive and risky it becomes.

There is conflict about what to do with gravity-based foundations. When it comes time to decommission, a marine habitat will have formed around the foundation. The ballast from the base must be removed and disposed of, which necessitates the mobilization of a suction dredging vessel, with ROVs or divers inspecting that it is done correctly. There are compacted sediments beneath the foundation that must be disaggregated in order for the foundation to be lifted off the seabed. It will then be transported aboard a transport vessel once this has been completed.

By cutting through each of the jacket's legs at a depth below the seabed, the jacket may be lifted in a single lift operation. The legs are composed of a pile driven into the seabed, a stub pipe at the bottom of the structure, and grout filling the space between them. Before the legs are cut, lift rigging must be installed from the jacket to the crane vessel, which is normally done using a diamond wire cutting tool and the assistance of ROVs in order to minimize risks to safety. To reach the cutting location, excavation on the seafloor is required. The structure can be totally lifted and loaded into a transportation vessel after the four legs are cut. While onshore, the steel can be recycled [39].

The cost of decommissioning an offshore wind farm is currently estimated to be 2–3% of total capital cost [40]. Most developers will accumulate this amount over the life of the wind farm to pay for its decommissioning. In fact, beginning accrual at the mid-life point is the preferred strategy because the early years will be dominated by snagging and post-commissioning costs; once these have subsided, end-of-life difficulties can be prepared for [41]. A decommissioning plan must be available at all times due to the possibility that a turbine will need to be removed earlier than expected, and being unprepared in such a large operation would be very expensive. The specialist vessel is critical to the process because it contributes a significant portion of the cost. A breakdown of the decommissioning cost for the fixed bottom offshore wind turbines can be found in Figure 32.

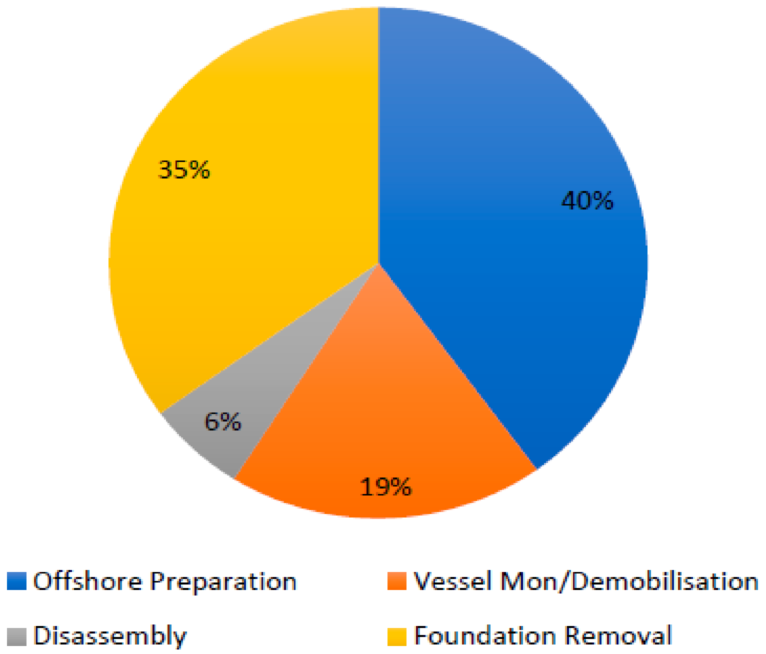

Figure 32. Decommissioning costs breakdown for bottom fixed offshore wind turbines [42]

As previously stated, foundation removal accounts for nearly half of the total cost because disassembly takes the greatest time, it is the most crucial task.

4. PROPOSAL OF A DECISION MATRIX

Deployment of offshore wind turbines in constantly increasing water depths has raised the issue of the appropriate selection of the most suitable foundations-structural supports system. In this study, the aim is to select the most optimum foundation-structural support in locations 30-50 m, among three most commonly used foundation systems for offshore wind turbines such as monopile, gravity-based, and jacket. Based on this aim, a decision matrix appropriate to the problem, which also incorporates the criteria established, will be chosen and structured.

4.1. Multi-Criteria Decision Making Methods (MCDM)

A multi-criteria decision making method (MCDM) can be employed, capable of evaluating the best from a set of alternatives in this decision making process which has conflicting multiple attributes. Attributes are also known as design criteria or decision criteria in general. MCDM methods have been widely applied in decision making for sustainable energy because of the complexity of socio-economic and biophysical systems and the multidimensionality of the sustainability target [43]. The purpose of MCDM is to provide support to the decision-makers in the process of making the choice between alternatives. As a matter of fact, practical problems are frequently characterized by several conflicting criteria, and there may be no solution that satisfies all criteria at the same time. As a consequence, the solution is a compromise solution based on the preferences of decision-makers.

4.2. TOPSIS Method

Various MCDM methods are considered to account for the complexity of decision making under imprecise and ambiguous situations, especially in the field of renewable energy. When there are multiple options from which to choose, the situation becomes even more complicated; in these circumstances, not only must each alternative be considered, but all of the alternatives must be treated consistently to ensure that a final comparison of all of the alternatives is justified. The decision matrix is a simple decision-making tool that can be very effective in making complex decisions, especially when there are multiple options to choose and several criteria of varied importance that need to be considered in making a decision. The TOPSIS (Technique for Order Preference by Similarity to the Ideal Solution) method is a powerful

MCDM method used commonly as a qualitative tool in design engineering to analyze alternatives, and has been chosen from the different types of weighting methods because its basic concept is perfectly suited to this analysis. Its basic principle is that the best alternative should be the furthest away from the Negative Ideal Solution (NIS) and the closest to the Positive Ideal Solution (PIS). The closeness index is used to determine the final ranking. This whole process would eventually lead to achieving the most suitable foundation system in the investigated locations 30-50 m water depth. The TOPSIS procedure consists of the following a sequence of simple steps as shown in Figure 33.

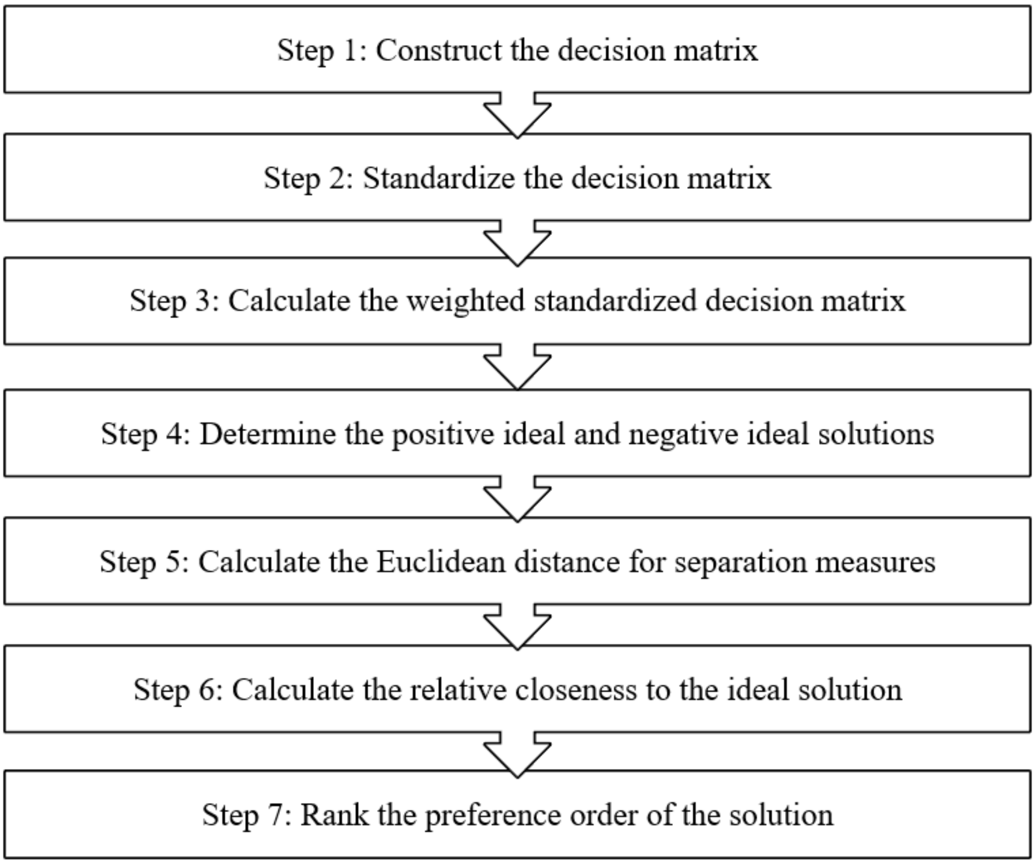

Figure 33.TOPSIS Method Flow Chart

The following are the requirements for using this tool:

- A well-defined list of alternatives to be rated in order to make a selection choice;
- A well-defined set of criteria that will influence alternative selection;
- A set of weights that estimate the degree of importance criteria; and
- A reference against which comparisons will be made.

4.2.1. Creating Decision Matrix by Identifying Alternatives and Attributes

When creating a decision matrix, it is important to understand the problem and its implications. Since this study aims to achieve the most suitable foundation system out of the three most commonly used support structure configurations (monopile, gravity-based, and jacket) though they each have their advantages and disadvantages, there are three alternatives (m = 3) and five main criteria which branched into twenty-three sub-criteria (n = 23) have been selected for this problem and listed in Figure 34.

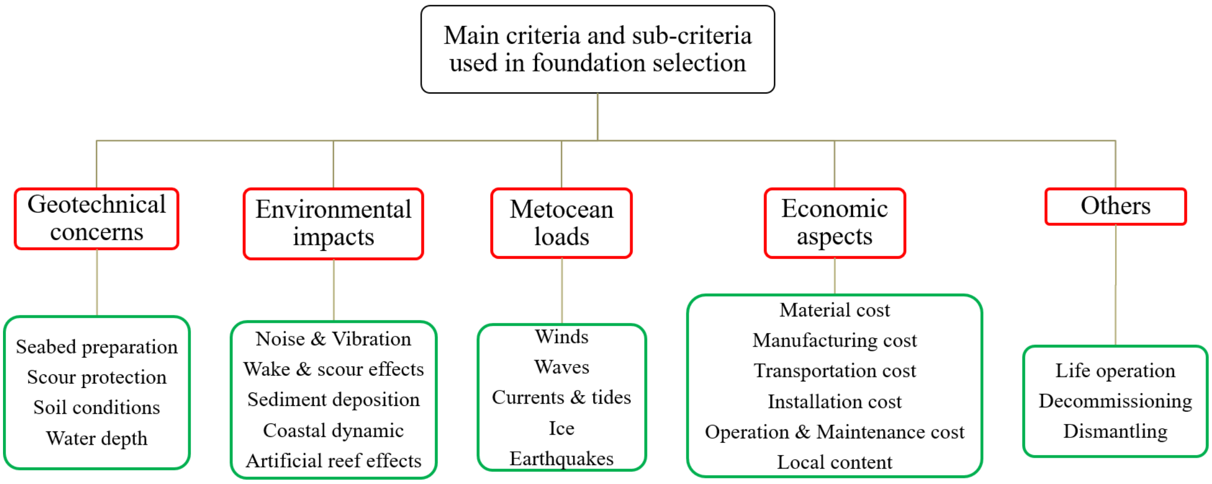

Figure 34. Criteria used for selection of most suitable offshore wind turbine foundation systems

Once the one has identified these aspects, the decision matrix can be built by rows and columns. It is a good idea to create by listing all the decision alternatives as columns and the relevant selections attributes affecting the decisions as rows. The decision matrix is performed in two phases, focused on the attributes weights to determine the relative importance of the different criteria used in the process and attributes ratings for each attribute of each option to make decision about selection.

4.2.1.1. Estimating Weighting Factors for Each Criteria

The decision matrix is based on the assigning values, which act as weights. Weighting factors must be determined to reflect the priority among design criteria. Therefore, it is an important consideration for each specification to indicate the relative importance and to assess the impact on the decision. Weights influence directly the decision making result and are based on the practical engineering expertise of the decision makers; consequently, the more experienced the decision makers are, the more objective the result. For this study, the weighting factors will be based on the experience of the experts in the offshore wind industry. These values are always a fixed number, generally called weighting factors. The ranking and all other procedures are carried out based on the assigned weighting factors. Therefore, some sort of weighting scale is normally assigned to account for this variation.

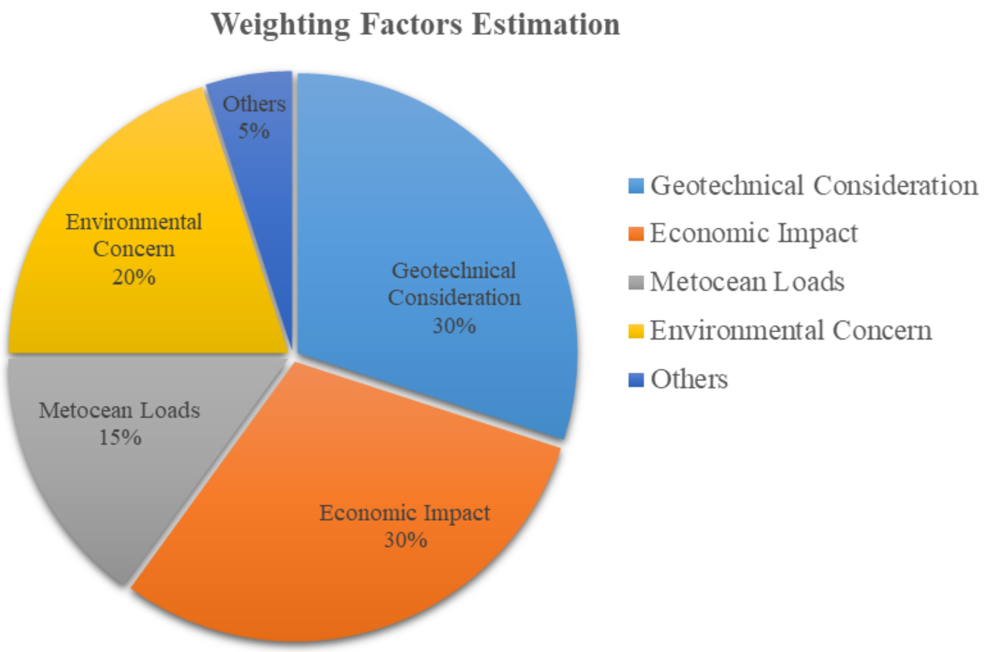

Figure 35. Weighting factor estimation for main criteria

When the results from different locations are compared, the sum of these weighting factors should be the same for this set of values. Therefore, total sum of the weighting factors depending on the characteristics of each type of foundation is adopted as fix parameter (100%) regardless of the location, with geotechnical considerations being 30%, economic impacts that contribute largely to the overall cost being 30%, environmental concerns being 20%, metocean loads being 15%, and life operation, decommissioning, and dismantling being 5% as can be seen in Figure 35. Geotechnical issues related to soil conditions and properties as well as economic impacts with respect to plant cost impacts and overall LCOE are considered to be the two most critical criteria in selecting the offshore wind turbine foundation systems according to the location of a project. Then, the other factors will follow the smaller amount of percentage with respect to their importance. The weighting factors from 1 through 10 are assigned to individual design criteria Figure 36 and usually, values are assigned as shown in Table 9.

Table 9. The fundamental scale for weighting factors

Degree of Importance	Values
Critical	[8,10]
Prioritized	[6,8)
Important	[4,6)
Essential	[2,4)
General	[0,2)

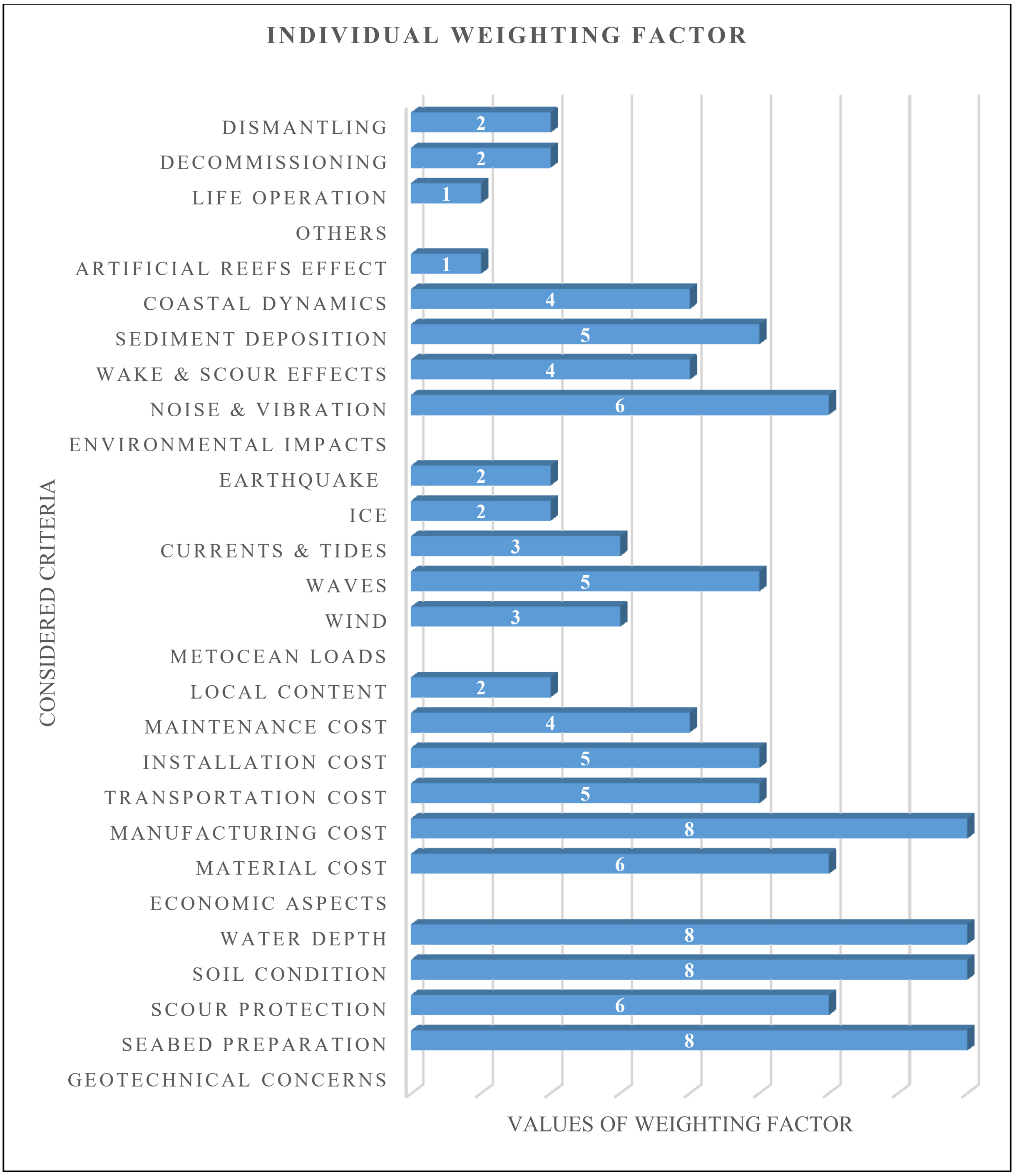

Figure 36. Individual weighting factors for considered criteria

4.2.1.2. Evaluating Rating Factors for Each Criterion

Now, the three alternatives have to be rated against the criteria on a predetermined scale. The aim of decision making method is to assist decision-makers in making decisions between alternatives. Therefore, the decision makers have to select the rating factors based on their experiences and preferences accordingly the wind farm characteristics. Since there is not a large variation between the options, a scale of from 1 through 3 is applied each criterion individually, where three is the best because higher values represent more preferable options for each value. Also, a slight adjustment in the rating factors could lead to different results and therefore, decimal numbers shall not be considered. However, choices of rating vary depending on the characteristics of the wind farm.

4.2.2. Determination of Standardized Decision Matrix

After the formulation of a design matrix with ratings for every attribute of each alternatives, standardization follows as:

$$\overline{X_{ij}} = \frac{X_{ij}}{\sum_{i=1}^{m} {X_{ij}}^2} \qquad \text{Eq. 4}$$

Where X_{ij}: Value of the component in *i*th row and in *j*th column of the decision matrix

m: Number of alternatives

4.2.3. Determination of Weighted Standardized Decision Matrix

After assigning the weighting factors and standardization, the next stage calculates the degree of satisfaction with respect to all the attributes of respective alternatives. This ensures that the more important considerations are being given more weight, which will ultimately help the decision-maker to select the best option. The weighted standardized matrix follows as:

$$V_{ij} = \overline{X_{ij}} \times W_i \qquad \text{Eq. 5}$$

Where W_i: Weighting factors in *i*th row of the decision matrix

4.2.4. Determination of Positive Ideal and Negative Ideal Solutions

The positive-ideal solution contents the maximal benefit solution. The negative-ideal solution represents a minimal benefit solution. Having obtained the Weighted Standardized Decision Matrix, the PIS (A^{+}) and the NIS (A^{-}), the ideal solutions are determined as:

$$A^{+} = \left(V_1{}^{+}, \dots, V_i{}^{+}, \dots, V_n{}^{+}\right) = \left\{\left(max_i\ V_{ij} \mid i = 1, \dots, n\right) \middle| \ j = 1, \dots, m\right\} \qquad \text{Eq. 6}$$

$$A^{-} = (V_1{}^{-}, \dots, V_i{}^{-}, \dots, V_n{}^{-}) = \left\{\left(min_i\ \ V_{ij} \mid i = 1, \dots, n\right) \middle| \ j = 1, \dots, m\right\} \qquad \text{Eq. 7}$$

4.2.5. Calculation of Euclidean Distance

Proximity of alternatives to the positive ideal solution (S_J^{+}) and separation from the negative ideal solutions (S_J^{-}) can be obtained using the square root of squared distances in the imaginary attribute space given in following equations.

$$S_J^{+} = \sqrt{\sum_{i=1}^{n}\left(V_{ij} - A_i^{+}\right)^2}, \qquad S_J^{-} = \sqrt{\sum_{i=1}^{n}\left(V_{ij} - A_i^{-}\right)^2} \qquad \text{Eq. 8}$$

4.2.6. Rank the Preference Order by Relative Closeness Index of Each Solution

Finally, the ranking of the alternatives will be realized by calculating the relative closeness of each solution from the PIS (S_J^{+}) and to the NIS (S_J^{-}). The relative closeness of each solution to the ideal (C_j) will be estimated as follows, and the most favorable will be the one closest to 1.

$$C_j = \frac{S_J^{-}}{S_J^{+} + S_J^{-}} \qquad \text{Eq. 9}$$

At this point, the option with the highest score is judged the best one, although other options may be chosen.

5. VALIDATION OF THE TOOL WITH WIND FARMS IN OPERATION

This section will investigate current offshore wind farms in order to give continuity to the validation of the proposed decision making methodology discussed in Section 4. During this step of validation, the data acquisition and collection of them are one of the major works. The data were at least double-checked from various sources. The proposed methodology is then applied to the three different wind farms such as "Thornton Bank I" located in Belgian waters, "Beatrice" located in United Kingdom, and "Horns Rev 3" located in Denmark respectively. Three wind turbine foundation types are being considered, including concrete gravity base structures, driven steel monopiles, jackets. Undoubtedly, the improper foundation choice might have been avoided if it had been assessed in the proposed decision matrix based on criteria which has been presented in previous section 3, which would have served as a preliminary estimate of the most favorable types of foundations according to the characteristics of the wind farms.

5.1. Thornton Bank I Offshore Wind Farm

The variety of viable places for offshore wind farm development is limited due to the relatively small area of Belgian territorial seas and the huge number of restricting constraints. Following a review of near-shore projects, public decision-making culminated in the identification of a zone for wind, water, and current energy generation in 2004.

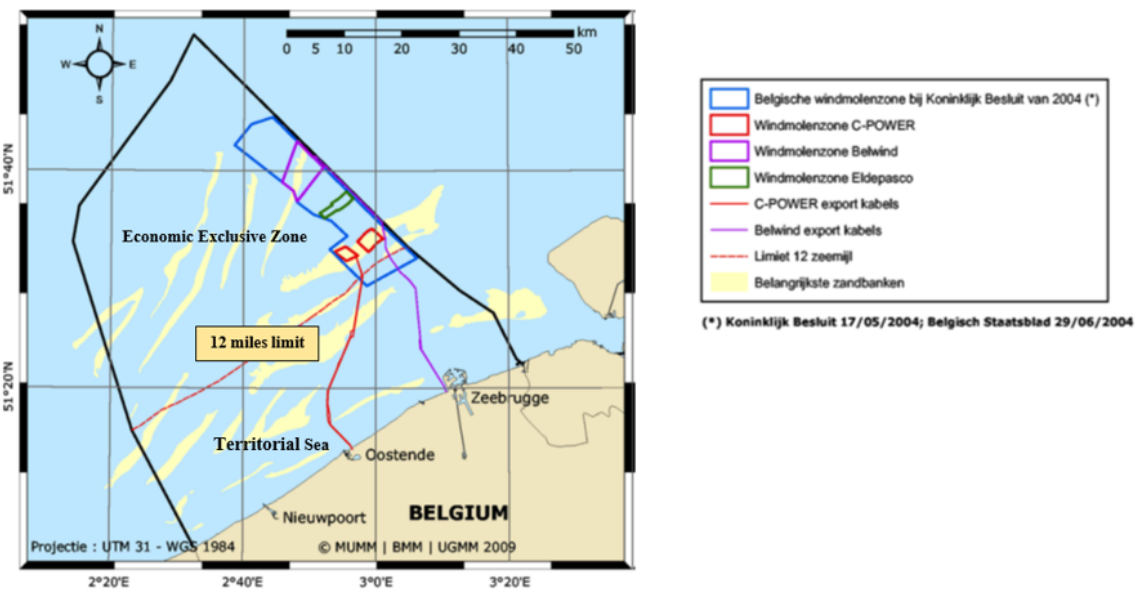

Figure 37. Territorial Sea and Exclusive Economic Zone of Belgium [44]

Within this zone, C-Power's preference was for a location outside the 12-miles zone. The Thornton Bank, one of the many sandbanks characterizing the Belgian section of the North Sea, turned out to be the most appropriate location for the development of a distant offshore wind farm. The Thornton Bank Wind Farm, the first offshore wind farm in Belgian waters, is located in the North Sea, some 30 kilometers off the Belgian coast. Along the Belgian-Netherlands boundary, a 238-square-kilometer zone has been set aside for wind farm construction. This zone has seen the construction of 341 wind turbines with a total capacity of 1,775 MW, grouped into seven wind farms, since 2008.

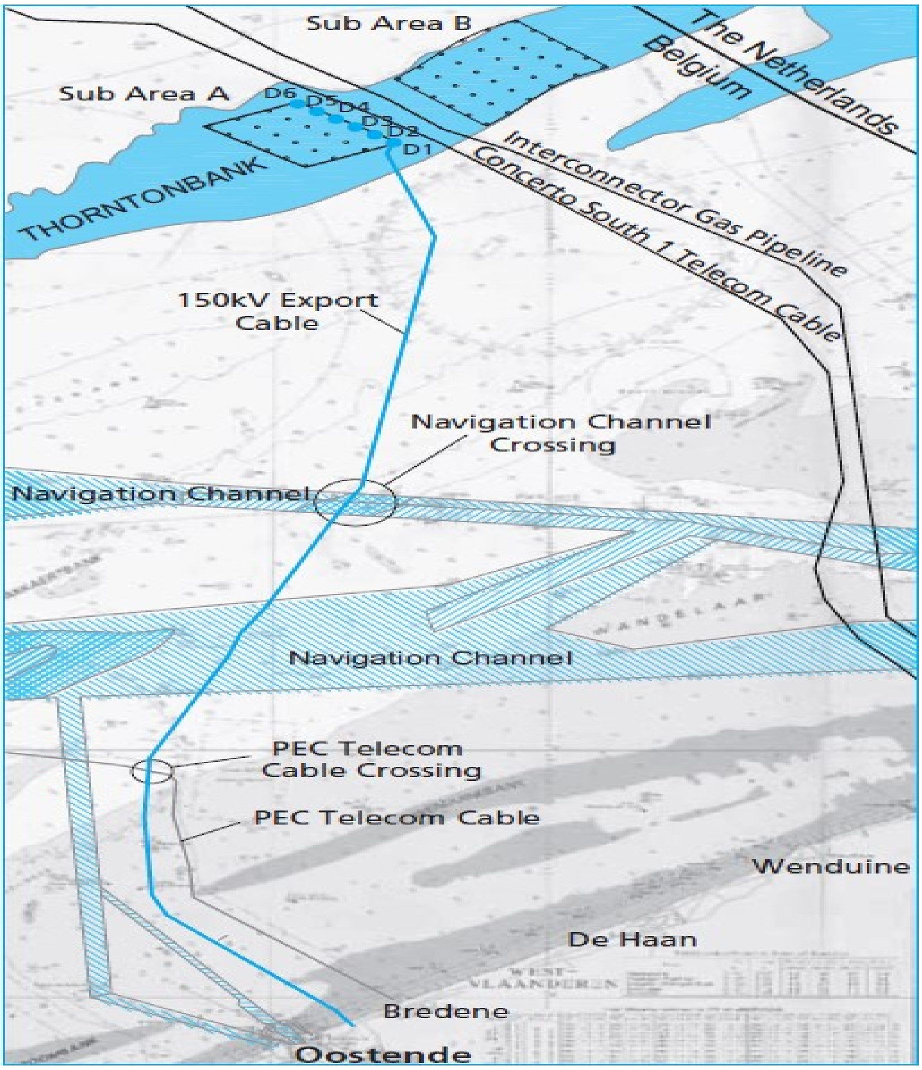

Figure 38. Location of the first six wind turbines and cable trajectory [45]

During the first phase of the project, the six first wind farms were built on row D of sub-area A. The distance between these wind turbine generators (WTGs) is 500 meters. The selected WTG is the Repower 5M model with a rotor diameter of 126 m, one of the largest and most powerful wind turbines in the world, specifically designed for offshore installation. The rated power of the WTG is 5MW, which is achieved at a rated wind speed of 13.0 m/s. The 6 WTGs have produced 4.6 TWh of electricity in 2019, representing about 6% of Belgium's total electricity consumption [46].

5.1.1. Geotechnical Considerations

5.1.1.1. Bathymetry

The bathymetry of the sub area A in which the wind power installation for 6 WTGs of phase I is analyzed. The 6 positions to be realized are D1 to D6. The irregular profile of the sandbank with dunes is clearly shown in Figure 39. It is observed that a sequence of sandy shallows with depths ranges from approximately -17 m TAW at D1 position to -23 m TAW at D6 position [47].

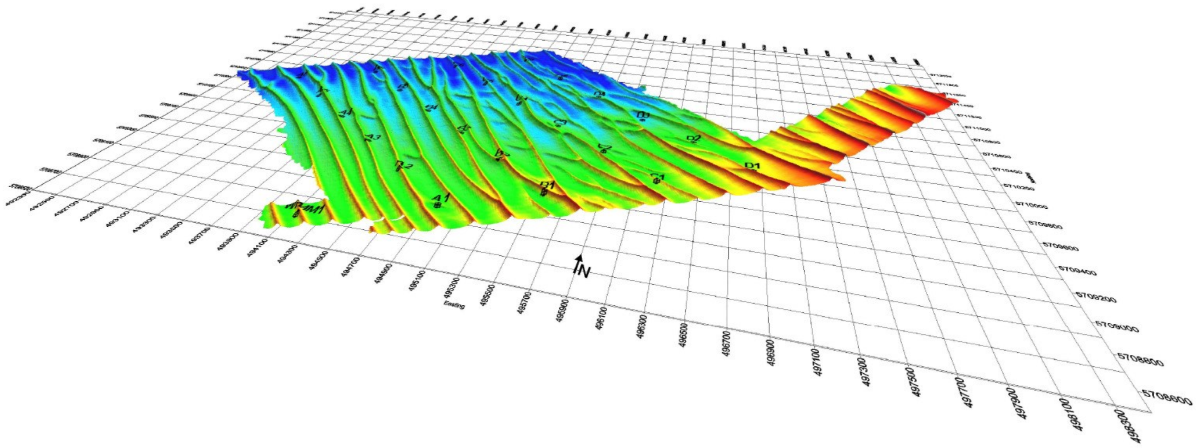

Figure 39. Bathymetric Survey [47]

Since the Thornton Bank is a sandbank with enormous dynamic dunes, leveling the seabed at the wind turbine location is required before the foundation can be installed. To withstand the strains generated by the offshore environment and the wind turbine, concrete gravity-based foundations rely on their mass, which includes ballast. For GBF foundations, an area of seabed may need to be dredged in order to provide a levelled surface upon which they are installed. Regarding the seabed preparation in this point, gravity based foundation is least unfavorable than monopile and jacket foundations. Seabed preparation may also be needed for installation of a concrete caisson. Other foundation types do not require any seabed preparation; however, jackets may require pre-dredging prior to piling for each jacket leg.

5.1.1.2. Seismic Loads

From the seismic reflection survey, the top of tertiary layers and some deeper reflectors clearly could be defined. Figure 40 shows a section along the D1-D6 line and one can see that an incision occurs in the top of the tertiary formations. This is a paleovaley which is filled with quaternary sediments. Such local effects are very important to be recognized and require extra attention on order to define soil layering and characteristics at the position of the WTG's located in these zones. In Figure 41, a 3D view of the top of the tertiary layers is given, which allows for a better understanding of the position of paleovaleys and the position of the tertiary formations with regard to the WTG locations.

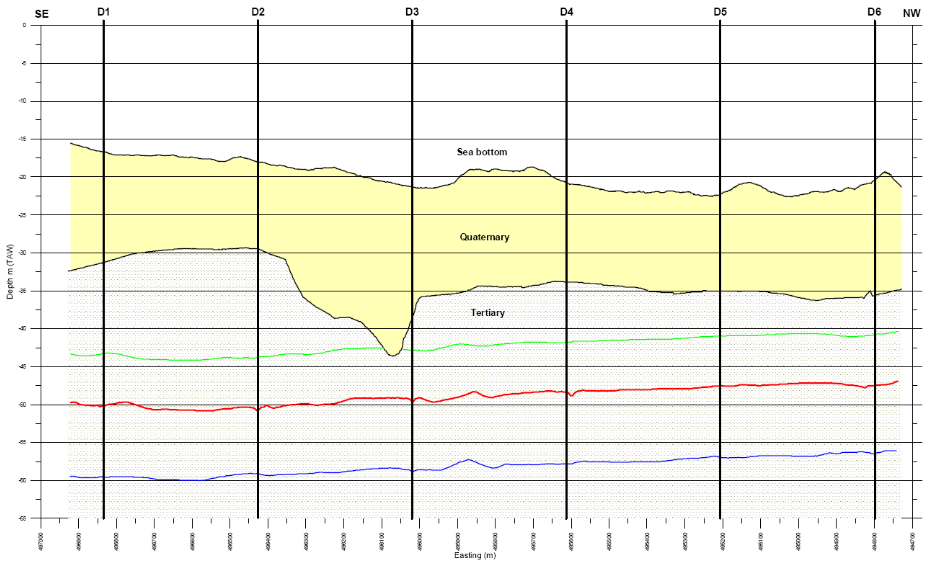

Figure 40. Seismic reflection interpretation – Line D1-D6 [47]

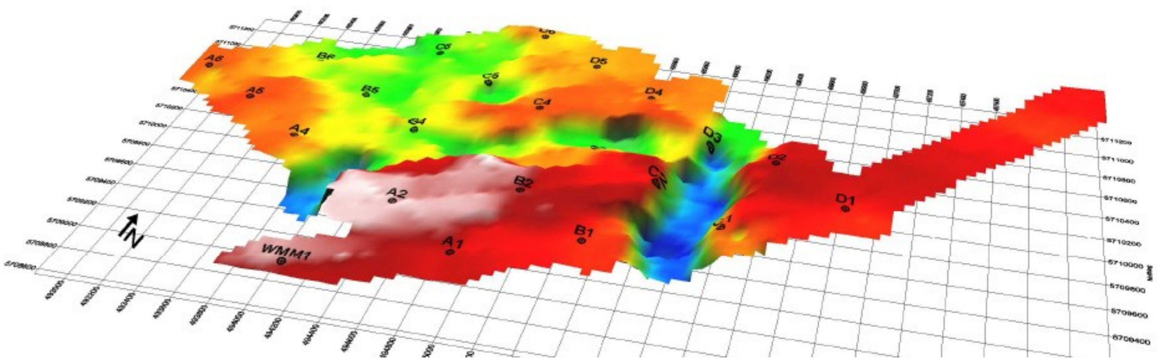

Figure 41. 3-D view of the top of the tertiary formation [47]

The loose to medium dense sandy soil surrounding the foundation may liquefy, affecting the foundation to behave differently. A monopile foundation may settle if it is not sufficiently embedded in non-liquefiable soil beneath the liquefiable soil, causing tilting or, in the worst-case scenario, bearing collapse. In this case, a jacket foundation will be the ideal solution.

5.1.1.3. Soil Condition

On the basis of the seismic results, in general the following soil layers can be distinguished from top to bottom [47]:

- Coarse to medium dense (loose at the top) sand with a gravelly horizon at the bottom,
- Stiff clay (tertiary layer), at the bottom a transition to more silty or sandy material,
- Dense sand, slightly silty to clayey,
- Very to extremely dense (aged) slightly silty to clayey fine sand with seams or pockets of clay,
- Stiff tertiary clay down to the end of the boreholes.

Regarding the rating factors in the decision matrix, monopiles and jackets are equally preferred for such kind of soil conditions. Gravity-based foundations, on the other hand, necessitate seabed preparation, which includes the dredging of foundation pits, the installation of crushed-rock foundation beds, and the construction of scour protection to guarantee that appropriate backfill remains in place. These dredging and dumping activities damage the seabed at and around the disposal sites as it becomes submerged in sediments; in the channels as a result of continuous removal of sediments; and in a larger surrounding area due to a change in sediment composition.

Monopile diameters rise in considerable water depths in proportion to average depths, resulting in larger and deeper scour holes. A jacket foundation, as opposed to monopiles, has the advantages of serial production and easy logistics. The jacket foundations are driven into the seabed using pre-piling. The jacket foundation's smaller piles do not have scour protection, unlike monopiles.

5.1.2. Economic Aspects

Thornton Bank I is one of the most technically intriguing offshore wind farms due to the gravity-based foundation used and the significant depths in the concession area ranging from 18 to 24 meters. These GBFs are hollow concrete constructions that rest on the seabed and are filled with sand. The GBF is stable due to its weight. The GBFs were built in the port of Oostende before being transported to the Thornton Bank. To begin with, the distance to the seaside has a detrimental impact on construction expenses. Out of the various Belgian ports located in the area, Oostende, located just over 30 km, was selected as the service port for the construction and maintenance work. In addition, the installation cost of gravity-based foundations will be extensively higher than other types of foundations. Moreover, North Sea installations of jacket foundations have reported ongoing grout joint issues, causing long periods of maintenance downtime to sustain structural integrity. Secondly, this distance has a negative influence on the losses associated with the transport of foundations. Therefore, jacket will be the most expensive one compared to other types of foundation.

Regarding the manufacturing cost, monopiles are easiest to fabricate and to install in such water depth at Thornton Bank wind farm among three types of foundation, however, to ensure modal performance in deeper seas, they require increasing amounts of material tonnage, which increases the cost of installation. By extending the substructure's footprint and concentrating mass away from the neutral axis, lattice substructures can provide needed structural rigidity, albeit at the cost of more time-consuming manufacture than monopiles. The GBF was chosen because of the general increase in steel prices on world markets, as well as questions expressed about the viability of pile drive.

5.1.2.1. Local Content of Belgium

Multipliers have been used to estimate future gross domestic product (GDP) and employment effects based on a detailed mapping of the various components of constructing and operating windmills, as well as the expenditure requirements across the value chain over time: the expenditures in the construction of the windmills (CAPEX) create a final demand stimulus for the products and services required to realize that expense. These products and services come from Belgium as well as other countries. Similarly, the operation and maintenance of windmills implies an increase in demand for products and services with a higher domestic content. Figure

42 describes the estimated contribution of Belgian industry to the construction of offshore wind projects in Belgium.

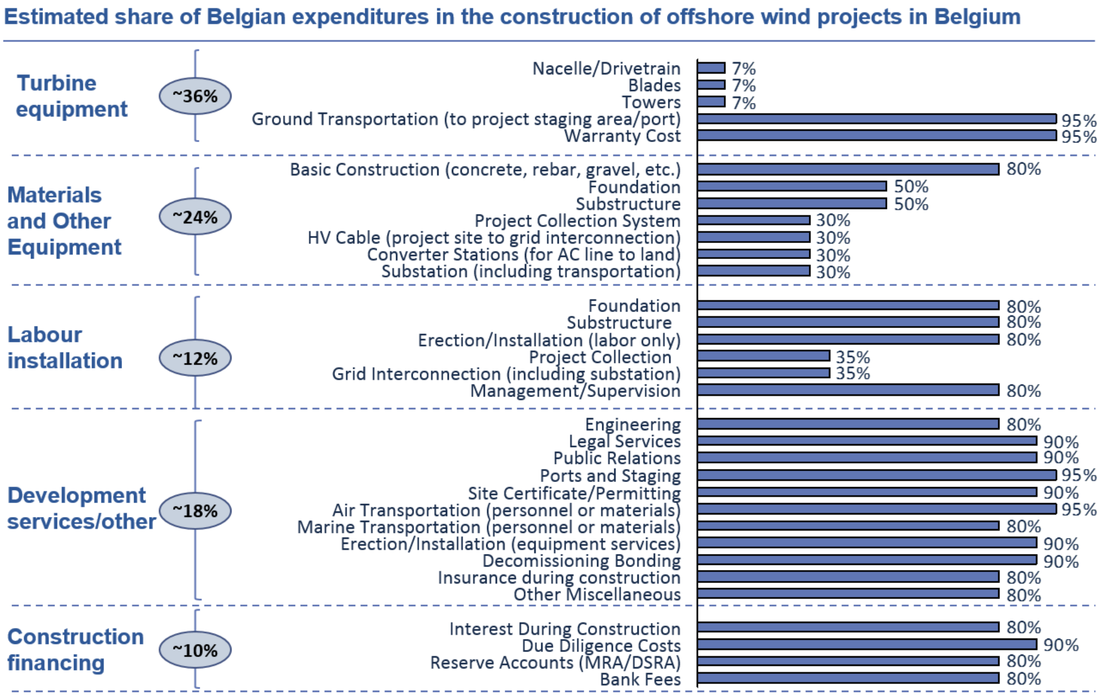

Figure 42. Estimated share of Belgian expenditures on the construction of offshore wind projects in Belgium [48]

For offshore wind projects in the rest of Europe, the share of the Belgian industry has also been assessed. For basic construction, Belgium demands 80% of concrete for the material and 50% for the foundation and substructure (see in Figure 42). It can be noticeable that gravity based structures have a tendency to build domestically due to the local content of Belgian industry.

5.1.3. Metocean Data

The maritime climate and metocean data should be examined according to the approach. Meteorological data (wind speed, wind direction, wave height, wave period, tide, pressure, temperature, visibility) has been discovered in real time on C-Power's offshore transformer platform are available on "meteo.c-power.be". The actual measurements taken at the C-Power OTS meteorological station in the area are shown in the following figure.

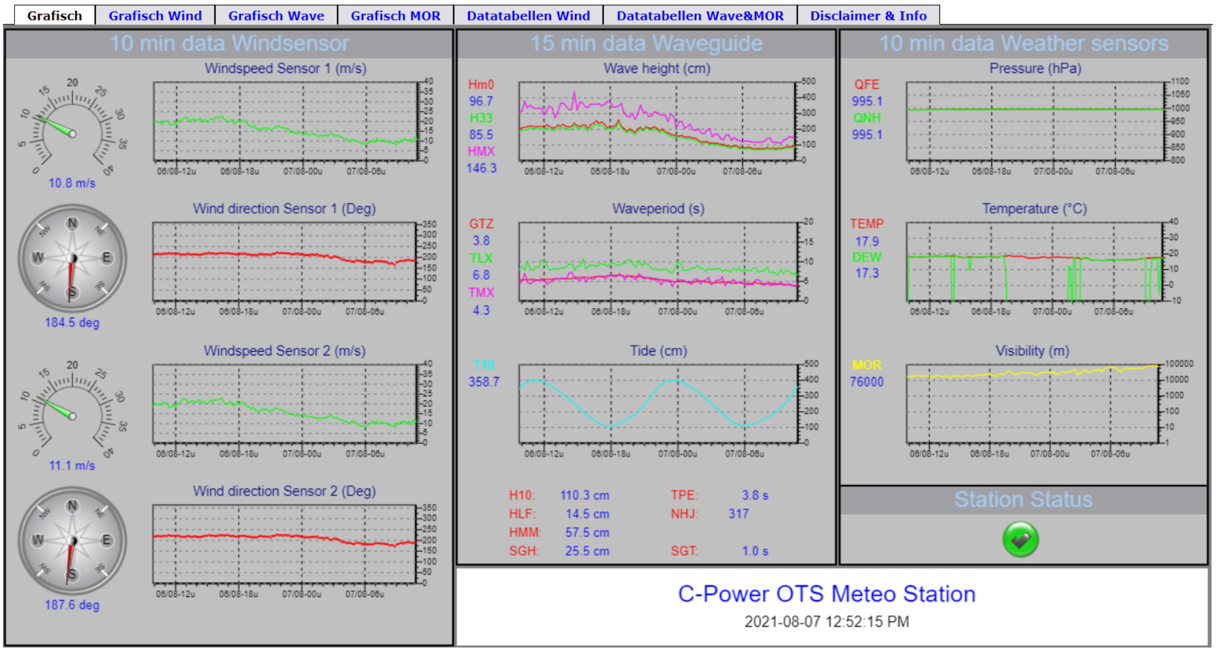

Figure 43. Maritime climate data from C-Power OTS Meteo Station

The significant wave height is around 4.5 m, the maximum wave period is around 8 s and the tidal run is 4 m which corroborates the results listed on map. Regarding wind speed and wind direction, the predominant wind direction is west-south-west. It is observed how the average expected wind speed over Belgian waters at the height whose elevation is closest to the hub height current of offshore wind turbines is between 8 and 11 m/s, which means the area is interesting from the point of view of wind resource.

5.1.4. Environmental Concerns

5.1.4.1. Underwater Noises and Sound Mitigation Measures in Belgian Waters

The construction of a new wind farm in the Belgian part of the North Sea nowadays relies on the installation of lower numbers of large steel monopiles which has 7 m diameter or greater. Because of the size of these larger monopiles, a large hydraulic hammer is needed to drive the steel piles 26 to 47 meters into the seafloor [49]. As a result, a significant amount of energy is introduced underwater in the form of sound, which must be absorbed by noise mitigation devices (insertion loss) in order to meet national regulations. In Belgium, impulsive sound should not exceed a zero to peak level of 185 dB re 1 µPa at 750 m distance from the source Belgian MSFD Regulation State (2018). In order to comply with Belgian State (2018), it is advisable to, at least, test on site the combination of sound mitigation measures before the construction works start and not rely only on predicted efficiency. Another possibility is to reduce the size of the monopiles used, or to return to jacket designs. Using smaller monopiles reduces the maximum emitted underwater sound to levels that can be efficiently reduced by today's mitigation systems, resulting in levels that are lower than the Belgian MSFD limits. Another option is to use new methods, such as blue piling technology, or to reconsider using different foundations.

5.1.4.2. Seabed Environment

The recurrent trend of more pronounced responses at Thornton Bank confirms the hypothesis that impacts can be site-specific and may differ between the three different turbine types (monopiles, jackets and gravity-based foundations). Thornton Bank could provide direct evidence of their potential effects. Wind turbines and especially, jacket-like foundations seem to form a very favorable substrate for Mytilus edulis colonization [50, 51, and 52]. In addition, finer and organically enriched sediment was found at the very close distances. While these results confirm the proposed impacts of blue mussels, it also shows that the presence of these organisms has the potential to expand the artificial reef-effect to areas beyond (> 30 m) the construction itself. Turbine-related influences on habitat characteristics such as sediment refining were discovered during two years of monitoring, with greater fine sand percentages at extremely close distances (i.e. 50 m) surrounding the jacket foundations at Thornton Bank.

Organic enrichment was also observed around the jackets in 2017, but not in 2018. On the other side, an opposite trend of lower average organic matter content was observed at very close distances around the monopiles at Belwind. In terms of benthic responses, general trends include higher densities and diversity in close proximity to the turbines, with effects most pronounced around the jackets at Thornton Bank, but there are indications that a similar process is occurring around the monopiles at Belwind. However, considerable variation was also found in terms of densities, richness and assemblage structure. Additionally, some hard substrate associated assemblages were found at very close distances around the jackets at Thornton Bank, which provided insights in the potential effects of epifouling communities on the surrounding infaunal macrobenthos.

5.1.5. Applying to Decision Matrix Based on Data Acquisition

Based on the proposed methodology, the initial Decision Matrix is defined as attribute weights as well as attribute ratings for three alternatives which were justified from Section 5.1.1 to 5.1.4:

Table 10. Initial decision matrix for Thornton Bank I Wind Farm

Decision Matrix		*RATINGS FOR THORNTON BANK I*		
Criterion	**Weighing factor**	**Monopile**	**GBS**	**Jacket**
Geotechnical Concerns				
Seabed preparation	8	3	1	2
Scour protection	6	2	1	3
Soil Condition	8	3	1	3
Water depth	8	3	2	1
Economic Aspects				
Material cost	6	1	3	2
Manufacturing cost	8	3	2	1
Transportation cost	5	3	2	1
Installation cost	5	3	1	2
Maintenance cost	4	2	3	1
Local content	2	2	3	1
Metocean Loads				
Wind	3	3	3	3
Waves	5	2	1	3
Currents & Tides	3	2	1	3
Ice	2	1	2	3
Earthquake	2	2	1	3
Environmental Impacts				
Noise & Vibration	6	1	3	2
Wake & Scour Effects	4	3	1	2
Sediment Deposition	5	2	1	3
Coastal Dynamics	4	2	1	3
Artificial Reefs Effect	1	1	3	2
Others				
Life operation	1	1	3	2
Decommissioning	2	2	1	3
Dismantling	2	2	1	3
Total	**100**			

The standardized Decision Matrix is obtained in APPENDIX A1 and the Weighted Standardized Decision Matrix is derived. Then, the Positive and Negative Ideal Solutions are also derived as:

Table 11. Weighted Standardized Decision Matrix for Thornton Bank I Wind Farm

Weighted Standardized Decision Matrix				*Ideal solution*	
Criterion	**Monopile**	**GBS**	**Jacket**	**A+**	**A-**
Geotechnical Concerns					
Seabed preparation	6.4143	2.1381	4.2762	6.4143	2.1381
Scour protection	3.2071	1.6036	4.8107	4.8107	1.6036
Soil Condition	5.5060	1.8353	5.5060	5.5060	1.8353
Water depth	6.4143	4.2762	2.1381	6.4143	2.1381
Economic Aspects					
Material cost	1.6036	4.8107	3.2071	4.8107	1.6036
Manufacturing cost	6.4143	4.2762	2.1381	6.4143	2.1381
Transportation cost	4.0089	2.6726	1.3363	4.0089	1.3363
Installation cost	4.0089	1.3363	2.6726	4.0089	1.3363
Maintenance cost	2.1381	3.2071	1.0690	3.2071	1.0690
Local content	1.0690	1.6036	0.5345	1.6036	0.5345
Metocean Loads					
Wind	1.7321	1.7321	1.7321	1.7321	1.7321
Waves	2.6726	1.3363	4.0089	4.0089	1.3363
Currents & Tides	1.6036	0.8018	2.4054	2.4054	0.8018
Ice	0.5345	1.0690	1.6036	1.6036	0.5345
Earthquake	1.0690	0.5345	1.6036	1.6036	0.5345
Environmental Impacts					
Noise & Vibration	1.6036	4.8107	3.2071	4.8107	1.6036
Wake & Scour Effects	3.2071	1.0690	2.1381	3.2071	1.0690
Sediment Deposition	2.6726	1.3363	4.0089	4.0089	1.3363
Coastal Dynamics	2.1381	1.0690	3.2071	3.2071	1.0690
Artificial Reefs Effect	0.2673	0.8018	0.5345	0.8018	0.2673
Others					
Life operation	0.2673	0.8018	0.5345	0.8018	0.2673
Decommissioning	1.0690	0.5345	1.6036	1.6036	0.5345
Dismantling	1.0690	0.5345	1.6036	1.6036	0.5345
PIS (S+)	5.701	9.478	7.888		
NIS (S-)	9.869	6.170	7.909		
Relative closeness index C	**0.634**	**0.394**	**0.501**		

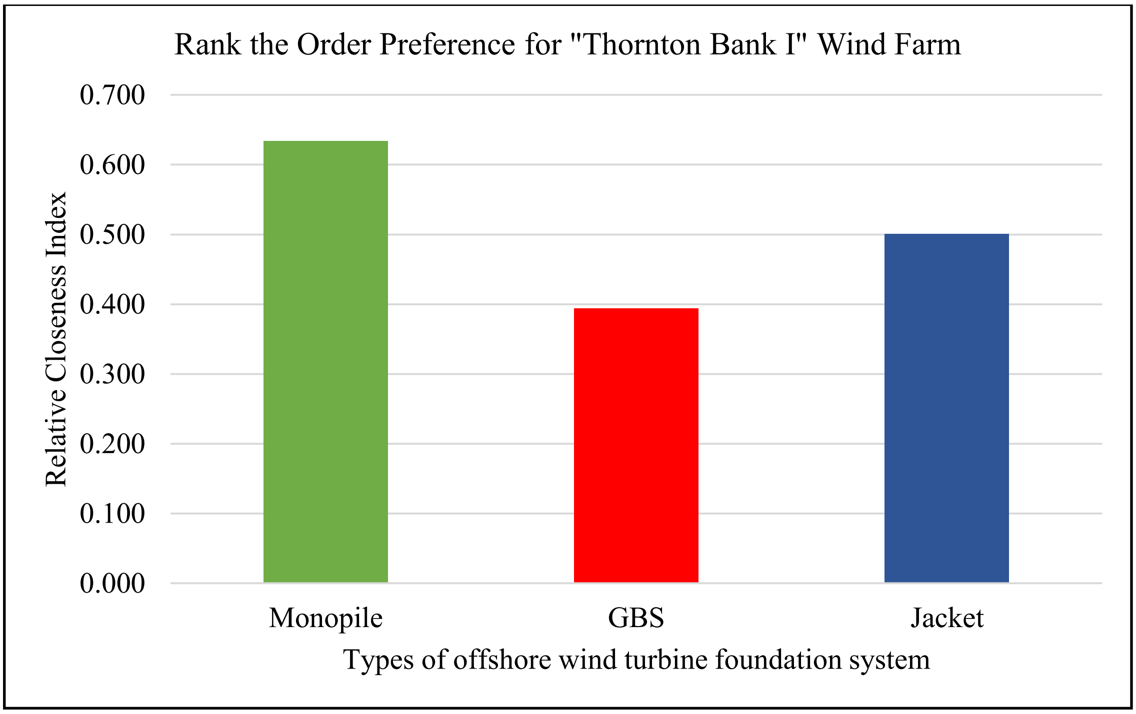

Figure 44. Rank the Order Preference for "Thornton Bank I" Wind Farm

Overall as can be seen in Figure 44, what stands out is that the score of monopile foundation calculating (0.634) have risen considerably against the gravity-based (0.394) and the jacket structure (0.501). As a result, in most cases, the optimal selection comes from technical and economic feasibility. Although a jacket foundation seems the best structure in regarding metocean loads and environmental impacts, monopile foundation can be found for this selection related to the economic aspects for considering lower costs in manufacturing, transportation and installation. Another remarkable point refers to gravity-based foundation which had the lowest score and on the other hand, according to what has been verified in the previous points in relation to "Thornton Bank I", it has been possible to detect that gravity-based foundation which is the one constructed in the wind farm is least favorable because the soil condition is sandy seabed and as a consequence, seabed preparation and other foundation costs can quickly escalate. Finally, the proposed decision tool determines that monopile is the best type of foundation.

5.2. Horns Rev 3 Offshore Wind Farm

The proposed methodology is being applied to the offshore wind farm "Horns Rev 3," which is located north of Horns Rev (Horns Reef) in a shallow area of the eastern North Sea. Horns Rev is a geomorphological feature that extends approximately 40 kilometers into the North Sea west of Blvands Huk, Denmark's westernmost point. Horns Rev 3 is located to the immediate northeast of the existing Horns Rev 2 Offshore Wind Farm and approximately 20 kilometers north-northwest of the existing Horns Rev 1 Offshore Wind Farm, as shown in Figure 45. The wind turbines at Horns Rev 3 will be installed in water depths ranging from 10 m to 20 m at lowest astronomical tide (LAT), with a Mean High Water Springs (MHWS) of LAT + 1.8 m at Blvands Huk [53]. The potential effects were conservatively assessed by selecting a foundation type based on the characteristics of the proposed Horns Rev 3 wind farm.

Figure 45. Location map of Horns Rev 3 in Denmark [53]

The HORNS REV 3 wind farm is Denmark's and Vattenfall's largest wind farm, with 49 wind turbines and a total installed capacity of 407 MW. It will generate approximately 1,700 GWh per year, increasing Danish wind energy generation by approximately 12%. This is enough to cover the annual consumption of around 425,000 Danish households [54]. Based on the criteria established in the Section 3.1 Water depth, depending on the depths of the site ranging between 10 m and 20 m, the most suitable typologies would be gravity foundations and monopiles.

5.2.1. Geotechnical Concentration

5.2.1.1. Bathymetry

Energinet.dk has supplied multibeam echosounder bathymetric data across the Horns Rev 3 pre-investigation area, which have been surveyed by GEMS Survey between 10th July 2012 and 25th August 2012 [55, 56]. The water depths across Horns Rev 3 varies from -10 m to -21 m, gradually deepening from southwest to northeast (Figure 46). The minimum water depths are defined as a ridge along the southwest of the area and the maximum water depths occur across the north and far west of the area.

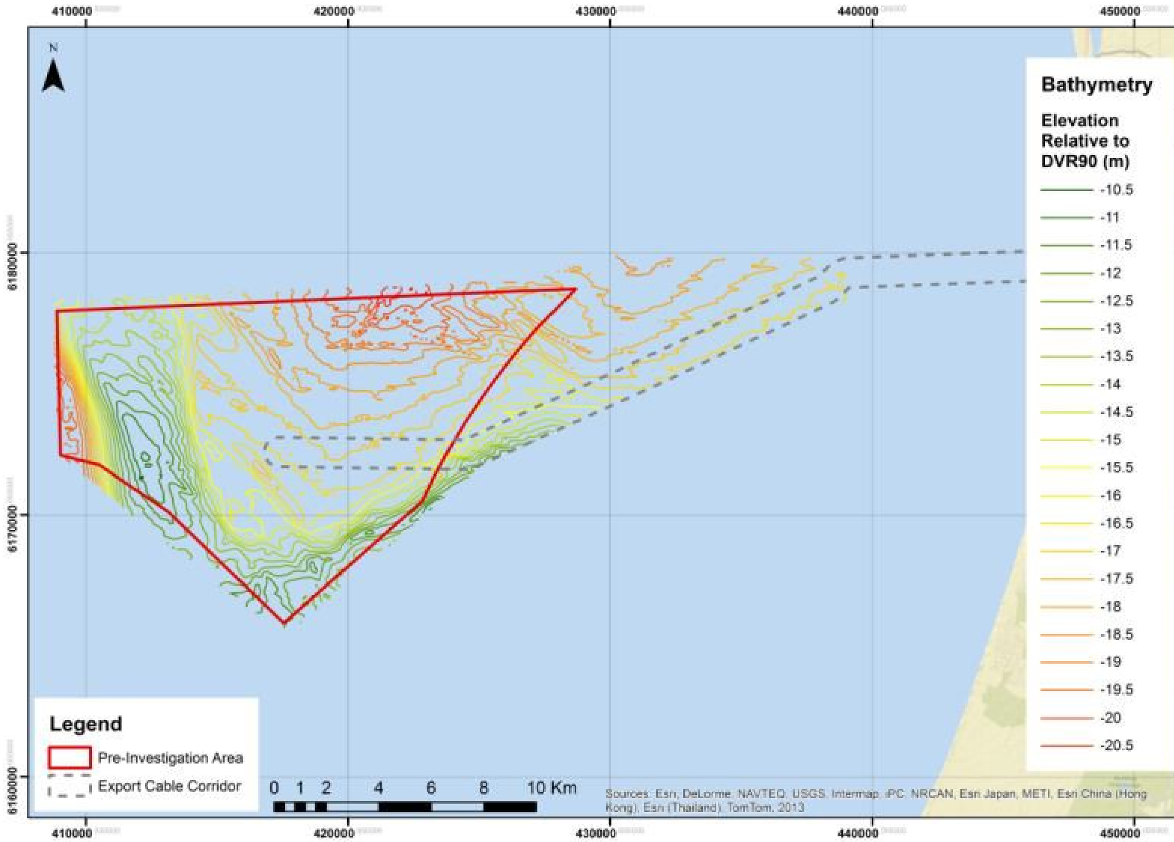

Figure 46. Bathymetry of Horns Rev 3 collected by Energinet.dk in July and August 2012 [55, 56]

5.2.1.2. Soil Condition

The seabed across Horns Rev 3 is mainly medium sand in the south and west also there is fine sand in the northeast side (Figure 47). The seafloor at Horns Rev 3 is composed of relatively well-sorted sand and gravel sediments with a few pockets of fine-grained sediment. The sediments are dominated by sand (96-100%) with one sample containing gravel. The predominant sand is medium sand (diameter 0.20-0.60 mm; using the DGF classification of 1988). Smaller patches of fine sand (0.063-0.20 mm) and coarse sand (0.60-2.00 mm) occur within the larger area of medium sand. All the samples within Horns Rev 3 contain less than 3.4% mud and the average median particle size (d_{50}) for all the samples, excluding the gravel sample, is 0.43 mm; including the gravel sample, the average d_{50} increases to 0.54 mm [53].

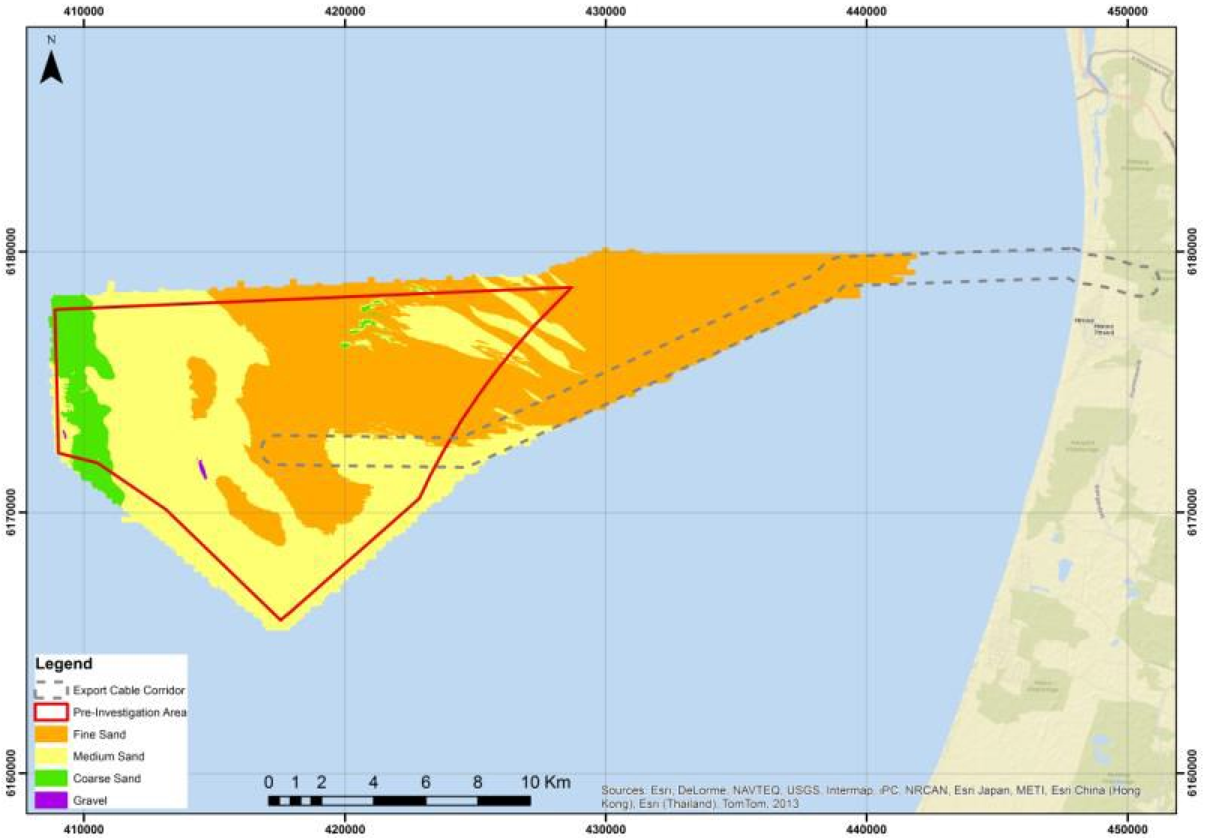

Figure 47. Seabed sediment characteristics across Horns Rev 3 (Ramboll, 2013a, b).

Similarly as mentioned in Section 5.1.1.3. Soil Condition for Thornton Bank, it can be affirmed that monopiles and jackets foundations would be the best foundations in this area.

Regarding scour protection, for monopile foundations, depending on the hydrodynamic environment, the horizontal extent of the armour layer can be seen according to experiences from former projects. Depending on the sediment properties at the installation site, scour protection may be required for gravity-based foundations. A ring of rocks around the structure may be included in the envisioned scour protection design. For jacket foundations, scour protection may be installed as appropriate by a Dynamically Positioned Fall Pipe Vessel and/or a Side Dumping vessel. The scour protection may consist of a two layer system comprising filter stones and armour stones. The effect of scour may be incorporated into the foundation design, in which case scour protection can be neglected.

5.2.2. Economic Aspects

In terms of manufacturing costs, monopiles are the simplest to construct and install in sea depths ranging from 10 to 20 meters, but the overall increase in steel prices on global markets, as well as concerns raised with regard to the feasibility of pile drive, favored concrete foundations, where installation cost for gravity based foundation represents the significant part of total cost in relation to the ballast material filling and seabed preparation. Installation port is the Port of Esbjerg, while the O&M port is the Port of Hvide Sande. According to the distance from installation port to the wind farm (Figure 48), jacket will be extremely expensive for a transportation usage of different vessels, installation, and more fabrication costs than that of the monopiles.

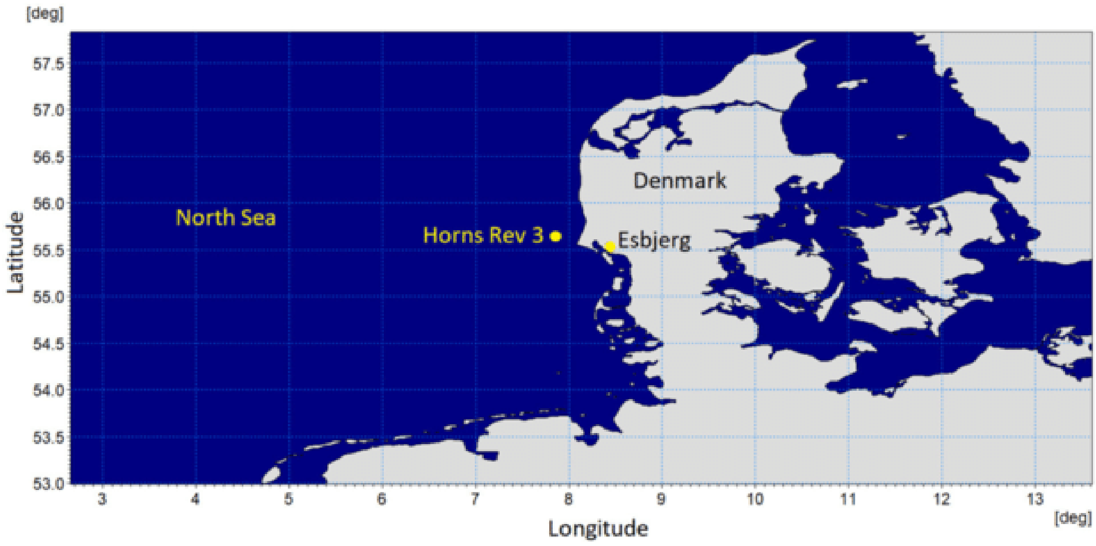

Figure 48. Location of the port of Esbjerg and Horns Rev 3 offshore wind farm [57]

5.2.2.1. Local Content of Denmark

The first country to install a commercial offshore wind farm over 30 years ago, Denmark remains a leading global hub for offshore wind energy, with the wind energy sector in Denmark (onshore and offshore) estimated to directly employ close to 33,000 people, equivalent to 2% of the private sector employment [58]. Since the beginning of the wind energy sector on land and the subsequent emergence of offshore wind farms, Denmark has built a unique global position in offshore wind, which includes a highly skilled workforce across all stages of the lifecycle, local production capabilities within offshore turbines and major components, specialized maritime and logistics services, leading facilities for testing prototypes, research institutions, ports specialized in offshore wind and, not least, a comprehensive network of local suppliers. As one of the leading suppliers of foundations and substations for the offshore wind market, Denmark industries has had the production facilities of monopile foundations at Lindø port of Odense, Denmark [59]. This means that the production of the monopiles are high local content in Denmark and it will eventually create new jobs.

5.2.3. Metocean Data

Metocean data including water levels, tidal currents and waves has been collated from a variety of stations located in the North Sea near the Danish coastline (Figure 49).

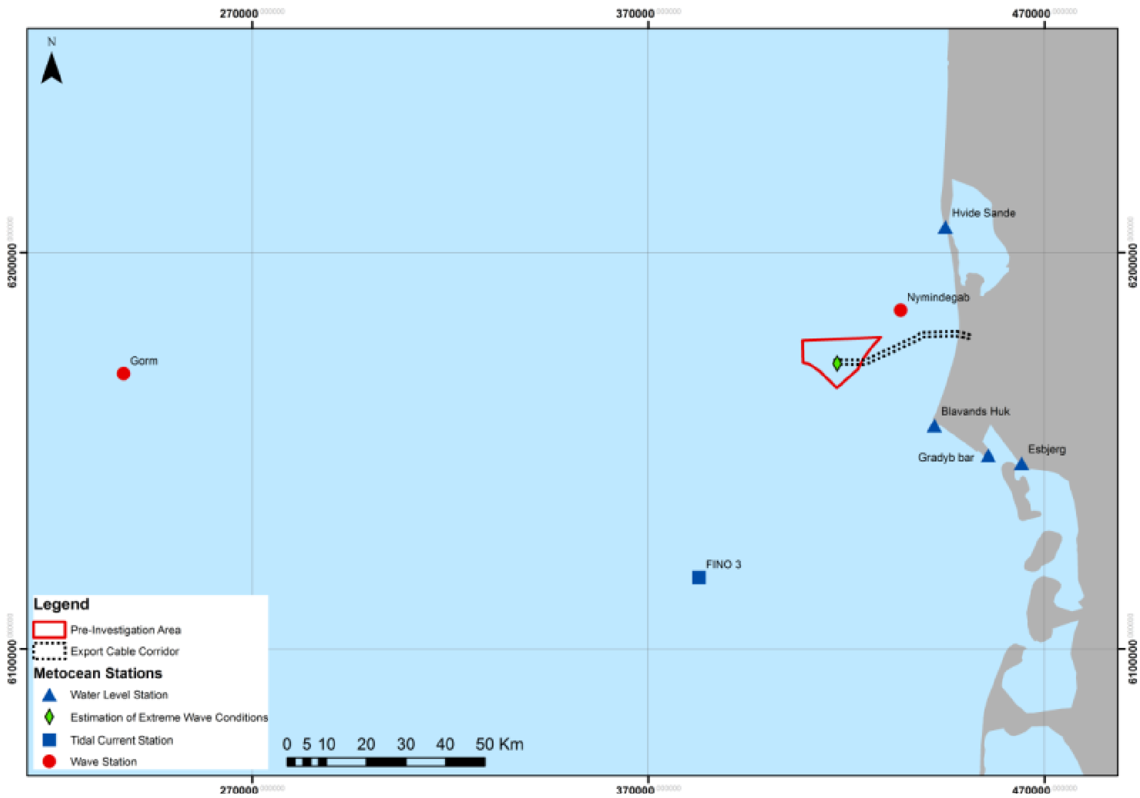

Figure 49. Location of Metocean data stations for Horns Rev 3 [60]

In relation to the wind resource, offshore winds were forecast using StormGeo's Weather Research and Forecasting model (WRF) applied at Gorm. The average wind speed is about 4 m/s to 8 m/s mainly from the northwest to southwest sector and predominant direction is west as can be seen in Figure 50.

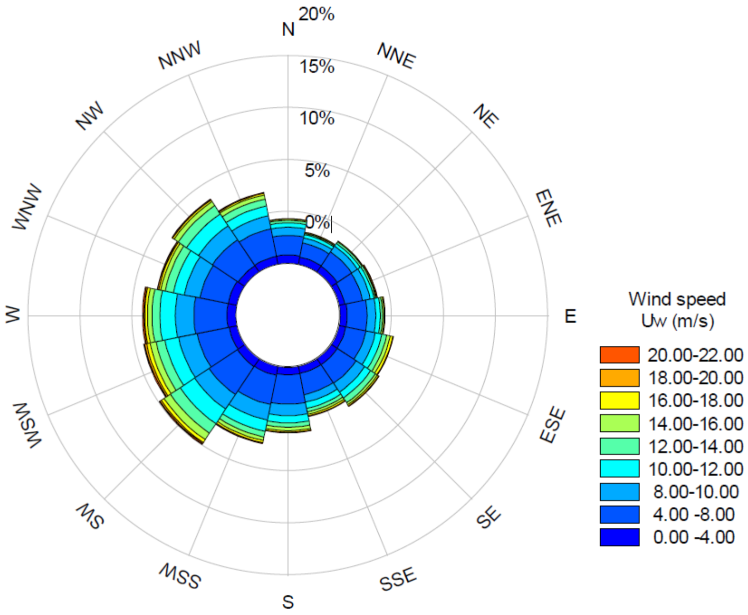

Figure 50. Wind climate forecast at Gorm [60]

Forecast time series wave data is available offshore at Gorm and measured wave data inshore is available between 2007 and 2012 at Nymindegab. Wave roses show the dominant wave directions are from the northwest and north-northwest at both locations (Figure 51). The average significant wave height ranges from 0.5 m to 1.0 m.

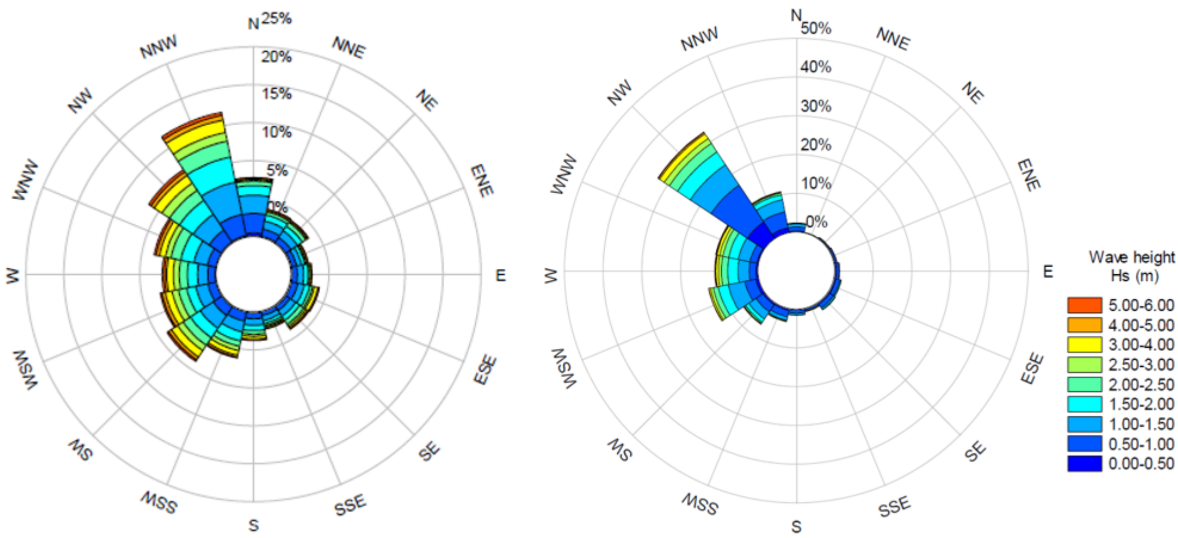

Figure 51. Significant wave height at the offshore Gorm platform (left) and the nearshore Nymindegab station (right) [60]

Table 12. Extreme significant wave heights at Horns Rev 3 [61].

Return Period (years)	Significant Wave Height (m)
1	6
5	7
10	7.4
20	7.8
40	8.2
50	8.3
100	8.7

Praem-Larsen and Kofoed (2013) estimated extreme wave conditions at a single location (55°41’13’’N, 07°41’24’’E) within Horns Rev 3. The results show that extreme significant wave heights of 6 m can be expected as often as once a year and the 50-year extreme significant wave height is 8.3 m (Table 12). Currents are induced by both tide, wind and waves, varying in direction and magnitude according to time of the day and season. Directions of the currents vary significantly in the area, but the tidal current rose shows the dominant flows were towards the north-northwest with peak current velocities greater than 0.7 m/s (Figure 52). Measured tidal current data was available for 2011 at FINO3 in 23 m of water. Discrete measurements were recorded for every 2 m of water depth equating to 11 points from 2 m to 22 m. Calm periods (less than 0.1 m/s) occurred approximately 6.5% of the time. The concrete GBS represents the worst case foundations, in terms of physical blockage to waves and tidal currents.

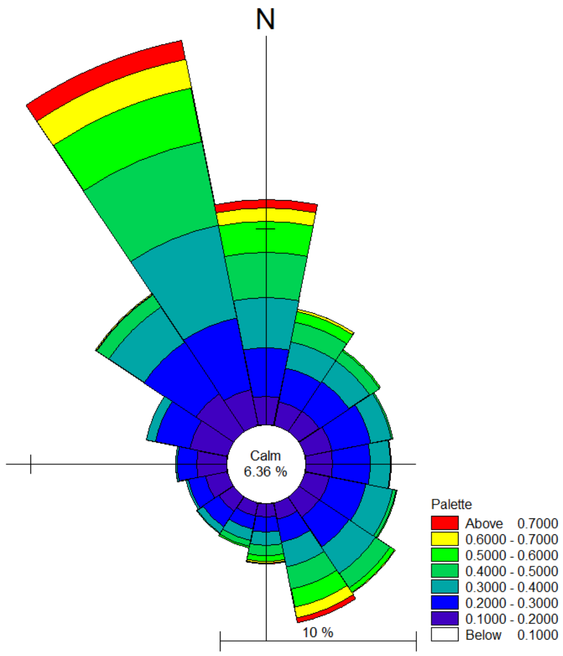

Figure 52. Depth-averaged tidal current distribution at FINO3 for 2011 [60]

5.2.4. Environmental Concerns

5.2.4.1. Underwater Noises and Sound Mitigation Measures

The main pressures during construction of the offshore wind farm Horns Rev 3 will be underwater noise (especially in case of pile driving), increased ship traffic and disturbance of the bottom sediment during foundation. These pressures are likely to cause displacement of Harbour porpoises and seals from the construction site. During different construction work types such as harbour construction or erection of offshore wind farms piling and dredging are important noise sources. Dredging is often necessary to prepare and level the sea bed for especially for alternative foundations like gravity based foundations. Noise emissions from underwater pile driving greatly exceeds those from the more constant noise source. During operation noise emissions and habitat changes due to artificial reef structures could affect harbour porpoises and seals. The Horns Rev 3 area is of medium importance to harbour seals without any special functions as haul-out or nursing area [60].

5.2.4.2. Seabed Environment

The main effect from establishing the Horns Rev 3 wind farm was the introduction of hard bottom structures onto seabed that almost exclusively consisted of sandy sediments. This has increased habitat heterogeneity and changed the benthic communities at the turbine sites from typical infauna communities to hard bottom communities. Abundance and biomass of the benthic communities increased at the position of the turbines compared to the native infauna communities. A consequence of the change in community structure was a local increase in biomass by 50 to 150 times, most of this as available food for fish and seabirds [60]. At Horns Rev 3, one important reason could be that the studies and investigations were made during the early stages of colonization of the turbine foundations that constitute the artificial reefs. The colonization of the foundations will probably progress over the coming years, which may lead to higher diversity and biomass of species. Moreover, sand eel (Ammodytidae spp.) is one of the most abundant group of fish in the area. Due to a known strong correlation between the distribution of sand eel and the composition of the sediments, the distribution of both sand eel and sediment composition was surveyed. The studies showed that the wind farm is unlikely to have a negative effect on the sand eel or any effect on sediment composition. Only a slight decrease in porpoise abundance was found at Horns Rev 3 wind farm during construction, and no effect of operation of the wind farm was seen. It is clear that the effects of pile driving operations were observed.

5.2.5. Applying to Decision Matrix Based on Data Acquisition

Based on the proposed methodology, the initial Decision Matrix is defined as attribute weights and attribute ratings for three alternatives which were justified from Section 5.2.1 to 5.2.4:

Table 13. Initial decision matrix for Horns Rev 3 Wind Farm

Decision Matrix		***RATINGS FOR Horns Rev 3***		
Criterion	**Weighing factor**	**Monopile**	**GBS**	**Jacket**
Geotechnical Concerns				
Seabed preparation	8	3	1	2
Scour protection	6	2	1	3
Soil Condition	8	3	2	1
Water depth	8	2	3	1
Economic Aspects				
Material cost	6	2	3	1
Manufacturing cost	8	2	3	1
Transportation cost	5	3	2	1
Installation cost	5	3	2	1
Maintenance cost	4	2	3	1
Local content	2	3	1	2
Metocean Loads				
Wind	3	3	3	3
Waves	5	2	1	3
Currents & Tides	3	2	1	3
Ice	2	3	1	2
Earthquake	2	3	1	2
Environmental Impacts				
Noise & Vibration	6	1	3	2
Wake & Scour Effects	4	3	1	2
Sediment Deposition	5	2	1	3
Coastal Dynamics	4	3	1	2
Artificial Reefs Effect	1	1	3	2
Others				
Life operation	1	1	3	2
Decommissioning	2	2	1	3
Dismantling	2	2	1	3
Total	**100**			

The standardized Decision Matrix is obtained in APPENDIX A2 and the Weighted Standardized Decision Matrix is derived. Then, the Positive and Negative Ideal Solutions are also derived as:

Table 14. Weighted Standardized Decision Matrix for Horns Rev 3 Wind Farm

Weighted Standardized Decision Matrix				***Ideal solution***	
Criterion	**Monopile**	**GBS**	**Jacket**	**A+**	**A-**
Geotechnical Concerns					
Seabed preparation	6.4143	2.1381	4.2762	6.4143	2.1381
Scour protection	3.2071	1.6036	4.8107	4.8107	1.6036
Soil Condition	6.4143	4.2762	2.1381	6.4143	2.1381
Water depth	4.2762	6.4143	2.1381	6.4143	2.1381
Economic Aspects					
Material cost	3.2071	4.8107	1.6036	4.8107	1.6036
Manufacturing cost	4.2762	6.4143	2.1381	6.4143	2.1381
Transportation cost	4.0089	2.6726	1.3363	4.0089	1.3363
Installation cost	4.0089	2.6726	1.3363	4.0089	1.3363
Maintenance cost	2.1381	3.2071	1.0690	3.2071	1.0690
Local content	1.6036	0.5345	1.0690	1.6036	0.5345
Metocean Loads					
Wind	1.7321	1.7321	1.7321	1.7321	1.7321
Waves	2.6726	1.3363	4.0089	4.0089	1.3363
Currents & Tides	1.6036	0.8018	2.4054	2.4054	0.8018
Ice	1.6036	0.5345	1.0690	1.6036	0.5345
Earthquake	1.6036	0.5345	1.0690	1.6036	0.5345
Environmental Impacts					
Noise & Vibration	1.6036	4.8107	3.2071	4.8107	1.6036
Wake & Scour Effects	3.2071	1.0690	2.1381	3.2071	1.0690
Sediment Deposition	2.6726	1.3363	4.0089	4.0089	1.3363
Coastal Dynamics	3.2071	1.0690	2.1381	3.2071	1.0690
Artificial Reefs Effect	0.2673	0.8018	0.5345	0.8018	0.2673
Others					
Life operation	0.2673	0.8018	0.5345	0.8018	0.2673
Decommissioning	1.0690	0.5345	1.6036	1.6036	0.5345
Dismantling	1.0690	0.5345	1.6036	1.6036	0.5345
PIS (S+)	5.574	8.272	9.717		
NIS (S-)	9.146	8.392	6.313		
Relative closeness index C	**0.621**	**0.504**	**0.394**		

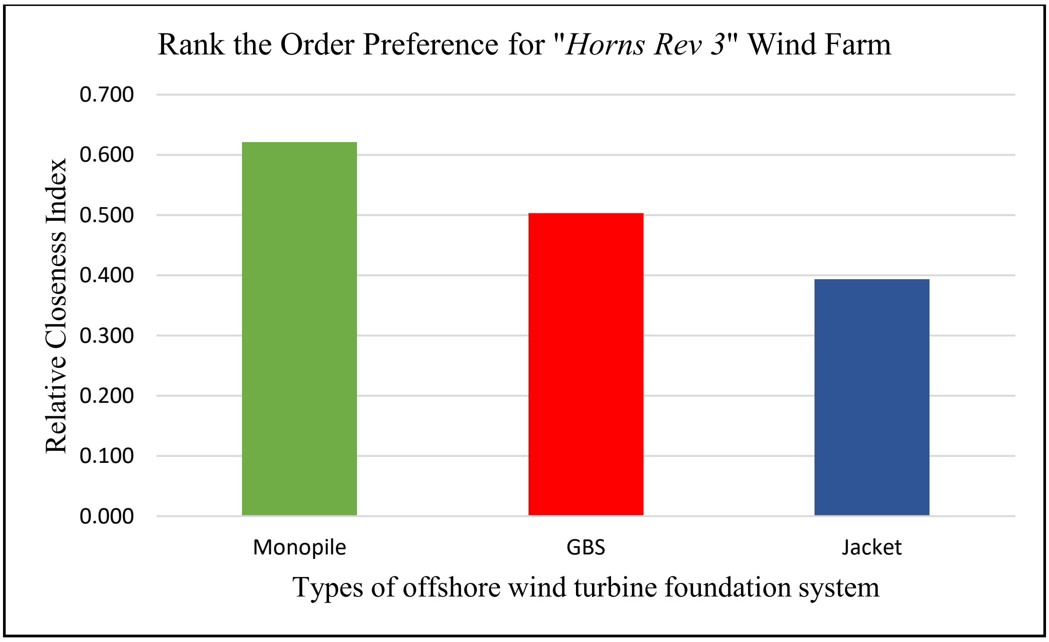

Figure 53. Rank the Order Preference for "Horns Rev 3" Wind Farm

It can be seen from the graph that the monopile was found to be the best option based on the calculation of the relative closeness of each support structure to the ideal solution whereas the jacket and gravity-based foundations had lower scores. Similarly, the one constructed in the wind farm is also monopile foundation as the proposed decision tool. It can be note that the most appropriate alternative in most wind farms located in shallow and intermediate depths. In contrast, it can be noticed that the monopile foundations provided the most cost effective solution in Denmark. According to the local content, the production of the monopiles are high local content in Denmark.

5.3. Beatrice Offshore Wind Farm

The Beatrice Wind Farm is located on the Smith Bank, a large sandbank in the north-west area of the Moray Firth, approximately 13 km off the northeast coast of Scotland, and in a water depth of 45 m (Figure 54). The bank is approximately 35 km long from south-west to north-east and 20 km wide, and rises from a base level of between 50 m and 60 m below sea level to approximately 35 m [62]. Approximately 40 km^2 of the bank is covered by water less than 50 m deep [63]. The WTGs will each carry a 5 MW turbine, and together they will deliver an estimated 10 MW of electricity to the platform.

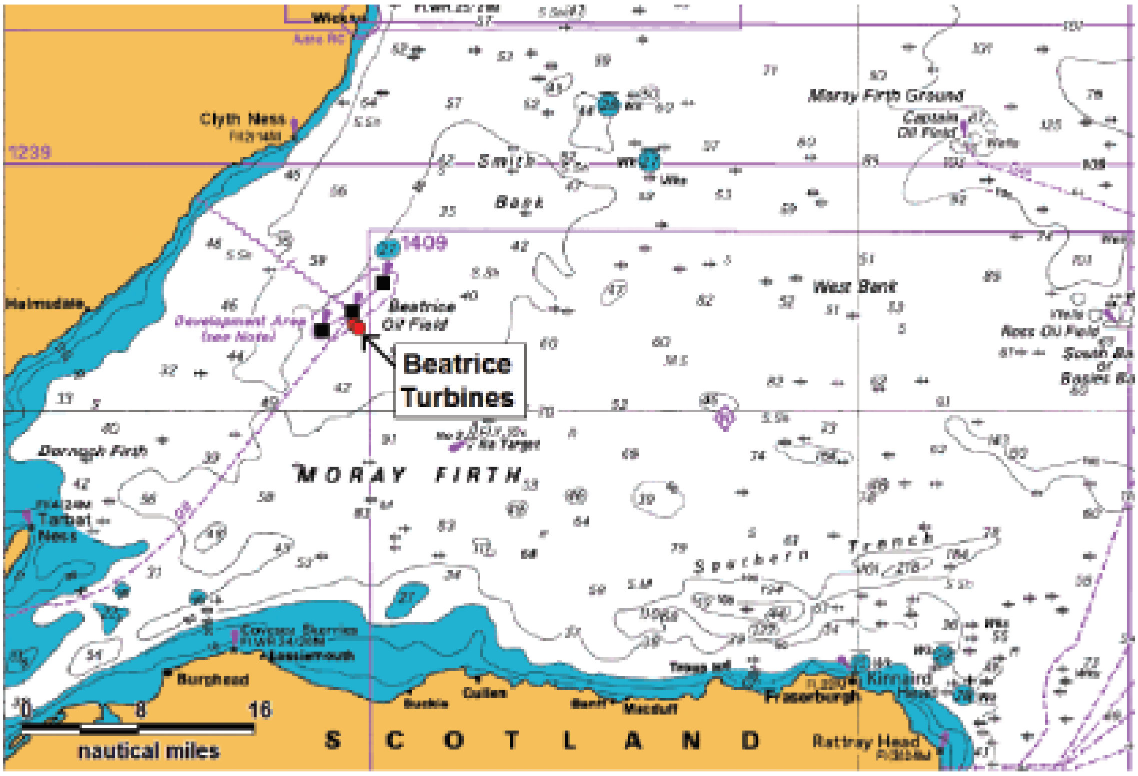

Figure 54. Location of the two WTGs in the Moray Firth [64]

Based on the criteria established in the Section 3.1 Water depth, depending on the depths of the site which is 45 m, the most suitable typologies would be jacket foundations. At low water depths, overall structural mass is similar among jackets and monopiles, but for the deepest site, the support structure mass when using the monopiles is nearly double that computed for jacket foundation systems. In general, it is expected that the monopile mass increases significantly with water depth; it is this increase in mass, along with the associated difficulties in the installation, that cause a decrease in the attractiveness for the monopiles when moving to deeper water sites. At transitional water depths (20–40 m), the most commonly used foundations are monopile and jacket typologies. The main difference between the two is the use of the second ones in depths from 35–40 m. For the jacket structures, their adaptability and excellent behavior in adverse conditions make them the best option in these depths, especially where the monopiles begin to experience deflection, buckling and instability phenomena, being necessary to resort to more stable structures with better behavior under severe marine conditions.

5.3.1. Geotechnical Considerations

5.3.1.1. Bathymetry

The site-specific survey, conducted in November 2005 using swath bathymetry, revealed that the seabed is generally flat over the central part of the site, with depths ranging from 44 m to 44.75 m. The minimum water depth within the survey area was approximately 43 m (to the north-east of the area) and the maximum was 46 m (to the north-west) (Figure 55).

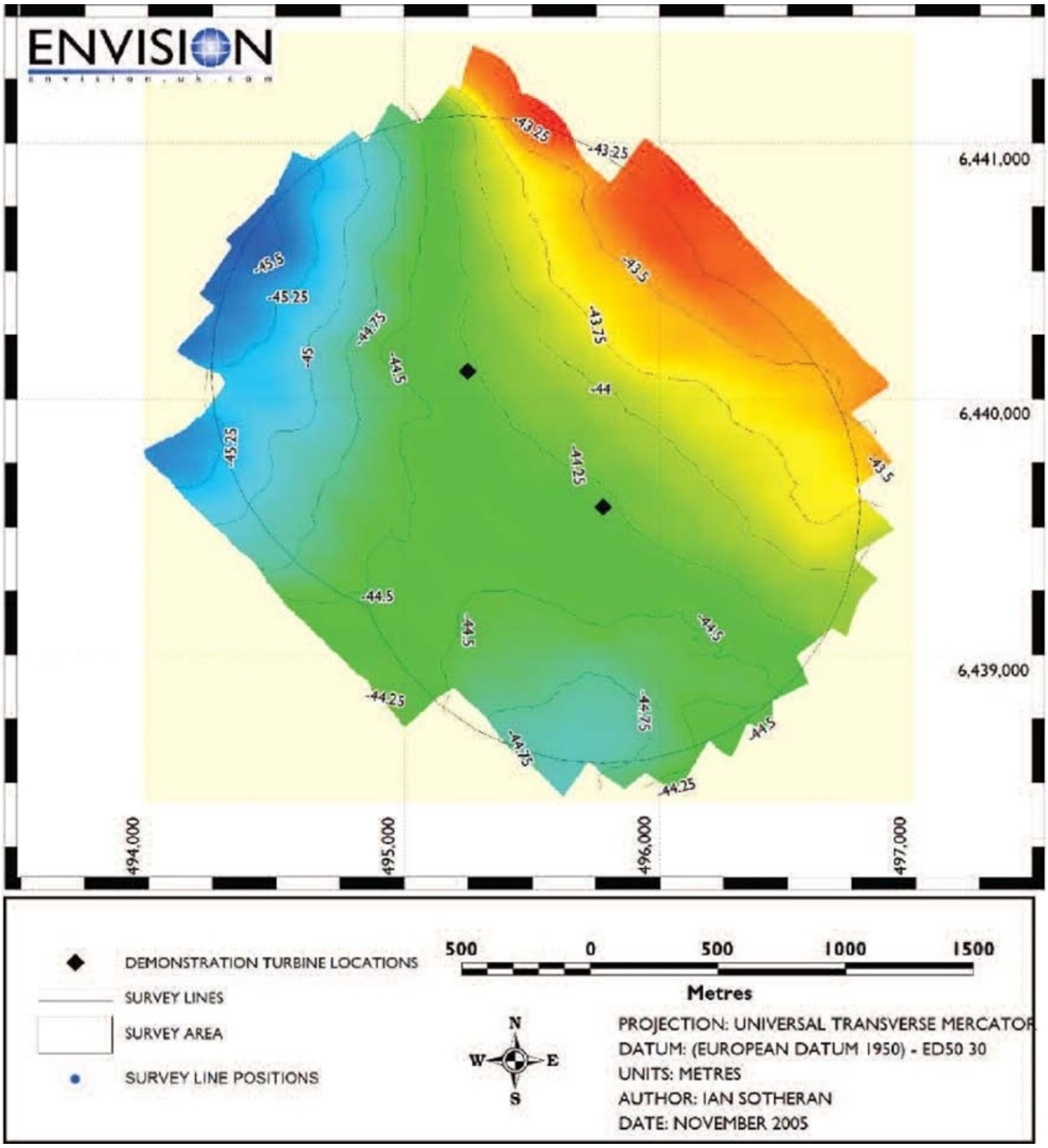

Figure 55. Water depths and sea bed topography of the "Beatrice" wind farm site [64]

5.3.1.2. Soil Condition

Surface sediments form a relatively thin (15 m) uniform cover throughout the Moray Firth, with sandy sediments predominating in the central and northern parts of the Firth [65]. These sandy sediments are generally moderately to well sorted, fine to medium grained, with a small percentage of shell debris, and form a layer 1 m to 2 m thick for the majority of the area. In the south, the sandy sediments of the central Moray Firth transition to muddy sand sediments. These muddy sands are moderately well sorted, with less than 20% mud content by weight. The coarsest sediments (sandy gravels) are found on the shallower north and east flanks of the Smith Bank, while finer sediments are found in the deeper western area [62]. The sediments on the Smith Bank are moderately to poorly sorted fine to medium sands with uniformly low mud content (1.4 % to 2.4 %) and variable gravel contents at depths of 40 m [66, 67 and 68].

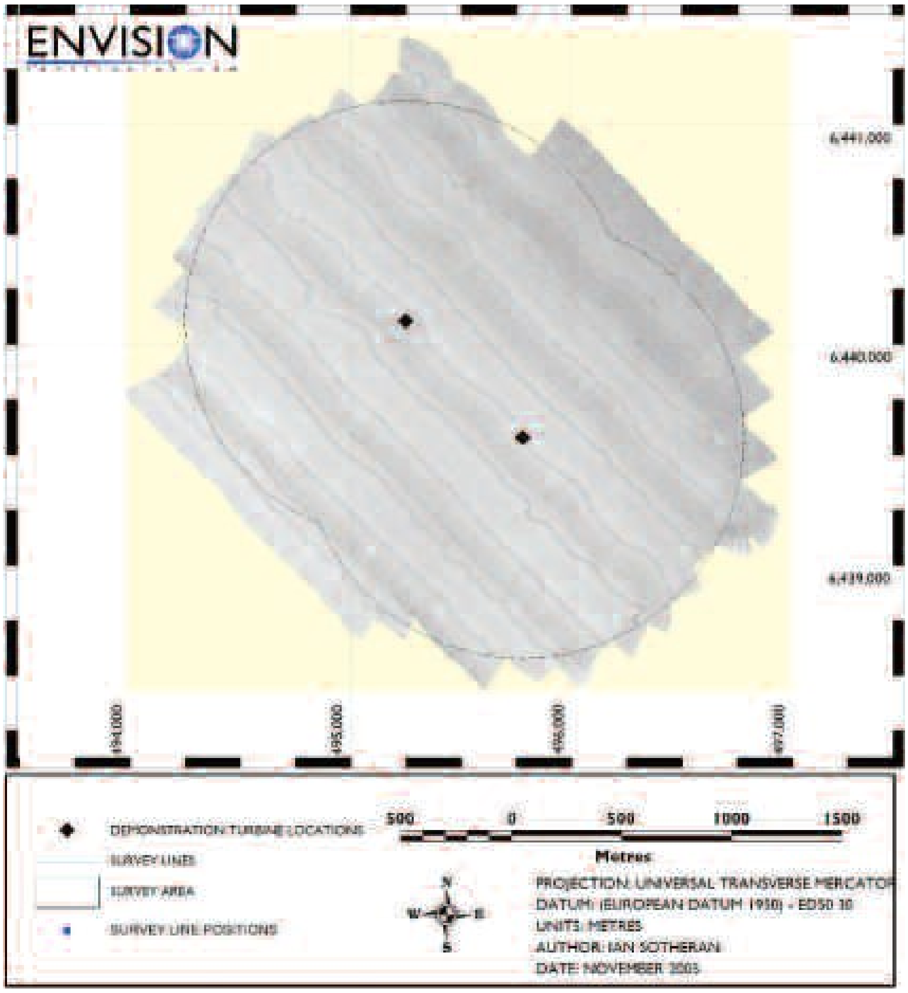

Figure 56. Side scan sonar image of the sea bed at the Beatrice Wind Farm, showing sand ripples running in a north-west to south-east direction (ERT, 2005)

The side scan sonar data collected during the site-specific study of the site (Figure 56) shows a slightly coarser seabed in the north-east area and softer sediments in the south-east and northwest areas. The results of particle size analysis of sediment samples collected during this survey match well with field observations, indicating that clean fine sand with broken shell material is the most common sediment type in the survey area. The silt/clay concentration (particles 63 m) varied between 3 and 4.5 percent [69]. According to the soil condition of the site, monopile and jacket foundations would be favorable.

5.3.2. Economic Aspects

Despite the fact that monopiles are significantly easier to make, when they get larger for deeper water, the cost of monopile supply increases significantly because of the increased steel demand in order to give sufficient stiffness, especially with heavier nacelles and larger, heavier, slow rotating rotors. The entire material costs overweigh the manufacturing costs, and the overall costs for monopiles become greater than those for other foundation designs. However, up to 50 meters of sea depth, monopile installation and assembly costs are still cheaper than jacket counterparts. Beyond this depth, transporting and installing the extremely heavy monopiles would necessitate a different type of vessel, resulting in a significant increase in overall cost. As a result, around 45 m water depth, the jackets become the more cost-effective choice in terms of plant cost and overall LCOE. Although the monopile-tower support structure has a higher mass than the jacket-tower support structure, the monopile is more economically beneficial than the jacket for water depths up to 40 m due to the overall cost impact on the LCOE of the support structures. On the other hand, gravity based foundation would be a huge issue for installation at 45 m of water depth and however, material cost and manufacturing cost would be cheaper than other types of foundation. Subsequently, some design bases had to be prepared that would be used to proceed with the selection of the most suitable type of foundation for this installation.

5.3.2.1. Local Content of United Kingdom

The leading supplier of steel in the UK, Tata, indicated that it was considering the investment needed to deliver the plate weight required for monopiles, including XL products. As material cost is the dominant contribution to total product cost, the supply of UK steel is a significant factor in achieving the potential UK expenditure on monopiles. The production process for monopiles is largely automated. This means that the number of jobs associated with this activity is less than for other foundation concepts, such as steel jackets or concrete gravity based foundations. Industry feedback was that the most common "deeper water, larger turbine" foundation design would be the four legged steel jacket. The production process for jackets is more labour intensive than that for monopiles. A high proportion of the materials for concrete foundations can be supplied from the UK. No offshore wind projects have used concrete foundations made in the UK. The UK is leading research to address the barriers to the commercial-scale use of concrete foundations. The Concrete Centre (part of the Mineral Products Association) has formed the Interest Group for Gravity Foundations that includes companies involved in the design, construction and installation of concrete gravity based foundations. A lack of economically viable demonstration opportunities is a key challenge that is delaying and may prevent the adoption of concrete designs on commercial projects.

5.3.3. Metocean Data

Meteorological wind and wave data for the area of the Beatrice offshore wind farm has been summarized from wind data recorded [64, 69]. Figure 57 shows the Beatrice area's all-year average mean wind direction distribution. The most likely wind direction is from the south west, as can be observed. Figure 58 shows the percentage exceedance distribution of significant wave height for the Beatrice area. The frequency of severe sea states (significant wave height exceeding 5 m) is approximately 0.1% per year.

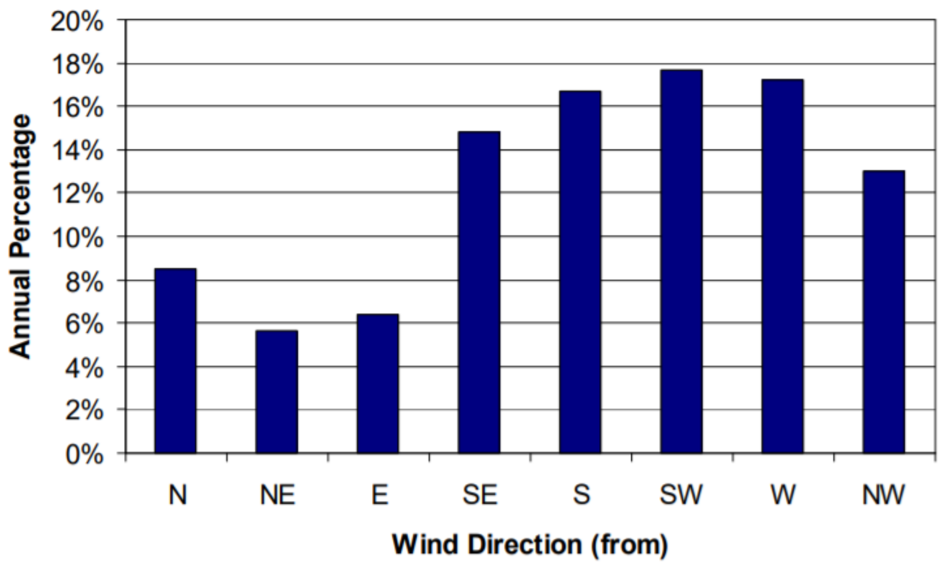

Figure 57. Annual Wind Direction Distribution for Beatrice Area [69]

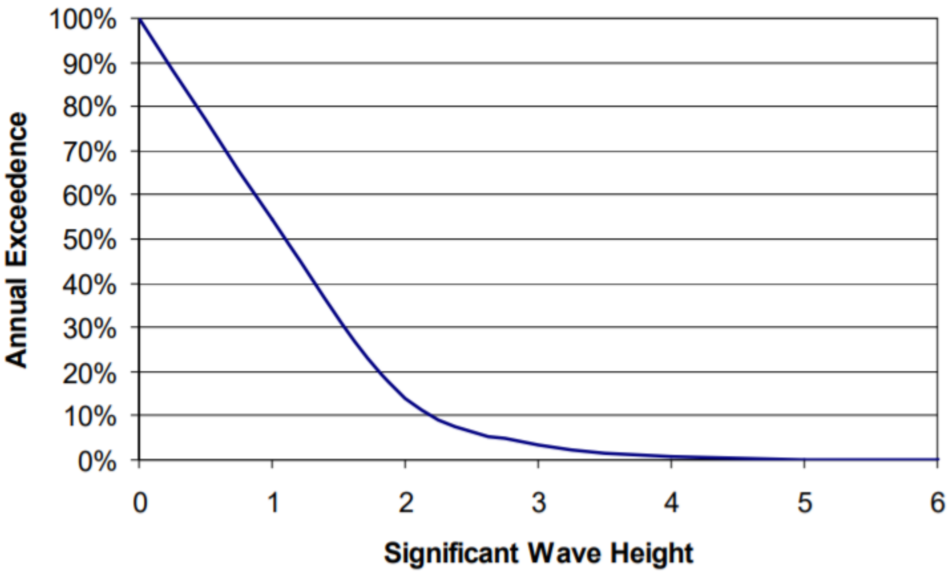

Figure 58. Annual Wave Height Exceedance Curve for the Beatrice Area [69]

Currents within the Moray Firth are primarily tidal, influenced by wind, and generally weak, with speeds of less than 0.5 m/s over the bulk of the Moray Firth during spring tides. Tidal currents in excess of 0.5 m/s are found in the Inner Moray Firth, with speeds of over 1.6 m/s between Fort George and Chanonry Point, and off Invergordon, during spring tides [69]. Chart Datum and Ordnance Datum for the Beatrice wind farm based on values recorded at Wick are presented in Table 15.

Table 15. Chart Datum and Ordnance Datum Figures from Wick

Tidal Level	Height above Chart Datum
HAT	4m
MHWS 3.5m	3.5m
Mean Sea Level (MSL) (approx.)	2.1m
Mean Low Water Springs (MLWS)	0.7m
LAT	0.1m

5.3.4. Environmental Concerns

5.3.4.1. Underwater Noises and Sound Mitigation Measures

The main qualifying interest of the Moray Firth SAC is the resident population of Bottlenose dolphins, thought to number between 120 and 170 individuals. Offshore, the Smith Bank, where Beatrice is located, is a commercial fishing area with spawning grounds for a variety of commercially fished fish and shellfish species. If the wind turbines were fixed to the seabed by driven piles, the noise from short-term piling operations may disturb marine mammals and fish in the area around the sites. The mitigation methods will focus on two things: first, ensuring that no marine mammals are present within 1km of piling operations, and second, encouraging people who are in the zone where perceived noise levels are likely to induce severe avoidance reactions to go further away. The use of marine mammal observers, and the application of a “soft-start” technique to alert marine mammals in the immediate vicinity (for example within 10 km) to reduce possible effects of the piling operations. However, in this case, monopiles would be the worst scenario than jacket and gravity based foundations.

5.3.4.2. Seabed Environment

The operations to install the foundations and the presence of the substructures on the seabed, may cause temporary or permanent effects to the seabed and seabed (benthic) communities. Benthic communities may be disrupted when sediments are disturbed, smothered by resettling suspended sediments, or permanently covering by parts of the facilities on the seabed. Together, these areas of potential disturbance represent about 0.02% of the seabed within the Beatrice field determination boundary [70]. The sediment is clean and uncontaminated, and although a very small proportion of the benthic community within the bounds of the Beatrice site licence may be impacted, the sediment will be quickly recolonized by animals from adjacent undisturbed sediment. The site-specific benthic survey at the Beatrice field did not find any evidence of the presence of beds of the horse mussel *Modiolus modiolus* [70]. The “reef” effect of the WTGs is likely to provide a small positive effect with jacket foundation. No rare or threatened species or communities will be affected. Installing the steel frames rather than concrete foundation is one way this impact might be minimized.

5.3.5. Applying to Decision Matrix Based on Data Acquisition

Based on the proposed methodology, the initial Decision Matrix is defined as attribute weights and attribute ratings for three alternatives which were justified from Section 5.3.1 to 5.3.4:

Table 16. Initial decision matrix for "Beatrice" Wind Farm

Decision Matrix		*RATINGS FOR Beatrice*		
Criterion	**Weighing factor**	**Monopile**	**GBS**	**Jacket**
Geotechnical Concerns				
Seabed preparation	8	3	1	2
Scour protection	6	2	1	3
Soil Condition	8	3	1	3
Water depth	8	2	1	3
Economic Aspects				
Material cost	6	1	3	2
Manufacturing cost	8	1	3	2
Transportation cost	5	3	2	1
Installation cost	5	3	1	2
Maintenance cost	4	3	2	1
Local content	2	1	3	2
Metocean Loads				
Wind	3	3	3	3
Waves	5	1	2	3
Currents & Tides	3	1	2	3
Ice	2	3	1	2
Earthquake	2	3	1	2
Environmental Impacts				
Noise & Vibration	6	1	3	2
Wake & Scour Effects	4	3	1	2
Sediment Deposition	5	2	1	3
Coastal Dynamics	4	3	1	2
Artificial Reefs Effect	1	1	3	2
Others				
Life operation	1	1	3	2
Decommissioning	2	1	2	3
Dismantling	2	2	1	3
Total	**100**			

The standardized Decision Matrix is obtained in APPENDIX A3 and the Weighted Standardized Decision Matrix is derived. Then, the Positive and Negative Ideal Solutions are also derived as:

Table 17. Weighted Standardized Decision Matrix for Beatrice Wind Farm

Weighted Standardized Decision Matrix				*Ideal solution*	
Criterion	**Monopile**	**GBS**	**Jacket**	**A+**	**A-**
Geotechnical Concerns					
Seabed preparation	6.4143	2.1381	4.2762	6.4143	2.1381
Scour protection	3.2071	1.6036	4.8107	4.8107	1.6036
Soil Condition	5.5060	1.8353	5.5060	5.5060	1.8353
Water depth	4.2762	2.1381	6.4143	6.4143	2.1381
Economic Aspects					
Material cost	1.6036	4.8107	3.2071	4.8107	1.6036
Manufacturing cost	2.1381	6.4143	4.2762	6.4143	2.1381
Transportation cost	4.0089	2.6726	1.3363	4.0089	1.3363
Installation cost	4.0089	1.3363	2.6726	4.0089	1.3363
Maintenance cost	3.2071	2.1381	1.0690	3.2071	1.0690
Local content	0.5345	1.6036	1.0690	1.6036	0.5345
Metocean Loads					
Wind	1.7321	1.7321	1.7321	1.7321	1.7321
Waves	1.3363	2.6726	4.0089	4.0089	1.3363
Currents & Tides	0.8018	1.6036	2.4054	2.4054	0.8018
Ice	1.6036	0.5345	1.0690	1.6036	0.5345
Earthquake	1.6036	0.5345	1.0690	1.6036	0.5345
Environmental Impacts					
Noise & Vibration	1.6036	4.8107	3.2071	4.8107	1.6036
Wake & Scour Effects	3.2071	1.0690	2.1381	3.2071	1.0690
Sediment Deposition	2.6726	1.3363	4.0089	4.0089	1.3363
Coastal Dynamics	3.2071	1.0690	2.1381	3.2071	1.0690
Artificial Reefs Effect	0.2673	0.8018	0.5345	0.8018	0.2673
Others					
Life operation	0.2673	0.8018	0.5345	0.8018	0.2673
Decommissioning	0.5345	1.0690	1.6036	1.6036	0.5345
Dismantling	1.0690	0.5345	1.6036	1.6036	0.5345
PIS (S+)	7.787	9.635	5.574		
NIS (S-)	8.442	6.798	8.975		
Relative closeness index C	**0.520**	**0.414**	**0.617**		

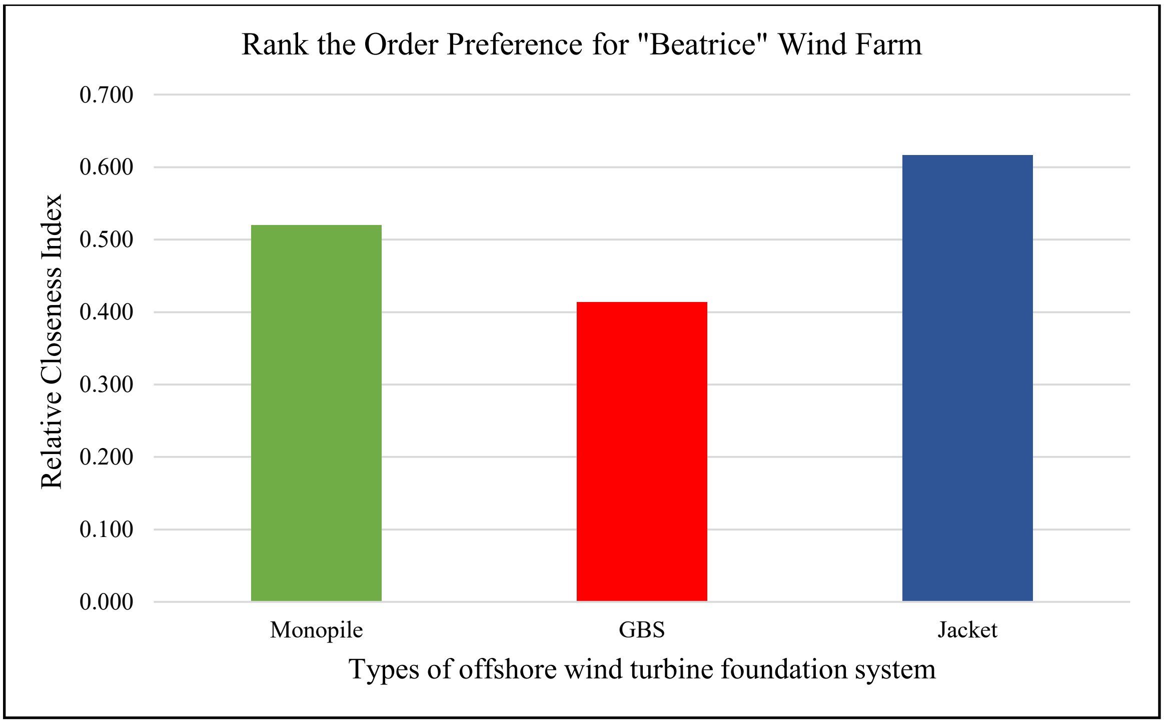

Figure 59. Rank the Order Preference for "Beatrice" Wind Farm

The least favorable foundation was occupied by the gravity-based concept for the Beatrice Wind Farm, which obtained least numbers in total, which means this concept clearly did not meet the requirements. In the intermediate level, the monopile concept was positioned. It is assumed that monopile foundations would not be the most suitable solution for this project. Nevertheless they might be part of a secondary solution. Finally, in the top level, jacket foundations obtained the score as the most proper solutions. From the calculation of the relative closeness of each support structure to the ideal solution, the jacket was found to provide the best option (0.617) against the gravity-based (0.414) and the monopile (0.520). In reality, the one constructed in the wind farm is also jacket foundation. The second approach is monopile foundation for the reason of the experienced allocation of weighting factors. However, gravity-based is in the last option to select and it is noticeably that offshore wind projects have not used concrete foundations made in the UK. In this water depth of 45 m, it seems reasonable that gravity-based foundation is not a suitable option.

6. CONCLUSIONS

The initially stated overarching aim of this research was to achieve which offshore foundations offer the most benefits and drawbacks compared to present foundation types. In order to balance the sustainable sector for socio-economic activities, several condition aspects were investigated in this investigation. Not only are the technical issues, economic profitability, and management of the installation taken into account, but also the installation for environmental compatibility.

In water depths of 30-50 meters, this study provided an analytical technique for identifying the most appropriate foundation from the three most widely utilized foundation-support structural designs - monopile, gravity-based, and jacket. A decision tool was created with that objective in mind, taking into account the effect of the water depth and the environmental consideration to the decision making process towards the selection of the most suitable configuration as well as the performance of other attributes.

In this decision-making process, a multi-criteria decision-making approach (MCDM) was used, which was capable of evaluating the best from a collection of possibilities. The goal of MCDM was to assist decision-makers in making decisions between alternatives. In this sense, practical problems were defined by a number of competing criteria, and there may be no solution that meets all of them at the same time. As a result, the solution was a compromise based on decision-makers' preferences. The result shows the importance of the experienced allocation of weight factors to the derived results.

Various MCDM strategies were available to account for the complexity of decision making under imprecise and ambiguous settings, particularly in the renewable energy area, where all alternatives were treated consistently to ensure that a final comparison of all alternatives was justified. There were numerous options to explore, as well as different factors of varying relevance to consider while making a decision. The TOPSIS (Technique for Order Preference by Similarity to the Ideal Solution) method was a powerful MCDM method that was commonly used as a qualitative tool in design engineering to analyze alternatives. It was chosen from among the various types of weighting methods because its basic concept is perfectly suited to this analysis. This entire process finally lead to the most appropriate foundation system being installed in the evaluated locations having depth of water from 30 m to 50 m. This decision matrix method had a significant flaw in that it does not account for uncertainty. Furthermore, a decision-preference makers could play a significant role in decision-making, particularly when assigning rating and weighting variables, but it was not documented in any way.

As a matter of fact, the impact of foundations on the economic profitability of an offshore wind project is very high, therefore the conditions that influence the selection of the type of foundation to be used in the feasibility analysis phase of alternatives must be known. Noticeably, it was interesting when Thornton Bank wind farm was tested with the proposed methodology. The best option was monopile and followed by jacket foundation. Gravity-based foundation, which had the lowest score; nonetheless, as evidenced by the previous points in regard to "Thornton Bank," it was possible to verify that monopile foundation type has to be chosen as a most proper foundation.

Similarly, the monopile was found to be the best option in Horns Rev 3 wind farm, whereas the jacket and gravity-based foundations had lower scores. Monopiles are the dominant offshore wind foundations in Europe while many proponents are promoting the value of jacket foundations due to their lightness and adaptability. This is partly due to the favorable seabed conditions in the most active European markets, but it is also because monopile production capacity is larger than jacket manufacturing capacity. Also in the range of 30-50 m water depth, monopiles are perfectly territory and attractive for wind farm developers.

The gravity-based design for the Beatrice Wind Farm had the least favorable foundation, receiving the fewest numbers in total, indicating that this concept obviously could not fit the standards. Overall, jacket foundations received the highest score as the most appropriate options. The jacket was judged to be the best option versus the gravity-based and the jacket structure after the relative closeness of each support structure to the optimal solution was calculated. This seems reasonable because, although the monopile is the most economical option and less harmful to the environment, the jacket suffers less from wave-resonance than the monopile.

Since the obtained results in the different sections provide a consistent end result, it can be concluded that the methodology that has been followed and is proposed in this study is appropriate. This includes the methodology used for the implementation of the TOPSIS method to provide an objective methodology for benchmarking the various support structure options, taking into account engineering, economic, and environmental criteria.

The outcomes of this extensive study, which included a more analytical assessment of the weighting factors used in the TOPSIS technique, indicated the impact of each of the different criteria on the total scoring, enhancing the objectivity of the classification of the various possibilities. Finally, the quantification of qualitative attributes using a reference unit would improve in making more informed decisions.

7. FUTURE WORK

The TOPSIS method is suitable for determining the fundamental ranking of alternatives in a multidimensional problem. However, the use of the Euclidian distance in the calculation renders this method ineffective in some situations. The final decision should not be made solely on the results of the decision matrix. The value of a decision matrix is that it forces to view the various alternatives in a careful and thoughtful manner. However, the analysis conducted has weaknesses that it does not take uncertainty into consideration. Moreover, preference of a decision-maker could highly involve in decision making, especially in assigning rating factors and weighting factors, but it is not captured in any form.

The decision-making outcome is directly influenced by weighting variables, which are based on the decision-makers' practical engineering skills; as a result, the more experienced the decision-makers are, the more objective the conclusion. Despite the fact that most of the characteristics may be quantified, this is a difficult undertaking. There is the problem of incomplete utilization of information and lack of data throughout the decision process for applying rating factors. One of the limitations of this study is that the percentage estimation of the most important key criteria such as geotechnical consideration, economic impact, metocean loads, environmental concerns and so on. It might be more accurate depending on the experience of decision makers in the offshore renewable field to estimate the percentage.

In addition to this study, a sensitivity analysis can be performed to determine the impact of modifying the weights of the main criteria on the arrangement of alternatives. The total performance of these three alternatives would change when the new relative closeness values are calculated.

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APPENDIX A1

Table 18. The standardized Decision Matrix for “Thornton Bank I” Offshore Wind Farm

Standardized Decision Matrix			
Criterion	**Monopile**	**GBS**	**Jacket**
Geotechnical Concerns			
Seabed preparation	0.8018	0.2673	0.5345
Scour protection	0.5345	0.2673	0.8018
Soil Condition	0.6882	0.2294	0.6882
Water depth	0.8018	0.5345	0.2673
Economic Aspects			
Material cost	0.2673	0.8018	0.5345
Manufacturing cost	0.8018	0.5345	0.2673
Transportation cost	0.8018	0.5345	0.2673
Installation cost	0.8018	0.2673	0.5345
Maintenance cost	0.5345	0.8018	0.2673
Local content	0.5345	0.8018	0.2673
Metocean Loads			
Wind	0.5774	0.5774	0.5774
Waves	0.5345	0.2673	0.8018
Currents & Tides	0.5345	0.2673	0.8018
Ice	0.2673	0.5345	0.8018
Earthquake	0.5345	0.2673	0.8018
Environmental Impacts			
Noise & Vibration	0.2673	0.8018	0.5345
Wake & Scour Effects	0.8018	0.2673	0.5345
Sediment Deposition	0.5345	0.2673	0.8018
Coastal Dynamics	0.5345	0.2673	0.8018
Artificial Reefs Effect	0.2673	0.8018	0.5345
Others			
Life operation	0.2673	0.8018	0.5345
Decommissioning	0.5345	0.2673	0.8018
Dismantling	0.5345	0.2673	0.8018

APPENDIX A2

Table 19. The standardized Decision Matrix for “Horns Rev 3” Offshore Wind Farm

Standardized Decision Matrix			
Criterion	**Monopile**	**GBS**	**Jacket**
Geotechnical Concerns			
Seabed preparation	0.8018	0.2673	0.5345
Scour protection	0.5345	0.2673	0.8018
Soil Condition	0.8018	0.5345	0.2673
Water depth	0.5345	0.8018	0.2673
Economic Aspects			
Material cost	0.5345	0.8018	0.2673
Manufacturing cost	0.5345	0.8018	0.2673
Transportation cost	0.8018	0.5345	0.2673
Installation cost	0.8018	0.5345	0.2673
Maintenance cost	0.5345	0.8018	0.2673
Local content	0.8018	0.2673	0.5345
Metocean Loads			
Wind	0.5774	0.5774	0.5774
Waves	0.5345	0.2673	0.8018
Currents & Tides	0.5345	0.2673	0.8018
Ice	0.8018	0.2673	0.5345
Earthquake	0.8018	0.2673	0.5345
Environmental Impacts			
Noise & Vibration	0.2673	0.8018	0.5345
Wake & Scour Effects	0.8018	0.2673	0.5345
Sediment Deposition	0.5345	0.2673	0.8018
Coastal Dynamics	0.8018	0.2673	0.5345
Artificial Reefs Effect	0.2673	0.8018	0.5345
Others			
Life operation	0.2673	0.8018	0.5345
Decommissioning	0.5345	0.2673	0.8018
Dismantling	0.5345	0.2673	0.8018

APPENDIX A3

Table 20. The standardized Decision Matrix for "Beatrice" Offshore Wind Farm

Standardized Decision Matrix			
Criterion	**Monopile**	**GBS**	**Jacket**
Geotechnical Concerns			
Seabed preparation	0.8018	0.2673	0.5345
Scour protection	0.5345	0.2673	0.8018
Soil Condition	0.6882	0.2294	0.6882
Water depth	0.5345	0.2673	0.8018
Economic Aspects			
Material cost	0.2673	0.8018	0.5345
Manufacturing cost	0.2673	0.8018	0.5345
Transportation cost	0.8018	0.5345	0.2673
Installation cost	0.8018	0.2673	0.5345
Maintenance cost	0.8018	0.5345	0.2673
Local content	0.2673	0.8018	0.5345
Metocean Loads			
Wind	0.5774	0.5774	0.5774
Waves	0.2673	0.5345	0.8018
Currents & Tides	0.2673	0.5345	0.8018
Ice	0.8018	0.2673	0.5345
Earthquake	0.8018	0.2673	0.5345
Environmental Impacts			
Noise & Vibration	0.2673	0.8018	0.5345
Wake & Scour Effects	0.8018	0.2673	0.5345
Sediment Deposition	0.5345	0.2673	0.8018
Coastal Dynamics	0.8018	0.2673	0.5345
Artificial Reefs Effect	0.2673	0.8018	0.5345
Others			
Life operation	0.2673	0.8018	0.5345
Decommissioning	0.2673	0.5345	0.8018
Dismantling	0.5345	0.2673	0.8018