Diploma thesis:

“A simulation framework for supporting logistical decisions during planning of a floating offshore wind farm installation project”

by

Lampros Tsiros

Thesis Supervisor:

Dr. Dimitrios V. Lyridis – Associate Professor, School of Naval Architecture and Marine Engineering, National Technical University of Athens

Athens

February 2023

Acknowledgements

This study was funded by the European Commission, through the Erasmus+ programme, to which I would like to express my sincere gratitude.

Second, I would like to thank Associate Professor Dimitrios V. Lyridis, for the supervision of this thesis and his valuable support throughout its development. His role was also instrumental in helping me carry out this research work at the University of Strathclyde, by introducing me to Professor Evangelos Boulougouris, and in collecting any required data for this thesis.

Third, I wish to thank Professor Boulougouris, for his warm welcome in the University of Strathclyde and his essential help and support during my Erasmus+ research placement in Glasgow. Professor Boulougouris played a key part in helping me overcome any challenges regarding the problem modelling and the development of this thesis. Furthermore, a big thank you to Dr. Laibing Jia and Ms. Alejandra Moir, who kindly guided me through the enrolment and research project application process.

Fourth, I would like to thank Dr. Takvor Soukissian from the Institute of Oceanography – Hellenic Centre for Marine Research, for providing his immediate support when I requested historical weather data for the implementation of the case study developed in this thesis.

Fifth, I am extremely grateful to Sheila and Richard for their much-needed help and encouragement during my stay in Glasgow. They provided me with a family and a warm home and I cannot thank them enough.

Finally, a special thanks to my family and friends for their constant support throughout my studies and this thesis.

A simulation framework for supporting logistical decisions during planning of a floating offshore wind farm installation project

by

Lampros Tsiros

Abstract

Offshore wind farms provide a promising technology to produce renewable and sustainable energy. With their current development progressing further offshore and increasing in size, the floating offshore wind energy industry is rapidly maturing and is bound to play a key role in delivering a cost-effective net zero. Nevertheless, at sites where the weather conditions are significantly harsher, the risk and uncertainty in relation to the cost and duration of any installation operation increase. Hence, a well-organised planning of the overall installation process is required; however, to-date there have been relatively few studies exploring this.

In this thesis, a simulation framework is developed to model the logistics of the floating offshore wind farm (FOWF) installation process and enable decision makers to assess different installation strategies. The developed discrete-event simulation tool employs a realistic model of the installation operations where weather restrictions, task duration uncertainty, distance matrix, vessel characteristics and costs are taken into consideration.

A case study of a FOWF installation project in Lemnos, Greece, consisting of ten wind turbines is presented in order to explore the impact of key logistical decisions on the cost and duration of the installation. The simulation tool is used to assess the variation of the expected costs and lead time in different installation start-dates and to obtain an understanding of the effect of fleet sizing on the project's total cost and duration. An installation schedule with consideration of seasonality was identified and four different installation strategies were evaluated. The results demonstrate that fleet size optimisation can reduce the total installation duration by up to 50%, while only increasing the total cost by 3.8%.

Contents

List of Figures

List of Tables

Abbreviations

AHTS	Anchor Handling Tug Supply
ANN	Artificial Neural Network
ARMA	Auto-Regressive-Moving-Average
CAGR	Compound Annual Growth Rate
CfD	Contract-for-Difference
CLV	Cable Laying Vessel
DES	Discrete-Event Simulation
DLM	Dynamic Linear Model
FBOWF	Fixed-Bottom Offshore Wind Farm
FOW	Floating Offshore Wind
FOWF	Floating Offshore Wind Farm
GBF	Gravity-Based Foundation
GHG	Greenhouse Gas
H_s	Significant wave height
HTV	Heavy Transport Vessel
LCOE	Levelised Cost of Energy
MAR	Multivariate Auto-Regressive
MLP	Multi-Layer Perception
MP	Monopile
NECP	National Energy and Climate Plan
OSP	Offshore Substation Platform
OWF	Offshore Wind Farm

RBF	Radial Basis Function
ROV	Remotely Operated Vehicle
SEPLA	Suction Embedded Plate Anchor
SPMT	Self-Propelled Modular Transporter
SVM	Support Vector Machine
TLP	Tension Leg Platform
VLA	Vertical Load Anchor
WS	Wind Speed
WT	Wind Turbine
WTG	Wind Turbine Generator
YoY	Year-over-Year

1. Introduction

1.1. Thesis motivation

Electricity has become a major foundation and guarantee for human survival and economic development. If current policy and technology trends continue, global energy consumption and energy-related carbon dioxide emissions will increase through 2050 by nearly 50%, as a result of population and economic growth [1]. Meanwhile, resource depletion and environmental concerns have forced the industry to aim not only to satisfy the increasing demand, in an affordable manner, but also to move towards more sustainable solutions.

To that end, many countries have enacted environmental policies to regulate the greenhouse gas (GHG) emissions from power production units using fossil fuels. Thus, although the global power structure is still heavily dependent on fossil fuels, the global share of coal power is declining, and the global primary energy structure is accelerating towards diversification, cleanliness and low carbon [2]. In this context, wind energy has achieved rapid growth, owing to its vast environmental benefits and commercial potential.

In particular, floating offshore wind (FOW) has gained a lot of interest and has become a fast-maturing technology with the potential to expand rapidly and deliver the renewable energy capacity the world needs [15]. However, with wind farms continuously progressing towards largest sites further offshore, in deeper water and exposed to harsher weather conditions, new challenges arise which drive the costs up. In these sites, the complexity of offshore operations, the uncertainty around planning and managing these operations and the total installation duration are substantially increased [44].

The process of installing a floating offshore wind farm (FOWF) is susceptible to these challenges, and installation and logistics have been identified as areas where significant cost-reductions can be achieved. In this setting, the goals of this thesis are to track the most cost-effective logistical decisions, which can be identified by improving the understanding of how cost and duration are affected by logistical decisions during the installation operations.

1.2. Problem statement

In general, about 15% to 20% of the total costs for OWFs can be attributed to logistics during the construction process [5], [45], and these costs increase significantly when the wind farm is located further offshore, as in the case of FOWFs. Still, to-date, literature regarding the logistics of installing a FOWF is extremely limited.

Therefore, this work will focus on designing and developing a detailed discrete-event simulation (DES) model of the FOWF installation process, so as to provide decision support to OWF developers at the planning or bidding phase of an installation project. This simulation tool is purposefully designed to provide an accurate representation of the installation process and give an insight into the planning of the logistics activities, enabling the assessment and comparison of alternative logistical decisions, in the context of expected duration of each phase of the installation process and the influences on the overall project lead-time and costs.

The remaining of this thesis is organised as follows: Section 2 provides background information regarding current offshore wind and floating offshore wind development and installation operations and describes the logistics problem under investigation and its modelling approaches; Section 3 presents the objectives of this thesis; Section 4 gives an insight into the modelling considerations; Section 5 describes the methodology adopted in this study; Section 6 employs the proposed simulation model to investigate the impact of logistical decision for a case study FOWF; Section 7 presents the output analysis of the case study and, finally, Section 8 provides conclusions and areas for future development.

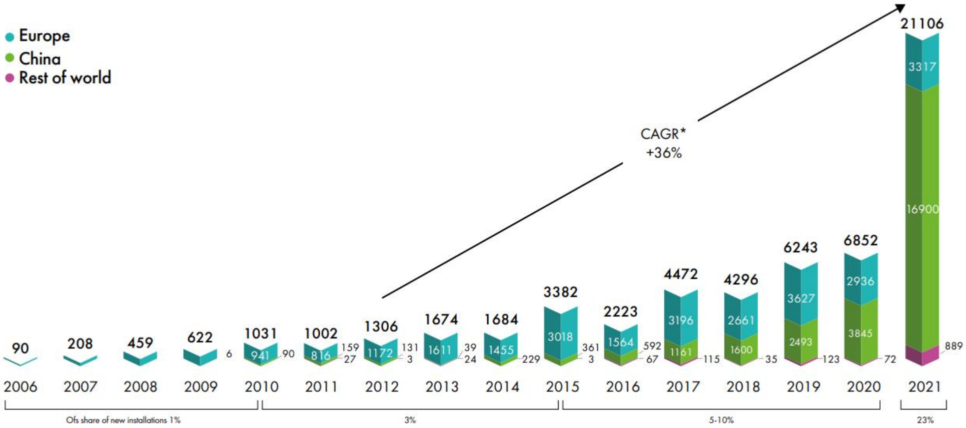
2. Background

2.1. Offshore wind

2.1.1. Offshore wind market

Currently, a large amount of renewable energy is generated using onshore and offshore wind farms, as the technology has achieved a high level of maturity. Indeed, almost 94 GW of wind power were installed in 2021, bringing the global cumulative wind power capacity to 837 GW and showing year-over-year (YoY) growth of 12% [3]. Of the 94 GW, 21.1 GW were commissioned in the offshore wind market, three times more than in 2020, setting a new record in the offshore wind industry and showcasing the market's dynamics (Figure 1) [4]. The 21.1 GW of new installations brings global cumulative offshore wind power capacity to 55.9 GW, showing YoY growth of 58% [4].

China contributed a remarkable 80% in new offshore installations, making 2021 the fourth year that China has led the world in new offshore wind installations (Figure 2). In total installations, Europe remains the largest offshore wind regional market as of the end of 2021, with the UK leading the way, followed by Germany, the Netherlands and Denmark (Figure 3) [4].



*Compound Annual Growth Rate.

Figure 1: New offshore wind installations 2006-2021 in MW [4].

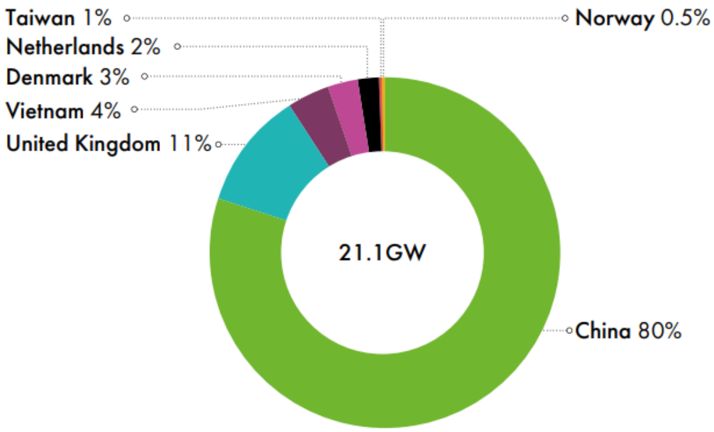


Figure 2: New offshore wind installations by market [4].

Outside Europe and Asia, North America has only 42 MW offshore wind in operation as of the end of last year, contributing just 0.1% of total offshore wind installations (Figure 4).

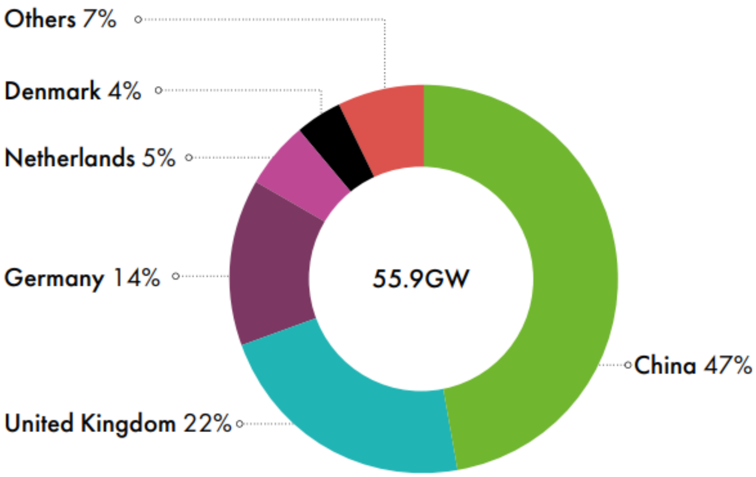


Figure 3: Total offshore wind installations by market [4].

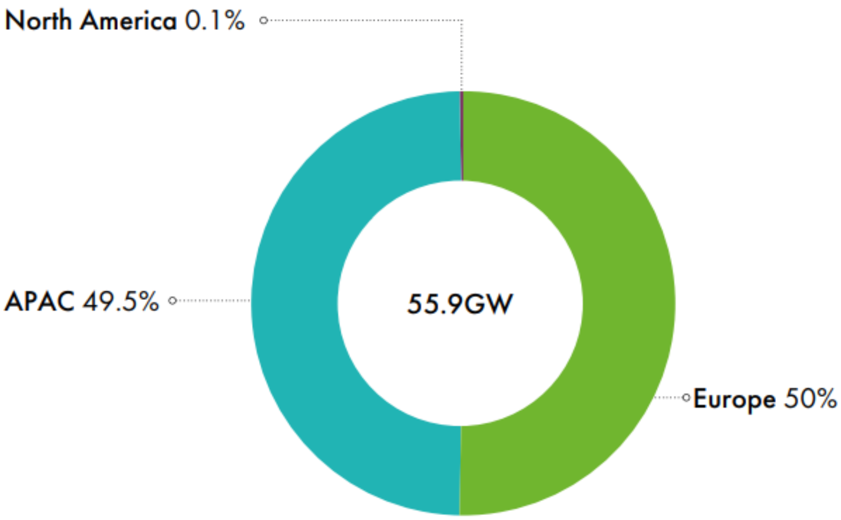
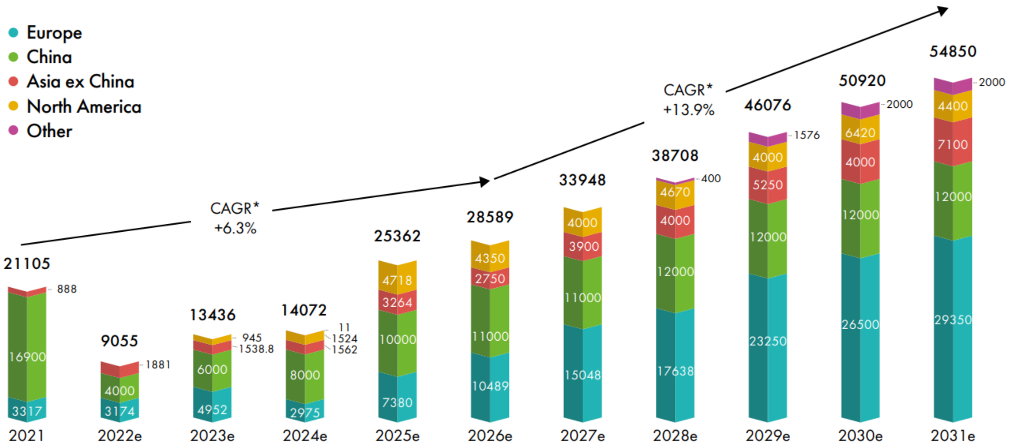


Figure 4: Total offshore wind installations by region [4].

2021 saw commitments to net zero gather global momentum at COP26. Coupled with renewed policy urgency for achieving energy independence from fossil fuels, the global offshore wind market outlook in the medium and long-term looks extremely promising (Figure 5).



*Compound Annual Growth Rate.

Figure 5: Expected new offshore wind installations in MW [4].

2.1.2. Installation of fixed-bottom offshore wind farms

This section summarises the main aspects of the different stages of a fixed-bottom offshore wind farm (FBOWF) installation process, providing a general overview of the way they are currently being installed and methods that have been developed so far.

a) Substructures

The installation process of an offshore wind farm is highly dependent on the type of substructure chosen [5]. A summary of the key features, challenges and constraints of each foundation type is provided in this section.

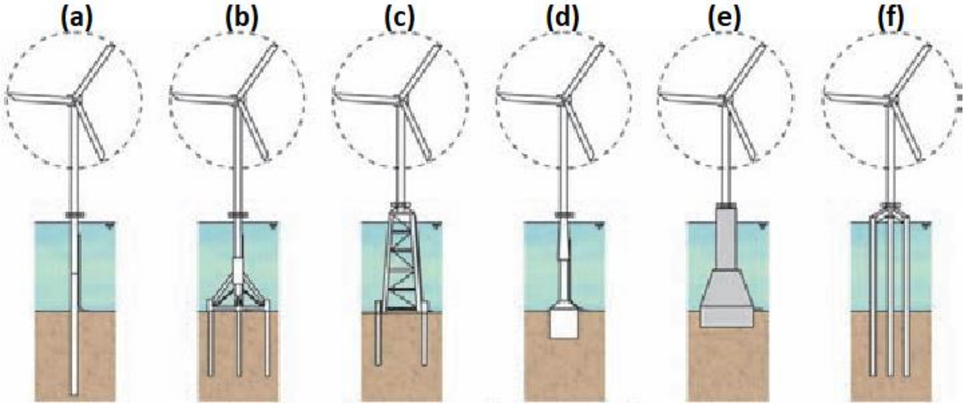


Figure 6: Types of foundation for fixed-bottom offshore wind turbines: (a) Monopile, (b) Tripod, (c) Jacket, (d) Suction bucket, (e) Gravity-based, (f) Tripile [6].

Monopiles

Design

The most typical offshore wind support system is a monopile [5]. Its design entails driving a cylindrical foundation pile into the seafloor, which mobilises horizontal earth pressures in the near-surface soils to provide lateral restraint to resist environmental loads.

Features

- Diameter: 4-6 metres with a transition piece of a larger diameter overlapping 10-12 metres. Monopiles are driven 20-30 metres into the seabed at a water depth of 30-35 metres [7]. Due to the recent trends in increasing turbine size and weight, extra-large monopiles (diameter above 7.5-8 metres) are required.
- Water depth: Monopile substructures are ideally suited to sites with water depths between 10 and 25 metres but can be used up to around 35 metres of water depth [5].
- Weight: A monopile typically weighs around 500 tonnes, making it one of the lightest support structures [5].

Construction and installation approach

Monopiles have some restrictions in terms of water depth. There are essentially two methods for installing the foundation pile, depending on the characteristics of the seafloor [5]:

- If the seabed presents a rocky structure, pile installation may require prior drilling.
- Otherwise, the foundation pile can be driven and placed firmly in the seabed with the use of a vibrating hammer or a hydro hammer. In some cases, a combination of drilling and driving needs to be employed.

Table 1: Advantages and disadvantages of monopiles [5].

Advantages	Disadvantages
Simple and quick fabrication process	Limitations of fabrication and handling from certain sizes
Proven concept	Limitations due to heavy installation equipment (hammers)
No seabed preparation required	Large scour protection required
Low price per ton of steel	Limitations of water depth
High serial production	Noise level generated during installation
Quick installation process	Difficult to remove after design life

Transportation of monopiles

Transporting a monopile from the fabrication yard or marshalling facility to the construction site is possible in a number of ways [5]. This decision is based on the installation tools being utilised, the sailing distances, and the port infrastructure.

- Floating: the monopile (MP) is plugged on both sides with a hydraulic plug, so it stays afloat when put in the water. The MP is towed to the construction site by tugs. This method is only possible when the fabrication yard is located near the marshalling harbor. Also, some on shore space is required to prepare the MP for towing. Upon arrival at the construction site, the MP is upended and both plugs are removed.

Figure 7: Monopile floating transportation [5].

- As cargo on the installation ship: when a big installation vessel is used or if the MPs are not too big, the MPs can be transported on board the installation vessel. This methodology requires an upending frame on board the vessel.

Figure 8: Cargo transportation of monopiles [5].

- With barge/offshore supply vessel: this method requires a very calm sea-state to transfer the piles from the supply vessel to the installation vessel.

Figure 9: Monopile transportation on an offshore supply vessel [5].

Gravity-based foundations (GBFs)

Design

Gravity bases are support structures which resist loads by their self-weight and ballast [5]. GBFs rely on a low center of gravity combined with a large base to resist overturning. The base structures are made of steel reinforced concrete on which the tower is placed.

Features

- Water depth: To date, concrete GBFs have been installed mainly in shallow water (7 – 27 metres) [7].
- Weight: A gravity-based foundation can weigh from 1200 to 3000 tonnes [5].

Construction and installation approach

Structures are typically transported to the location site on a barge [5]. Sometimes the support structure is floated to the installation site and towed there. This latter option results in a significant cost reduction. Some developers envision GBF designs with supplemental buoyancy that call for a dedicated transport vessel to provide buoyancy assistance. Concrete volume can be decreased thanks to this idea. These two ideas have not yet been applied, however there are plans for small-scale tests.

Table 2: Advantages and disadvantages of GBFs [5].

Advantages	Disadvantages
Reduced fatigue sensitivity compared to other concepts	Limitations of transportation and installation due to the high weight
Low environmental impact due to the absence of piling during the installation	High production cost
No transition piece installation	Challenging and complex logistical requirements
Low levels of corrosion protection	Require seabed preparation (dredging, levelling) and scour protection
Fully removable (decommissioning)	Large "footprint" (environmental impact when installed)
Possibility to be internally J-tubed	Not suitable on soft seabed surfaces
The structure can be floated	Requires special operations on deep waters
Long design life	Difficult to handle above 50m water depth as size and weight increase
	Large port infrastructure required for construction on site
	Installation procedure requires intervention of large vessels, subject to weather risks

Jackets

Design

A jacket is a structure made up of three or four legs connected by slender braces. All the elements are tubular and they are joined by welding. Each of the joints has to be specially fabricated, taking a lot of time to complete the whole structure.

Like monopiles, jackets need a transition piece to support the wind turbine tower. Melting the transition piece with the jacket substructure becomes one of the key activities during the jacket manufacturing.

Features

- Water depth: Jacket substructures are generally installed to sites with water depth up to 45 metres.
- Weight: Jacket foundations can weigh up to 2000 tonnes [8].

Construction and installation approach

Once the substructure is fully assembled, it is transported on a barge to the installation site where it meets with the installation vessel. There are two procedures when it comes to installation of a jacket: pre-pilling and post-pilling [5].

Table 3: Advantages and disadvantages of Jackets [5].

Advantages	Disadvantages
Lightweight and stiff structure	Complexity of fabrication
Better global load transmission compared to monopiles	Large number of joints required compared to other latticed structures
Large variations in water depth can be covered through cantilevering piles or modifying the geometry	Logistical issues due to the templates (pre-piling case)
Structural redundancy	Complex connection to transition pieces
Low soil dependency	High manufacturing lead-times
Good response to wave loads	No standardized design that leads to long certification processes
Limited storage area compared to GBFs	Requires special operations on deep waters
Faster fabrication compared to GBFs (serial production)	Difficult to handle above 50m water depth as size and weight increase
Better quality control	Large port infrastructure required for construction on site
Easy decommissioning	Installation procedure requires intervention of large vessels, subject to weather risks
No scour protection required	

Tripod

Design

A tripod is a standard three leg structure made of cylindrical steel tubes. These legs are connected to the main tubular, in the centre of the structure, making the transition to the wind turbine tower. The foundation piles are driven into the seabed through sleeves at the ends of each leg of the substructure. The tripod foundation extends the footprint of the monopile design for deep water installations [5].

Features

- Water depth: Tripod foundations can be installed to sites with water depth up to 50 metres [5].
- Weight: Weight can vary from 700 to 900 tonnes [5].

Construction and installation approach

The tripod support structures are pre-assembled in a construction yard. The standard installation procedure is to load several tripods onto a barge and tow them to the offshore location site where the support structures are lifted by a crane and guided to the final position. It does not require any seabed preparation [5]. The support structure is slowly lowered onto the seabed, ensuring that the structure is entirely levelled.

Table 4: Advantages and disadvantages of Tripods [5].

Advantages	Disadvantages
Lightweight and stiff structure	Complexity of fabrication
Better global load transmission compared to monopiles	Limitations of transportation due to the width
No seabed preparation required	Limitations of storage due to large sizes
No scour protection required	Slow fabrication process
Possibility to be internally J-tubed	Impractical in shallow waters
Easy to remove after design life	Main join susceptible to fatigue
Limited storage area compared to GBFs	Difficulties for mass production

Tripile

Design

A tripile is a structure made up of three individual tubular steel piles and a three-legged transition piece that connects to the turbine tower on top. The transition piece is made of flat steel elements and weighs approximately 490 tonnes [5]. The joints between the piles and the transition piece are grouted permanently. The tripile foundation is also a relatively new adaption of the traditional monopile foundation. Instead of a single beam, three piles are driven into the seabed, and are connected just above the water's surface to a transition piece using grouted joints.

Features

- Water depth: Tripile foundations can be installed to sites with water depth up to 50 metres [9].
- Weight: Weight can reach 1100 tonnes [5].

Construction and installation approach

During the installation the piles are first driven into the seabed. Afterwards, with the top of the piles rising above the water, the transition piece is placed on top, with each leg-end aimed into a pile [9].

One challenge during installation is accurately positioning the three piles. With the assistance of a seabed template and the Global Positioning System, the piles are hammered down one by one [5]. Afterwards, the tops of the piles rise above the sea, allowing subsequent operations to be performed above water. This contrasts with monopiles, where a large portion of the transition piece is below the mean sea level.

Table 5: Advantages and disadvantages of Tripiles [5].

Advantages	Disadvantages
No bolted or welded connection between piles and transition pieces	Complexity of transition piece manufacturing
Easily adjustable to water depths	Complexity of transition piece installation
Loads transferred by the grout alone	Only one test facility to date
Compact construction relatively costeffective	Difficulty for mass production
All connections above the water surface	
Less dependency on weather conditions	

Suction bucket

Design

Suction bucket is a large diameter cylinder, with a closed cap, resembling a gravity base foundation in shape and size. Once the bucket is installed, vacuum pressure is removed [9]. This type of structure has been used to assist levelling of a traditional GBF or as a support for a jacket or tripod structure.

Features

- Diameter: From 2 to 4 metres in diameter for water depths less than 5 metres, and up to 12 to 15 metres in deeper waters [9].

- Weight: A prototype monopod suction bucket at the Aalborg University offshore test facility in Frederikshavn weighs approximately 150 tonnes. Second prototype in Wilhelmshaven, Germany, came up to 450 tonnes [5].

Construction and installation approach

The installation method and the load transfer mechanisms are different from the gravity base substructures. Suction bucket is placed on the seabed and a pump is activated subsequently to remove water from within its hollow section [9]. This creates suction underneath the cap and drives the bucket into the seabed. Once the pressure is removed, the wall friction keeps the bucket in place. Suction buckets provide the possibility of integrating the transition piece, and hence the need for grouting the transition piece once the foundation is installed.

Table 6: Advantages and disadvantages of Suction buckets [5].

Advantages	Disadvantages
Faster installation process with no dependency on jack-up vessels, no seabed preparation, no diving need	Since installation is reliant on the pressure difference a minimum water depth is required
Capability to accommodate a broad range of site conditions, loadings and operational performance requirements	Installation proved in limited range of materials
No pile driving eliminating the associated environmental concerns regarding noise and avoiding 'no pile driving' periods in the year	More expensive construction
Easy to remove by reversing the installation process	Installation and lifetime use is very site specific
Possibility of integrating the transition piece eliminating the need for a grouted connection	Complex equipment for pumping
Reduced or no need for scour protection	Time for pumping and checking of leveling
The foundation weighs less than traditional foundation structures	
Manufacturing easiness (less steel and simpler welded joint)	

b) Fixed-bottom offshore wind turbine installation

After the foundations and transition piece are in place, the turbines are installed. There are various options for turbine installation, depending on the number of lifts required (from 6 to 1 lift) [5]. Generally, turbines are delivered at port in seven key components: 3 blades, 2 tower sections, the nacelle and the hub. Some quayside assembly is done to reduce the number of offshore lifts, and the amount of pre-assembly influences vessel selection and installation time. The turbine is then taken to the site in its main components and then it is erected on top of the foundation substructure using a jack-up vessel (barge or self-propelled) and/or crane barge.

For the turbine installation, the following vessels are the most commonly used and the pros and cons of each one are set out as follows [5]:

- Jack-up barge:
    - Limited storage capacity
    - Sufficient lifting power and height
    - Slow, hauler needed
    - Less susceptible to waves
- Jack-up crane vessel (self-propelled):
    - Large storage capacity
    - Sufficient lifting power and height
    - Fast, flexible and independent
    - Less susceptible to waves
- Heavy-lift crane vessel:
    - Very limited storage capacity
    - Strong lifting power, low height
    - Slow, hauler needed
    - Susceptible to waves

c) Cable installation

Before starting the cable installation process, a survey on the seabed is required to identify the possible obstacles and specify the routes of the cables [10]. This survey is also required to ensure that the cable paths are free of any potentially hazardous obstacles, such as the location of existing pipes and unexploded weapons, which could endanger seabed users. Furthermore, debris must be removed from the cable paths, which can be accomplished through pre-lay grapnel run or other methods.

Generally speaking, the installation process for both of the export and array cables includes the four main steps as follows: i) cable laying, ii) cable burial, iii) connecting cable to tower, offshore substation platform (OSP), and onshore substation, and iv) testing. The types and the number of vessels required for cable installation depend on the seabed condition and the available facilities of the contractor. Various cable installation methods can be categorised as follows [10]:

- Method I: This method is performed by using a cable plough, in which the cable is fed to plough by a turntable attached to the vessel. Since this method simultaneously inserts and buries the cable into the seabed, the cable installation costs are relatively less than other methods. By using the water jet technology, this method can bury the cables in a 3 m up to 4 m trench below the seabed. The applicability of this method, however, is dependent on the soil specifications. This method has been used to instal export cables in various wind farm projects. It is worth noting that the cable plough method cannot be used near wind turbines (WTs) or OSPs, and that an additional operation with a trenching remotely operated vehicle (ROV) is usually required to connect the cable to WTs.
- Method II: In some cases, an ROV, which is carrying a given length of cable, is used to lay and bury the cable into the seabed. Since the cable carrying capacity of the ROV is limited, this method is more appropriate for installing inter-array cables.
- Method III: This method pre-excavates a trench using a backhoe dredge and lays the cables within the trench by using a cable laying vessel (CLV). Finally, the cables are buried using the dredge.
- Method IV: In some cases, the cable first is laid on the seabed and then, an ROV is used to bury the cable into the seabed.

- Method V: In this method, which is applicable only for inter-array cables installation, the cables are pulled between the WTs using a winch and then, the cables are buried into the seabed by using a cable laying vessel.
- Method VI: In some cases, combinations of the abovementioned methods are used.

2.1.3. Major fixed-bottom offshore wind projects

There are numerous key FBOWFs across the globe, but the large majority of them are situated in the UK, which hosts 22% of the total, global, offshore wind installations [4]. More specifically, the three largest OWFs are located in the North Sea providing the grid with a total of 3450 MW [11].

First, the 1.3 GW Hornsea 2 offshore wind farm is the largest operating wind farm in world. It comprises of 165 Siemens Gamesa 8MW SG 8.0-167 DD turbines which power a total of 1.4 million UK homes with clean electricity [12]. Located approximately 89 kilometres off the Yorkshire coast in the North Sea, where the normal water depth ranges between 30 and 40 metres, the wind farm spans an offshore area of 462 square kilometres.

Preceding the largest offshore wind farm in the world, is the 1.2 GW Hornsea 1 wind farm, which is the second largest [13]. Comprising of 174 Siemens Gamesa 7MW SWT-7.0-154 turbines, it powers over 1 million UK homes. It is adjacent to its successor, the Hornsea 2, located approximately 120 kilometres off the Yorkshire coast in the North Sea, and it covers an area of 407 square kilometres.

Finally, the third largest offshore wind farm in the world is the 950 MW Moray East project [14]. It comprises of 100 Vestas V164-9.5MW wind turbines capable of powering a total of 950 thousand UK homes. Situated in the Outer Moray Firth, just 22 kilometres off the coast of Scotland, at an average water depth of approximately 40 metres, it spans an offshore area of 295 square kilometres.

2.2. Floating offshore wind

2.2.1. Floating offshore wind market

Floating offshore wind is a fast-maturing technology with the potential to expand rapidly and deliver the renewable energy capacity the world needs [15]. The most significant advantage of FOW is the fact that it unlocks new renewable energy potential. Around 80% of the offshore wind resources is located in waters of more than 60-meter depth, where bottom-fixed offshore wind is not economically viable [16], [21]. In addition, average wind speeds are higher and more consistent further from shore. This means FOWFs can produce more energy throughout the year and have high capacity factors.

In the past decade, MW-scale floating technologies have been tested through demonstration and pilot projects in both Europe and Asia, so the sector is still in a pre-commercial phase [4].

However, there are floating offshore wind farms operating successfully in the UK and Portugal, as well as a significant pipeline of projects in different markets across the world [17]. Specifically, 57.1 MW of floating wind was installed in 2021, of which 48 MW was in the UK, 5.5 MW in China and 3.6 MW in Norway. As of 2021, a total of 121.4 MW of net floating wind is installed globally, of which 78 MW is located in the UK, 25 MW in Portugal, 5.9 MW in Norway, 5.5 MW in China, 5 MW in Japan and 2 MW in France.

Floating wind's current contribution to total offshore wind installations is only 0.2%, but it will play an increasingly key role toward the end of this decade, accounting for 6.0% of total installed offshore wind capacity by 2030 [4].

2.2.2. Installation of floating offshore wind farms

Installation operations for floating offshore wind turbines are different from the ones for fixed-bottom offshore wind turbines, mainly due to the fact that they mostly take place onshore [16]. This section provides a general overview of the methods that have been currently developed in order to install and commission a FOWF.

a) Substructures

Depending on the floating substructure used, the installation process varies. Floating wind platforms can be mainly classified into three broad categories according to the restoring mechanism for attaining hydrostatic equilibrium. They can be ballast stabilized, buoyancy stabilized, mooring stabilized or combinations of these [17]. Figure 10 demonstrates how the different floating offshore wind turbines (FOWTs) developed around the world fit into a stability triangle.

Generally, floating wind installation requires a greater number of vessels compared to fixed wind, but the vessels are cheaper to hire and easily available [17]. Even though many floating wind concepts have been developed, only a few have been successfully deployed and commissioned in a commercial level. In fact, there are four dominant types of floating wind foundations in use or development (Figure 11), with the semi-submersible and the spar floater concepts being currently used by the three largest FOWFs in operation.

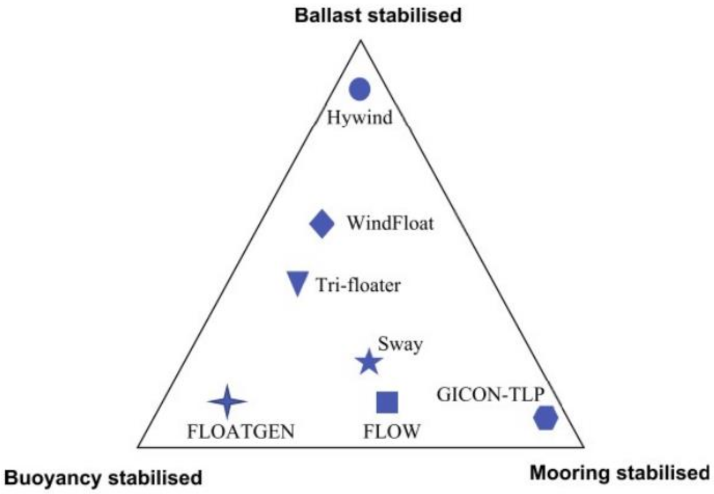


Figure 10: Stability triangle for floating structures [17].

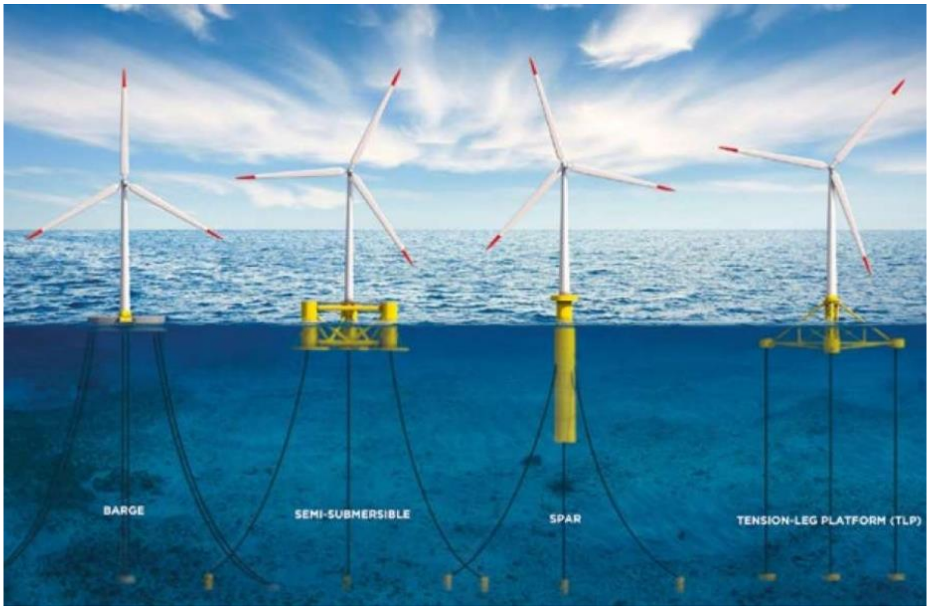


Figure 11: Floating offshore wind platform types [16].

Barge-type

Design

A barge is a hull made of either steel or concrete whose stability is ensured primarily by its water plane area moment due to the comparably large diameter and shallow draft [18]. It is also ballasted with seawater. Even though the barge type foundation is suitable for shallow water ports, due to its low draft, it has the most sensitive reaction to wave motions that other types of floating substructures [19]. Some barge designs include a moonpool to suppress wave-induced loading [20].

Features

Barge type foundations are anchored to the seabed using catenary mooring lines, while their weight can vary between 2000 tonnes (steel) and 8000 tonnes (concrete) [21].

Construction and installation approach

Full system assembly can be completed quayside and a general construction workflow is as follows [19]:

- Substructure components are constructed and joined close to shipyard quay
- For the generic case where the foundation is not constructed at the marshalling and assembly port, self-propelled modular transporters (SPMTs) must be used to loadout the completed substructure onto a heavy transport vessel (HTV)
- The substructure is transported to the marshalling and assembly port
- It is then floated off from the HTV and moored to the fit-out quay
- The tower, nacelle and blades are fitted to the top of the substructure using an onshore crane
- The completed system is towed to the offshore location using tugboats and anchor handling tug supply (AHTS) vessels
- It is finally connected to the pre-installed mooring lines and inter-array cables and commissioned

Table 7: Advantages and disadvantages of barge-type substructures [21].

Advantages	Disadvantages
Operable at depths starting 30 metres to accommodate complex seabed conditions	Sensitive to wave-induced loading
Builtable in steel or concrete, offering flexibility in using the highest local content	Robust mooring systems required, increased complexity
Simple shape and fabrication techniques	
Scalable to support heavy substation	

Semi-submersible

Design

The most popular floater concept is the semi-submersible substructure, which is a hull with columns, typically three, that are connected to each other with bracings [5], [21]. Semi-submersibles are buoyancy-stabilised floaters whose stabilising righting moment is contributed by the large water-plane area of the hull and the low center of gravity which lies below the center of buoyancy [17]. This is achieved by adding ballast to the bottom of the columns.

Features

Semi-submersibles are anchored to the seabed using catenary mooring lines, while the specific weight of the structure [tonnes/MW capacity] varies from 400 tonnes/MW to 700 tonnes/MW [21]. In current designs, the distances between each two columns are approximately 50 metres and their diameter is in the region of 24 metres. In operating conditions, hull draft is approximately 25 metres [22].

Construction and installation approach

The installation of a floating offshore wind turbine supported by a semi-submersible foundation is no different than the one of barge-type foundation [19]. The system can be fully constructed and assembled onshore and then towed to its location using tugs and/or AHTS vessels.

Table 8: Advantages and disadvantages of semi-submersible substructures [21].

Advantages	Disadvantages
Reduced heave response	Non-industrialised fabrication
Broad weather window for installation	Complex structure, fabrication
Flexible port depth	Requiring special fabrication yard with skid facilities
Cheap and simple mooring and anchoring system	
Overall lower risk	
Simple installation and decommissioning	

Spar

Design

A spar-buoy (or spar) is a cylindrical, ballast-stabilised structure that has a center of gravity far below the sea surface and its center of buoyancy [17]. Its weight induced stability provides minimum sensitivity to wave motions, thus making it a very competitive alternative to the semi-submersible floater concept.

Features

In general, a spar substructure can have a diameter of approximately 15 metres, a length of 90 metres and a steel weight of 2300 tonnes [23]. Fully upended and ballasted, it can weigh more than 10000 tonnes. It is anchored to the seabed using catenary mooring lines [5].

Construction and installation approach

The spar-type substructures have high draughts which require the use of offshore system assembly [17]. In particular, the assembly of the steel substructure is performed onshore by building the spar hull horizontally. The substructure is loaded out onto a heavy transport vessel, taken to a sheltered location for float off. The Spar hull is then upended using water ballast, in deep sheltered water. Then solid ballast is added to the base. The topside turbine (tower, nacelle and blades) is assembled on land and fitted onto the Spar hull, in sheltered water using a heavy-lift vessel. The concrete spar starts off by being slip formed vertically in a dry dock. The completion of the substructure continues in deep water using slip forming. Solid ballast is added to the base. Both steel and concrete types of spar require temporary moorings to be set up in sheltered water and also work barges to be alongside.

Table 9: Advantages and disadvantages of spar-type substructures [21].

Advantages	Disadvantages
Minimum sensitivity to wave motions	High cost due to the size of the construction
Suitable for higher sea states	Deep drafts limit port access
Cheap and simple mooring and anchoring system	Challenging and time-consuming assembly at sheltered deep waters
Simple fabrication process	Expensive heavy-lift vessel needed for turbine assembly
Low operational risk	
Little susceptibility to corrosion	

Tension Leg Platform (TLP)

Design

The basic design of a TLP includes four air-filled columns forming a square, which are supported and connected by pontoons, similar to the design of a semisubmersible production platform [24]. The buoyant hull supports the topside of the platform and an intricate mooring system keeps the platform in place. The buoyancy of the hull of the platform offsets the weight of the platform, requiring clusters of tight tendons, or tension legs, to secure the structure to the foundation on the seabed. The foundation is then held in place by piles driven into the seafloor.

Features

They are suitable for intermediate water depths, starting from 70 metres, which is an approximate upper limit for fixed-bottom offshore wind turbines, and 200 metres, beyond which the spar-type platforms are more cost-effective [24]. The specific weight of a TLP can be in the region of 330 tonnes/MW [21].

Construction and installation approach

The installation of a conventional TLP system is a complex process [24]. The tendons, which hold the platform in place, are usually installed before the platform. The TLP floater is constructed onshore and towed to the location using tugboats or transported using a bespoke barge. The platform is ballasted and connected to the pre-installed tendons. Finally, the platform is de-ballasted to a draught where the tendons attain the optimum tension and the TLP is secured.

Table 10: Advantages and disadvantages of TLPs [21].

Advantages	Disadvantages
High stability, low motions	Unstable during assembly, requiring the use of special vessel
Good water-depth flexibility	High vertical load moorings
Short mooring lines	Complex and expensive anchors and mooring lines
Simple and light structure	Mooring tendons present higher operational risk in case of mooring failure and add requirements on site seabed conditions
Lower material costs due to structural weight	

b) Anchoring and mooring systems

A key component of floating offshore wind farms installation operations is the anchoring and mooring system used to hold the wind turbines in place. This section provides an overview of the currently developed anchoring systems.

i. Design of anchoring and mooring systems

The process of designing a mooring system for a floating energy production system is complex, but the overall process is mature. As such, years of past work and project experience in offshore industries show that many factors must be considered. Factors will vary depending on the type of floating system being moored and the geographic region in which it is intended to operate. These include [25]:

- Mooring system design, fabrication, installation, inspection, maintenance and repair requirements and applicable regulatory codes and standards to obtain and maintain regulatory classification
- The floating system's station-keeping performance requirements to design a mooring system that will facilitate and maximize energy production and power transmission (e.g., cables, umbilicals, etc.)
- The system's design life and long-term inspection, maintenance and repair requirements and constraints as they affect mooring component selection

- Site-specific metocean environmental conditions and geotechnical properties that the mooring system and its components must withstand and can be anchored in
- Availability, fabricability and maturity of the selected mooring components
- Installation vessel availability, accessibility and capability
- Local staging and mobilization yard accessibility, availability and capability for mooring equipment and offshore operations support
- Logistical requirements and constraints for shipping, importation and the receipt of mooring and installation equipment

With floating wind turbines, there are additional elements to consider [25]. Turbine proximity to other turbines, for example, must be considered because it affects energy production efficiency. The interaction of the system with other marine users and marine life must be assessed. Multiple turbine arrays moored and anchored together can have an impact on marine traffic and local fisheries. Consideration of these effects during planning and design can help to alleviate potential concerns. Last but not least, it is critical to ensure that the anchoring and mooring costs are integrated into the overall economics of the wind farm, so that the project can meet its economic goal in terms of the levelised cost of energy (LCOE).

ii. Types of anchoring systems

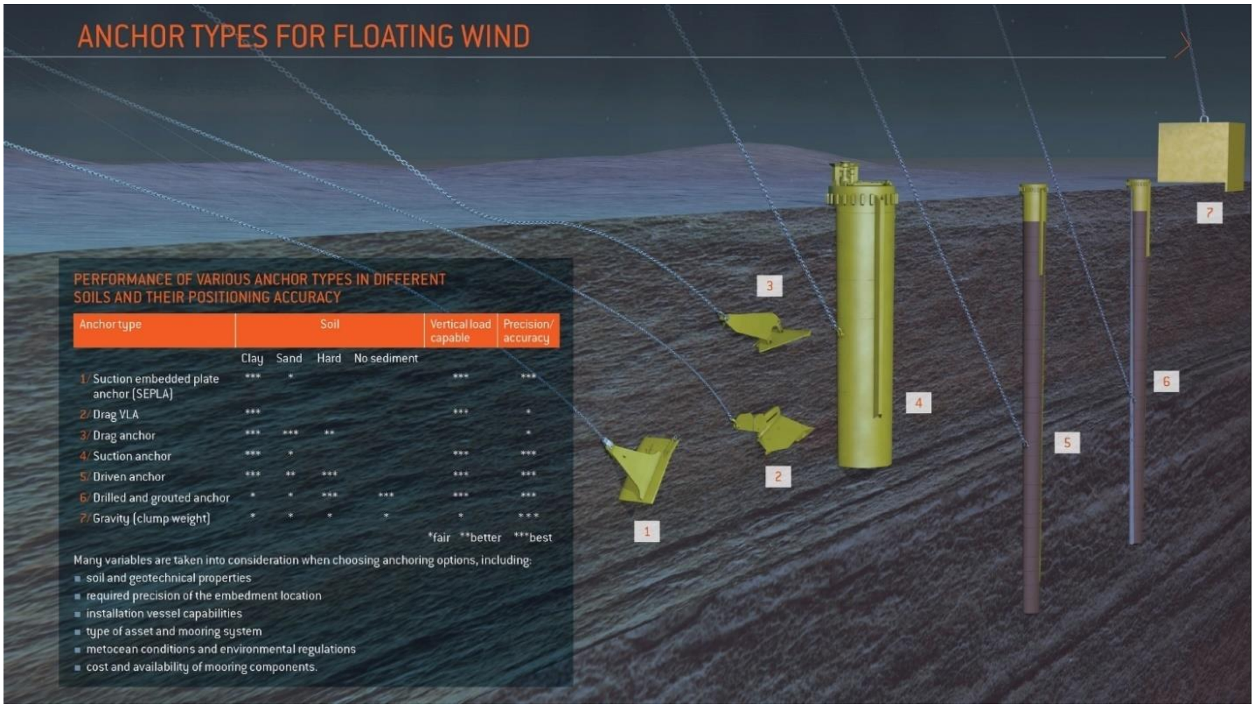
There are differences in bottom soil conditions all over the world. These soil conditions have a big influence on the load capacity of any anchor system [26]. A greater load capacity of any anchor can be achieved by a deeper embedding, also the greater quantity of affected soil [25], [26]. Therefore, permanent anchors can be designed for different types of soils. These will further be discussed in this section.

The most effective resisting force is by applying the force parallel to the bottom without deep embedment [26]. As the resisting forces increases, it will dig deeper into the seabed. The catenary mooring system is using this principal advantage. Heavy chains are being used that form a catenary shape. An average horizontal force of the platform is reacted from the point of attachment to the sea floor. Catenary moored anchors are less expensive, because the mooring forces are mainly horizontal, which requires less accurate anchor drop [26]. Unfortunately, a greater motion is experienced compared to other mooring systems, like taut-leg or vertical tension-leg systems.

The deeper the embedment, the greater the pull-out load, which is the key to maximize the load. Since horizontal loads can embed themselves deeper and deeper, vertical loads will take more effort to get deeper. Vertical loaded anchors are therefore more expensive to install [26]. Finding a relatively cheap anchoring system with a high vertical load capacity that is easy to install is very challenging.

Elements that define the cost of an anchoring system depend on the material cost, the type of installation and mooring lines of chain, cable, or pipe. The different types of seafloor anchors most commonly used are listed below [27]:

- Suction embedded plate anchor (SEPLA)
- Drag Vertical Load Anchor (VLA)
- Drag anchor
- Suction anchor
- Driven anchor
- Drilled and grouted anchor
- Gravity anchor



PERFORMANCE OF VARIOUS ANCHOR TYPES IN DIFFERENT SOILS AND THEIR POSITIONING ACCURACY

Anchor type	Soil				Vertical load capable	Precision/ accuracy
	Clay	Sand	Hard	No sediment		
1/ Suction embedded plate anchor (SEPLA)	***	*			***	***
2/ Drag VLA	***				***	*
3/ Drag anchor	***	***	**			*
4/ Suction anchor	***	*			***	***
5/ Driven anchor	***	**	***		***	***
6/ Drilled and grouted anchor	*	*	***	***	***	***
7/ Gravity (clump weight)	*	*	*	*	*	***

*fair **better ***best

Many variables are taken into consideration when choosing anchoring options, including:

- soil and geotechnical properties
- required precision of the embedment location
- installation vessel capabilities
- type of asset and mooring system
- metocean conditions and environmental regulations
- cost and availability of mooring components.

Figure 12: Anchor types for floating wind [27].

Suction embedded plate anchor (SEPLA)

Design and installation

The SEPLA technology combines two proven anchoring concepts – suction piles and plate anchors – to increase the anchor point efficiency of pre-set moorings and reduce mooring system costs for floating structures [28]. It is applicable to oil and gas as well as floating renewables.

It uses a suction follower (similar to a suction anchor) to embed a plate anchor deeply in the soil. The suction follower is retracted once the plate anchor is brought to design soil depth and can be used again and again to install additional plate anchors [28].

Key advantages

The advantages of suction embedment and plate anchors are combined in the SEPLA technology. As they utilise a suction follower, SEPLA anchors are classified as direct embedment anchors [28]. This means the precise location and depth of the anchor is known (whereas location and depth of drag-embedded anchors can only be estimated). In congested fields, where a clear area to drag in an anchor may not exist, SEPLA is the ideal solution. Other advantages include [28]:

- Suction pile precision
- No dragging necessary
- Vertical load capable (VLA)
- Geotechnically more efficient than suction piles (higher ratio of holding capacity to weight)
- Less material used (more weight efficient)
- Simple fabrication process
- Efficient transport/installation
- Recoverable system

Drag Vertical Load Anchor (VLA)

Design and installation

The drag vertical load anchor is installed with a low angle between the mooring line and the fluke [29], [30]. When the required installation load is reached, the anchor is triggered to the normal loading mode. The load arrives perpendicular to the fluke, providing a high pull-out resistance [30].

They are similar to drag anchors as they are installed in the same way. However, the vertical load anchor can withstand both horizontal and vertical mooring forces [29]. It is used primarily in taut leg mooring systems, where the mooring line arrives at an angle at the seabed.

Key advantages

Main advantages of the drag vertical load anchor are listed as follows [29], [30]:

- Suitable for taut leg mooring systems
- Deep penetration in soft clay soil conditions
- Simple installation
- Loading in all directions possible
- Ratio of ultimate holding capacity to installation load: 2.5 to 3.5
- Recoverable system

Drag anchor

Design and installation

One of the most popular anchoring solutions, the drag anchor is dragged along the seabed until it reaches the required depth [29]. It uses soil resistance to keep the anchor in place as it penetrates the seafloor. The drag embedment anchor is primarily used for catenary moorings, where the mooring line is laid horizontally on the seabed. It does not perform well when subjected to vertical forces.

Key advantages

The advantages of this anchor type are [29]:

- Suitable for catenary moored systems because precise placement is not needed
- Simple installation
- Low cost
- Good horizontal mooring forces resistance
- Recoverable system

Suction anchor

Design and installation

Suction anchors have a physical look of a long pipe, which is open at the bottom end and closed at the top. These are a good alternative for the driven pile anchor. In order to evacuate the water which sucks the pipe into the bottom soil, the closed end is outfitted with pump fittings [26]. A transverse tension direction is achieved on the pipe by attaching an anchor line to a pad eye near the midpoint of the pipe. In this way the tension line is placed well down in the deeper soil allowing a large wedge of soil to support the line load. Suction anchors can have a length of 16 metres, a diameter of 5 metres and a weight of approximately 300 tonnes [31]. They are very effective for vertical loading and a common anchoring approach.

Key advantages

Major advantages of this anchor type include [26]:

- Suitable for catenary moored systems because precise placement is not needed
- Simple installation and easy application at greater water depths
- Low cost
- Very effective for vertical mooring forces
- Easily removable during decommission

Driven anchor

Design and installation

The driven pile anchor concept is a simple and reliable anchoring approach which has been developed over the years of experience in the oil and gas industry [26]. This anchor type is simply hammered into the seabed and a mooring line is attached to it, capable of withstanding loads in every direction.

Key advantages

Key advantages of this anchor type include [26]:

- Simple design, fabrication and installation
- Very reliable solution
- Suitable of withstanding mooring forces in all directions

Drilled and grouted anchor

Design and installation

A drilled pile mooring system may be required when the seabed lacks permeable soil conditions in which an anchor can be easily embedded [26]. Instead of driving a pile into the seabed, a pile or ground anchor is drilled into the seafloor and grouted [29]. The used pile will contain of similar in size and shape as the driven pile.

Key advantages

The advantages of drilled and grouted pile compared to driven piles are [26]:

- Applicable in hard soil conditions
- More reliable
- Can achieve higher vertical loads

Gravity anchor

Design and installation

Perhaps the simplest anchoring solution is the gravity anchor. Gravity-based foundations and clump weights are used as mooring foundations for floating offshore wind turbines in shallow waters and soil conditions where suction anchors are ineffective due to soil penetration limitations and risk. [32]. The vertical and horizontal load capacity of the mooring anchors on the seabed is dependent on the coefficient of friction at the specific site, where the soil could typically be a combination of sand, gravel and silt/clay [32]. The difference between the anchor's weight and its buoyancy defines the load carrying capacity. Artifical reefs and scour protection may be included in the design.

Key advantages

Main advantages of the gravity anchor include [26], [32]:

- Simple and cheap solution
- Suitable for TLPs
- Simple installation
- Recoverable system

iii. Mooring system installation considerations

Mooring installation is a significant cost contributor for FOWTs. The fairlead connector (e.g., stopper or uni-joint) design and the selected anchor type have a significant impact on the installation method [33]. To reduce costs, simple and cost-effective installation methods are required. The installation method for shallow water mooring applications is well-established in the oil and gas industry. Mooring lines are typically pre-laid on the seafloor. The top segment of the lines can either be connected to the pre-laid system, tentatively suspended and held by marker buoys, or attached to FOWT inshore and used for offshore tow [33]. When the floater is towed to site, it is connected to the pre-laid mooring lines by an AHTS vessel [33], [34].

A cost-effective solution for installation (i.e., mooring pre-lay and hook-up) is much needed. Tensioning of mooring lines is one of the main tasks during hook-up [33], [34]. The conventional method used on oil and gas floaters is to place a temporary chain jack (or a winch) on the platform to tension up the mooring lines. Two alternative methods have the potential to reduce the cost and requirement for manual operations onboard FOWT [33], [34]. The first involves the use of multiple tugboats to pull the floater and connect the mooring line to an anchor handling vessel via an H-link. This method, however, may prove difficult for mooring systems that require higher pre-tension levels, as will be the case with increasing turbine and FOWT size. Another method is to use an in-line tensioner. With an in-line tensioning system, tensioning of the mooring line is carried out using an anchor handling vessel on the sea surface and pulling on the active chain through in-line tensioner with the vessel winch. The in-line tensioner itself is not an on-vessel device, but rather a permanent component in the mooring line. Disconnection, or later reconnection if required, can be done by use of a ROV operable chain connector. For a 3-line system, only one of the lines will require active tensioning [34]. The two first lines can be passive and connected to FOWT at low tension. This translates into lower capital costs and lower maintenance costs for the tensioning system onboard.

iv. Novel mooring solutions

Mooring systems deployed in early demonstration projects are a natural extension from the practice of the traditional oil and gas industries. The number of mooring lines is limited. However, as the floating wind industry grows, the large volumes of mooring lines and anchors pose significant installation, transportation, logistics, and supply chain challenges. Floating wind technology developers may underestimate the total mooring system costs, which include design, installation, operations, and maintenance [33]. Taking installation logistics into consideration during the design phases, technologies that enable rapid and low-cost transportation and installation may become attractive. Therefore, novel solutions are constantly being investigated. Many concepts and ideas are being pursued to develop different anchoring devices and mooring configurations. Some involve multiple floaters that are moored together (i.e., lines connecting adjacent floaters) and multiple mooring lines anchored with shared anchors [17], [25].

Indeed, a shared anchoring system is currently being developed for the 88MW Hywind Tampen floating offshore wind farm [35]. In fact, for large floating offshore wind farms, the mooring lines and anchors can be shared with multiple FOWTs, reducing total mooring line length, saving construction material for anchors and reducing the need for marine operations by optimising utilisation of installed infrastructure [17]. In a shared mooring system (Figure 13), the FOWTs are inter-connected using mooring lines, reducing the frequent connections to the seabed using anchors. In a shared anchor system, a single anchor takes multiple mooring lines and the number of anchors can be reduced. Both of these systems are suitable for large wind farms, and significant cost savings are possible due to material cost savings.

Other kinds of mooring line components are also being researched, developed and tested [25]. Low stiffness synthetic lines like nylon are being augmented and constructed in ways that make them more fatigue-resistant to accommodate long design lives. Traditional mooring components are being combined in varying ways to achieve composite stiffnesses that achieve preferred station-keeping performance characteristics. Mechanical devices that offer a more compact way of providing design specific stiffness characteristics and load monitoring capability are also being developed.

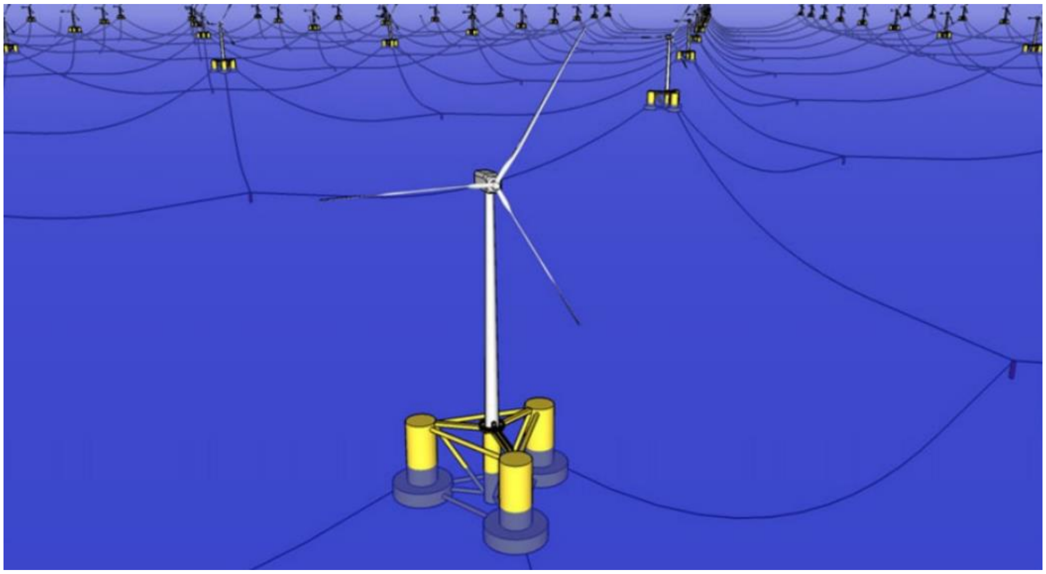


Figure 13: Shared anchor system [17].

In terms of installation, new and innovative mooring installation methods and techniques are being tested in order to maximise the economies of scale that come with arrays of multiple floaters moored together or close to each other. Off-vessel tensioning devices and techniques are also developed in order to reduce the capital expenditure associated with housing and installing winches and fairleaders on the floater, as well as to facilitate long-term mooring maintenance and repair work with minimal operational expense [25]. Methods and products that can be installed in shorter amounts of time are also being developed. Saving a short amount of time on a given operation can result in significant savings on commercial wind farms, as that operation may occur hundreds of times throughout a campaign.

c) Cable installation

Compared to conventional, fixed-bottom offshore wind turbines, floating wind turbines require a both a static and a dynamic cable system [36]. Cable installation follows the same approach as explained in Section 2.1.2, with the addition of floating components which make the cable dynamically suspended and enables it to move with the floater [36], as shown in Figure 14. These buoyancy modules are essential for the dynamic power cable since they enable motion decoupling between the floating installation and the touchdown point on the seabed [37]. Buoyancy module attachments will likely be required to achieve the required shape for the extra-length of cable and several equally spaced buoyancy modules need to be installed on the cable. Other important dynamic cable components can also be seen in Figure 14.

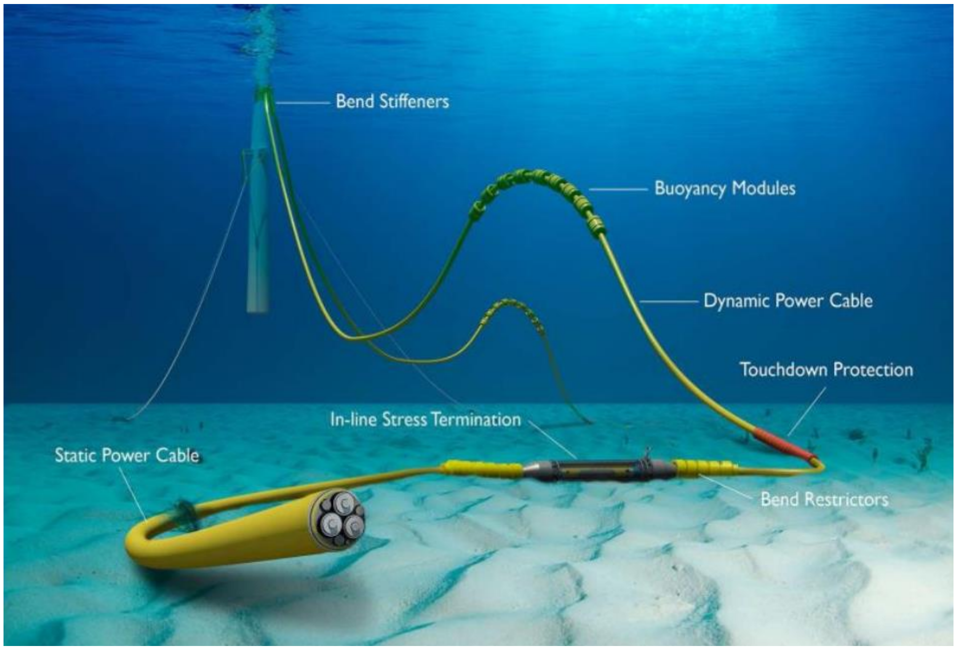


Figure 14: Dynamic cable related components [38].

2.2.3. Floating offshore wind key benefits

As part of Net-Zero goals and ambitious energy transition objectives, offshore wind projects are multiplying around the world and floating wind systems are allowing the industry to move further offshore towards greater water depths. This section examines the key benefits of floating offshore wind.

The most significant advantage that floating offshore wind offers is the fact that it unlocks new renewable energy potential. Around 80% of the offshore wind resources is located in waters of more than 60 metres depth, where fixed-bottom offshore wind is not economically attractive [16], [21]. In addition, average wind speeds are higher and more consistent further from shore. This means floating offshore wind farms can produce more energy throughout the year and have high capacity factors [16]. Also, FOW opens new markets (e.g., France, Norway, Spain and Portugal) for the offshore wind energy industry and enables the harnessing of great wind resources in shallower waters (as low as 30 metres) where the seabed quality makes fixed-bottom offshore wind economically unviable [16].

Further, floating offshore wind is a natural complement to fixed-bottom offshore wind. There are many synergies between the two technologies, notably regarding turbine design, structures and construction [16]. Realising the potential of FOW will increase economic opportunities for the entire wind energy supply chain, resulting in the creation of new jobs. Furthermore, floating wind will develop its own supply chain, particularly for mooring and electrical cabling systems, as well as offshore installation works. It will also drive the need for new innovative technologies and installation procedures to continue cost reductions.

Floating offshore wind projects have also less environmental impact than fixed-bottom ones [16]. By allowing the wind turbines to be installed further offshore, floating wind farms face less of the aesthetic-induced resistance from local communities, since visual impact over the skyline and noise issues are minimised. Their installation is also less invasive than traditional fixed-bottom offshore wind farms. Indeed, drag anchors, SEPLA anchors, suction piles, and other anchoring solutions minimise the need for noisy piling installation, posing less threat for fish and marine mammals. They are also easier to retrieve if necessary. They have less of an impact on the fragile coastal ecosystem and landscape because they are further away from shore. They also have a lower impact on other marine users like fishing, pleasure boats, and marine transportation.

Moreover, FOW impacts local marine infrastructure positively. It would increase local economic activities in ports and would support job growth in all marine industries at a local, regional and national level. Most floating designs enable manufacturers to perform big operations (maintenance, repair and installation) at ports, be it dry-dock or in the harbour itself [16]. Smaller secondary harbour facilities are also ideal for developing the sector. Because they can convert their existing infrastructure, industrialised coastal regions affected by the decline in shipbuilding stand to benefit the most from investing in floating wind.

Finally, one of the major cost benefits of floating wind systems is a lesser reliance on large and expensive installation vessels [39]. Contrary to fixed turbines which require heavy-lift vessels to install the foundations, transport and assemble the parts on-site, and erect the turbine, floating turbine platforms are assembled in port and towed to site by tugs and anchor handling vessels, which can result in significant cost savings. Apart from being safer and more controlled, assembling the parts of the floating wind system in port also means minimising highly weather-dependent operations such as offshore heavy lifts. The ability to use smaller vessels with less weather-dependent operational methods means that the project can avoid significant delays while waiting for optimal weather windows and has fewer safety risks. As for the installation, certain maintenance operations can also take place in port, whether for turbine maintenance or part exchange and repair, avoiding the need for crews staying offshore for extensive periods as well as the need for large construction vessels.

2.2.4. Major floating offshore wind projects

Even though floating offshore wind is still in a pre-commercial phase [4], there are a few key FOWFs already commissioned, as well as a significant pipeline of projects across the globe. This section outlines the three largest FOWFs currently in operation, along with future goals of the sector.

First, the 50 MW Kincardine Floating Offshore Wind Farm is the largest operating FOWF across the globe, with five Vestas V164-9.5 MW and one V80-2 MW turbine, each installed on WindFloat semi-submersible platforms designed by Principle Power [40]. The wind farm is located 15 kilometres off the coast of Aberdeenshire, Scotland, in water depths ranging from 60 to 80 metres.

Second, the 30 MW Hywind Scotland pilot park is the world’s first FOWF, being in operation since 2017, using five 6 MW turbines, each installed on spar-type substructures developed by Equinor [31]. The wind farm is located 30 kilometres off the coast of Aberdeenshire, Scotland, in water depths ranging from 95 to 120 metres.

Third, the 25 MW WindFloat Atlantic project, similar to the Kincardine project, uses three Vestas V164-8.4 MW turbines, each installed on WindFloat semi-submersible platforms designed by Principle Power [41]. The wind farm is located 20 kilometres offshore Viana do Castelo, Portugal, in water depth of approximately 100 metres.

There are also many larger-scale FOWF currently under construction or development, like the 88 MW Hywind Tampen project [35]. The floating wind farm will consist of 11 wind turbines upgraded from 8 to 8.6 MW, installed on spar type floating concrete substructures with a shared anchoring system. It will be located 140 kilometres off the Norwegian coast, in water depths ranging from 260 to 300 metres. Other future floating wind projects include the 1.3 GW MunmuBaram wind farm, which is currently at a feasibility assessment stage [42], [43]. The FOWF will consist of 84 Vestas V236-15.0 MW turbines and is expected to generate up to 4.65 TWh of clean energy every year, providing renewable power from floating offshore wind to over 1 million Korean households. If realised, the wind farm will be located between 65 and 80 kilometres from the city of Ulsan, South Korea, at water depths ranging between 120 and 160 metres, covering an area of approximately 240 square kilometres.

2.3. General framework of a maritime logistics problem for a floating offshore wind farm installation project

In an OWF installation project there are a number of various asset-types to be considered, with a large number of each type of asset to be installed [46]. The most notable assets are the wind turbine generators (WTGs), which in the case of a FOWF are installed on top of a floating substructure. The WTGs with their foundation structures are hooked up to mooring lines which are fixed to the seabed by anchors and keep the foundation firmly stable on the ocean surface, even in high winds and waves. Offshore substation platforms (OSPs) may be included to collect and convert the generated power for transmission to the onshore grid [46]. OSPs can also be placed on a floating foundation or be fixed to the seabed [15]. Energy from each turbine is sent to the OSPs through dynamically suspended inter-array cables and the OSPs are connected to the onshore grid via export cables.

Each asset-type is associated with a distinct set of installation operations that are typically repeated many times. There are, also, a number of support operations associated with each asset-type, which prepare or complete the asset installation process. This results in a large number of specific repeated tasks that must be completed in order to instal all assets. Each individual task has certain operational limits including daylight and weather restrictions, that are dependent on the task itself and the capabilities of the particular vessel used to perform it [44]. Thus, the expected duration of each operation is dependent on the installation vessel used and the actual task duration is subject to uncertain weather conditions. Installation vessels may be used for the installation of multiple asset-types and some asset installations may be supported by supply barges.

Apart from vessel logistics, each type of asset may be loaded from a different port and each port will have specific operational capabilities and capacities. Assessing the comparative benefits of different logistical decisions – in terms of the impact on the total duration of the installation and the net costs – over an entire FOWF installation project is therefore challenging, and the problem is even more demanding for large scale projects where the total number of repeated tasks increases significantly [44].

Key logistical decisions to be made include decisions on fleet size and composition, which will define the number of installation vessels employed for each category of asset installation as well as the kind of specific vessels to be utilised, where each vessel will have unique operating characteristics. Additionally, decisions on vessel scheduling will determine how each vessel is used in terms of the order of assets installed, the chartering start-dates, and any periods of unavailability. Decisions on ports used for loading each asset also play a major role in the installation process, as they influence the installation operations through loading capacity and unavailability, loading times and transit times between the port and FOWF site. The impact of these decisions is modelled over the total installation-horizon of the project, subject to uncertain weather conditions. The unique complexity of the problem is due to the large number of operations being subject to specific operational limits with stochastic weather conditions [44], [46].

The challenges in modelling this problem are primarily driven by the practitioners' need for sufficient accuracy and usability to support decision-making on these large-scale installation projects, which can cost up to hundreds of millions of EUR [44]. Therefore, each stage of the installation process must be modelled with sufficient accuracy to be sensitive to the potential differences related to various aspects of the problem described above. Aside from precisely representing the logical relationships between the different vessels and tasks, particular challenges include precise accurate modelling of: (i) the uncertain weather conditions, (ii) the uncertain task durations given favorable weather conditions, (iii) vessel failures and maintenance, (iv) operations which can be completed in stages, (v) operations which may require weather windows longer than the expected duration, for safety reasons,

(vi) the installation of different asset-types using a single port with restricted loading capacity (which prohibits the compartmental modelling of the installation of different asset-types), (vii) groups of operations which may require installation within the same weather window, and (viii) the various ways in which a vessel may be supported by supply barges [44].

2.4. Weather forecasting approaches

As highlighted in Section 2.3, the diversity of installation operations requires a comprehensive representation of the weather uncertainties and their impact on the installation. For this reason, many methodologies have been used in the past to accurately forecast site weather conditions. This section provides an overview of the most common weather forecasting approaches.

a) Persistence

The simplest method of forecasting is to assume that current conditions predict future conditions exactly. For weather forecasting, e.g., wave height, the persistence approach assumes that the wave height at time t is the same as the wave height at time $t + n$, for some point n hours in the future [55]. This technique does not make use of wind speed, or any historical wave height data apart from the most recent measurement. The persistence model is considered to be the baseline that other techniques are in general compared against.

b) Real historical weather data

Similarly to the first method, weather forecasting can be achieved by assuming that historical weather data are representative of current and future site weather conditions, so by re-creating past weather conditions in a simulation tool. This can be done by gathering site research data from past years and considering that the exact past weather conditions will re-occur in the future.

c) Probabilistic approach

A slight improvement of the previous method is to fit probability density functions to the historical weather data [52]. Thus, a synthetic weather time series can be generated with a Monte Carlo simulation, calculating the quantile function of the random variable in each simulation and then taking the average of the sample produced. However, special attention should be given for random variables like wind speed and wave height, as the synthetic weather time series cannot be generated independently, since the two random variables are correlated.

d) Exponential smoothing

One of the most basic, yet fundamental, models in forecasting is the exponential smoothing model [55]. The model is widely used in industry, in part due to its simplicity (both computationally and intuitively) and in part due to its accuracy. Even large data sets can be processed quickly and easily computationally within standard spreadsheet packages. Intuitively, the model simply weights past data to predict future data. Studies have demonstrated that despite its simplicity, there is sometimes little difference in accuracy between exponential smoothing and other forecasting techniques such as autoregressive-moving-average (ARMA) models.

The model assumes that the data is stationary and non-trending. The following formula is used for the exponential smoothing model [55]:

$$S_t = a \cdot X_{t-1} + (1 - a) \cdot S_{t-1}$$

where S_t is the prediction for time step t, X_{t-1} is the observed value in time step $t - 1$ and α is a smoothing factor. Typically, small values of α are chosen; usually between 0.1 and 0.3. Where the model does not perform well for these values, typically a more complex model is adopted. A value of α close to 1 places greater emphasis on recent data. Note that a value of $\alpha = 1$ is equivalent to the persistence model.

e) Trigg and Leach

Trigg and Leach extended the simple exponential smoothing approach by including a dynamic smoothing constant that adjusts the performance of the forecasting by either increasing or decreasing the weight applied to historical data depending on the local stability of the series being forecast [55]. The performance of the forecasts is measured through a Tracking Signal:

$$Tracking\ Signal \approx \frac{smoothed\ error}{smoothed\ absolute\ error}$$

As such, the tracking signal must be between -1 and 1 as the absolute error must be at least as large in magnitude. The sign of the signal indicates the bias's direction, and the magnitude provides insight into the extent of the bias. A signal near 1 or -1 indicates systematic over or underestimation, whereas a value near 0 indicates unbiased forecasting. The use of exponential smoothing for these evaluations enables the analyst to apply more weight to recent observations.

The absolute value of the tracking signal is then used to provide an adaptive exponential smoothing constant. A value close to 0 implies that the series is “currently” stationary and as such more weight can be applied to recent history. A value close to 1 implies that the series tends to be either increasing or decreasing and as such more weight should be applied to the most recent observation.

f) Cubic spline

A number of statistical tools have been subsequently developed from their original purpose, such as regression models, to model time series data. One such example of that are splines, which have been used for modeling time series data in different domains [55]. A spline aims to link data points through a simple function;

the simplest being a straight line. Functions with higher degrees, such as polynomials with degree n, can also be considered.

Cubic splines have been proposed as a method for local-linear extrapolation when modeling a time series with non-linear trend. To model the time series data, a cubic spline is developed, based on historical data, and then linearly extrapolates. When predicting $t + 1$, this produces an improved estimation when compared with persistence. However, using this extrapolation performs poorly for $t + i$ when $i \geq 4$ [55].

g) Dynamic Linear Models

Dynamic Linear Models (DLMs) give an approach to time series analysis in which the response, in general a vector, X_t, is assumed to move through time based on the value of an unobserved state vector θ_t [55]. The state vector then evolves through each successive time step $t = 1, \ldots, p$. A further requirement of DLMs is that all unknowns are assumed to be normally distributed within the model. The general structure of a DLM is then

$$X_t = F_t \cdot \theta_t + v_t, \quad v_t \sim N(0, V_t)$$

$$\theta_t = G_t \cdot \theta_{t-1} + w_t, \quad w_t \sim N(0, W_t)$$

and, to complete the specification, $\theta_0 \sim N(m_0, C_0)$, which is the prior distribution for θ_0 given a mean vector m0 and covariance matrix C_0. The parameters v_t and w_t represent observation and evolution errors with possibly non-diagonal variance matrices V_t and W_t respectively and F_t and G_t are the observation and evolution matrices. This flexible structure allows DLMs to take many specific forms including a simple random walk, ARMA processes, polynomials, regressions and seasonality. Complex models are built up from combinations of these simple components.

h) ARMA models

Auto-Regressive approaches to describe time series data have been applied widely in different fields of study. Of particular relevance to this work, AR models have been used to describe significant wave height, mean wind speeds for wind turbine power generation, and wind turbine maintenance. The AR model, normalized to the mean, μ, of the data at time step t, X_t is [55], [56], [57], [58]:

$$X_t = \mu + \varepsilon_t + \sum_{i=1}^{p} \varphi_i \cdot (X_{t-i} - \mu)$$

where ε_t is a random noise term influencing the t^{th} data-point, φ_t is a correlation coefficient acting on the i^{th} data-point before X_t and p is the order of the model.

Due to the of a Gaussian noise term ε, this equation is valid only for the datasets that can be approximated by a normal distribution [56]. However, wind speed, wave height, and wave period datasets cannot be represented by a normal distribution and therefore the non-stationary trends have to be removed [56], [58]. By removing a fit of monthly mean and diurnal variation from wind speed dataset, the overall distribution approximates a normal distribution. For significant wave height, Hs_t, it is necessary to apply the Box-Cox transformation described in Equations (1) and (2), where the transformed data time series is Y_t, and $\hat{\mu}$ represents a Fourier series fit of the seasonality observed in the transformed data [56].

$$Y_t = ln(Hs_t) - \hat{\mu}_{ln(Hs_t)}, \quad for\ \Lambda = 0 \quad (1)$$

$$Y_t = \frac{Hs_t^{\Lambda-1}}{\Lambda} - \hat{\mu}_{Hs_t^{\Lambda-1}/\Lambda}, \quad for\ \Lambda > 0 \quad (2)$$

Model order is chosen by optimising Schwarz’s Bayesian Criterion and coefficients are estimated using a stepwise least squares estimation process, both standard methodologies [56]. Determination of appropriate Box-Cox transfer coefficient can be determined using an iterative approach, minimising the error observed between data and simulation mean, variance and probability distribution [56]. Seasonality is preserved by re-trending simulated wind time series directly and adding the seasonal component of (1) and (2) to simulated wave time series.

i) Markov Chain

Markov Chains have been deployed to solve several problems in the wind energy literature. A pure Markov Chain (that is memory-less and has time-homogeneous parameters) with discrete time and discrete state space can be applied to model and forecast weather conditions [55]. The bin size, which determines how the state space is partitioned, is the main criterion for setting up the chain. This is established first by determining the data set's maximum value. Then, depending on the variable being modelled, an appropriate bin size is chosen (for example, the modeller should consider the resolution of the original data when selecting the bin size). The parameter estimation process is based on the normalized frequency of transition from one state to another and the frequency balance method of Billinton and Allan [59], is summarized below:

$$P_{a,b} = P(s_b, t_{k+1} | s_a, t_k), \qquad k = 1, 2, 3, \ldots, N$$

where $P_{a,b}$ is the probability of transit from state α (s_α) to state b (s_b), and t_{k+1} is time at $k+1$ up to a maximum number of states N.

It is noted that performance improvement for the Markov chain could theoretically be achieved by partitioning the model into seasonal or monthly models. However, this drastically cuts down on the data available to estimate the model parameters, and results in a highly sparse matrix [55]. In this sense the Markov chain is much more data-intensive than the other forecast methods in this study.

j) Neural Networks

The Artificial Neural Network (ANN) is perhaps the most commonly applied intelligent system technique for non-linear regression problems and has in the past been applied to weather modeling [55]. The attraction of an ANN is that with a three-layer network comprised of simple units (neurons), any function can be approximated. Each neuron performs a weighted sum of its inputs before passing the result through an activation function to produce an output. Common activation functions include the sigmoid, hyperbolic tangent, and linear.

The three layers are termed the input layer (data inputs plus a bias term), the hidden layer, and the output layer, and this architecture is also referred to as the multi-layer perception (MLP). Each layer is fully connected to the next, meaning all inputs connect to all hidden neurons, and all hidden neurons connect to all output neurons.

Training is performed using a back-propagation algorithm, where the network output for sample input is compared against the target value, and neuron weights are updated to minimise error.

k) Support Vector Machines

In contrast to the ANN, which has been widely applied for weather prediction, the Support Vector Machine (SVM) has seen less study. The SVM maps input data into a space using a particular function called a kernel function. Originally used for classification, the SVM learns the boundary separating one class from another with maximal distance [55]. The kernel function aims to translate a problem which is non-linearly separable into a feature space which is linearly separable by a hyperplane. When used for regression, the hyperplane represents the function in feature space, rather than a classification boundary.

The SVM is parameterized through the choice of kernel function. Common functions used include linear, polynomial, and radial basis function (RBF). While there is no definitive methodology for appropriate training of SVMs, there are some generally agreed best practices to follow. For a problem which may be non-linear, the RBF kernel is recommended. This is parameterized by the error cost c, and the RBF width parameter γ. Standard practice is to optimize these parameters through a two-stage grid search: firstly, trying pairs of c and γ values with large steps across a wide space (rough grid search); followed by smaller-stepped pairs of values around the region of the best rough values (fine grid search).

l) Ensemble Learning

Research suggests that ensemble forecasters, which aggregate multiple predictions together, can outperform individual models [55]. For physics-based forecasting, an ensemble is used to find the most probable forecast given small variations in model initial conditions. For the statistical models presented above, an ensemble can be created to aggregate the predictions of each model, with the intention of improving forecast accuracy.

2.5. Simulation

Simulation plays an essential role in many OR studies, especially when developing a design or operating procedure for some stochastic system, such as the installation of a FOWF. The performance of the real system is imitated by using probability distributions to randomly generate various events that occur in the system [53]. As a result, a simulation model synthesises the system component by component and event by event. The model then runs the simulated system to obtain statistical observations of the system's performance as a result of various randomly generated events.

To prepare for simulating a complex system, a detailed simulation model needs to be formulated to describe the operation of the system and how it is to be simulated. A simulation model has several basic building blocks [53]:

1. A definition of the state of the system.
2. Identification of the possible states of the system that can occur.

3. Identification of the possible events that would change the state of the system.
4. A provision for a simulation clock, located at some address in the simulation program, that will record the passage of (simulated) time.
5. A method for randomly generating the events of the various kinds.
6. A formula for identifying state transitions that are generated by the various kinds of events.

Significant progress is being made in the development of special software for efficiently integrating the simulation model into a computer programme and then performing the simulations [53]. Nevertheless, when dealing with relatively complex systems, simulation tends to be a relatively expensive procedure. After formulating a detailed simulation model, considerable time often is required to develop and debug the computer programs needed to run the simulation. In addition, many long computer runs may be needed to obtain good data on how well all the alternative designs of the system would perform. Finally, all these data (which only provide estimates of the performance of the alternative designs) should be carefully analysed before drawing any final conclusions. This entire process is typically time-consuming and labor-intensive.

Simulation is typically used when the stochastic system involved is too complex to be analysed satisfactorily by analytical mathematical models [53], [62]. One of the main advantages of a mathematical model is that it abstracts the essence of the problem and reveals its underlying structure, providing insight into the cause-and-effect relationships within the system. Therefore, if the modeler is able to construct a mathematical model that is both a reasonable idealization of the problem and amenable to solution, this approach usually is superior to simulation [53]. However, many problems are too complex to permit this approach. Thus, simulation often provides the only practical approach to a problem.

2.5.1. Monte Carlo simulation

One of the most common simulation techniques to date is the Monte Carlo simulation, a modelling scheme that estimates stochastic or deterministic parameters based on random sampling [62]. It is a technique used to understand the impact of risk and uncertainty, modelling the probability of different outcomes in a process that cannot easily be predicted due to the intervention of random variables, and it is the technique implemented in this thesis.

The Monte Carlo method acknowledges an issue for any simulation technique: the probability of varying outcomes cannot be firmly pinpointed because of random variable interference. Therefore, a Monte Carlo simulation focuses on constantly repeating random samples. A Monte Carlo simulation takes the variable that has uncertainty (e.g., wave height, wind speed or uncertain task duration) and assigns it a random value, with respect to its probability distribution. The model is then run and a result is provided. This process is repeated again and again while assigning many different values to the variable in question. Once the simulation is complete, the results (e.g., installation durations and costs) are averaged to arrive at an estimate [62].

2.5.2. Types of simulation

The execution of present-day simulation is based generally on the idea of sampling used with the Monte Carlo method. Two broad categories of simulations are *discrete-event* and *continuous* simulations [53], [62].

A *discrete-event simulation* is one where changes in the state of the system occur instantaneously at random points in time as a result of the occurrence of discrete events [53], [62]. Such events may for example, be an element entering a station or leaving it, or, of relevance to this work, an installation operation. Any change in between the points (events) is of little interest for the simulation itself. What is important is that the entrance and the exit events are assessed correctly. Most applications of simulation in practice are discrete-event simulations and so is the simulation application of this thesis.

A *continuous simulation* is one where changes in the state of the system occur continuously over time [53], [62]. Continuous simulations typically require using differential equations to describe the rate of change of the state variables. Thus, the analysis tends to be relatively complex.

By approximating continuous changes in the state of the system by occasional discrete changes, it often is possible to use a discrete-event simulation to approximate the behavior of a continuous system [53]. This tends to greatly simplify the analysis it is the most common approach for modelling real systems.

2.5.3. Common types of applications of simulation

Simulation is a highly adaptable technique. It can be used to investigate almost any type of stochastic system (with varying degrees of difficulty). Because of its versatility, simulation has become the most widely used OR technique for studies involving such systems, and its popularity is growing.

It is impossible to list all of the specific areas in which simulation has been used due to the enormous diversity of its applications. However, in this section, some particularly important application categories are briefly described.

a) Design and Operation of Queueing Systems

Many mathematical models are available for analyzing relatively simple types of queueing systems. Unfortunately, these models can only provide rough approximations at best of more complicated queueing systems. However, simulation is well suited for dealing with even very complicated queueing systems, so many of its applications fall into this category [53].

b) Managing Inventory Systems

Mathematical, analytical, models for the management of simple kinds of inventory systems when the products involved have uncertain demand do exist and have been used in the past. However, inventory systems that arise in practice often have complications that are not taken into account by these particular models.

Although other mathematical models sometimes can help analyse these more complicated systems, simulation often plays a key role as well [53].

c) Estimating the Probability of Completing a Project by the Deadline

One of a project manager's primary concerns is whether his or her team will be able to complete the project by the deadline. Although there are methods for estimating the likelihood of meeting the deadline with the current project plan, simplifying approximations are used, which means that the resulting estimate is always overly optimistic, and sometimes by a significant amount [53].

Consequently, it is becoming increasingly common now to use simulation to obtain a better estimate of this probability. This involves generating random observations from the probability distributions of the duration of the various activities in the projects. By using the project network, it then is straightforward to simulate when each activity begins and ends, and so when the project finishes. By repeating this simulation thousands of times (in one computer run), a very good estimate can be obtained of the probability of meeting the deadline.

d) Design and Operation of Manufacturing Systems

Surveys consistently show that a large proportion of the applications of simulation involve manufacturing systems. Many of these systems can be viewed as a queueing system of some kind (e.g., a queueing system where the machines are the servers and the jobs to be processed are the customers) [53]. However, various complications inherent in these systems (e.g., occasional machine breakdowns, defective items needing to be reworked, and multiple types of jobs) go beyond the scope of the usual queueing models. Such complications can be handled readily by simulation.

e) Design and Operation of Distribution Systems

Any major manufacturing corporation requires an efficient distribution system to transport goods from factories and warehouses to customers. The operation of such a system involves numerous uncertainties. When will vehicles be available to transport the goods? How long will it take for a shipment to arrive? What will the various customers' demands be? [53] By generating random observations from the relevant probability distributions, simulation can readily deal with these kinds of uncertainties. Thus, it is used quite often to test various possibilities for improving the design and operation of these systems.

f) Financial Risk Analysis

Financial risk analysis was one of the first areas of simulation application, and it is still a very active area. A typical example is the evaluation of a proposed capital investment with uncertain future cash flows. By generating random observations from the probability distributions for the cash flow in each of the respective time periods (and considering relationships between time periods), simulation can generate thousands of scenarios for how the investment will turn out. This provides a probability distribution of the return (e.g., net present value) from the investment. This distribution (*risk profile*) enables management to assess the risk involved in making the investment [53].

A similar approach enables analyzing the risk associated with investing in various securities, including the more exotic financial instruments such as puts, calls, futures, stock options, etc [53].

g) Military applications

Perhaps no other sector of society employs simulation as extensively as the military [53]. The military's reliance on simulation for war gaming dates back several centuries. However, the introduction of powerful computers has resulted in a phenomenal increase in the military's use of simulation. To plan future military operations, update military doctrine, and train officers, war gaming to simulate military operations is now routinely used. Simulation is also commonly used to aid in military procurement decisions.

h) Health Care Applications

Health care is another area where, like the evaluation of risky investments, analyzing future uncertainties is central to current decision-making. However, rather than dealing with uncertain future cash flows, the uncertainties now involve such things as the evolution of human diseases.

Here are a few examples of the kinds of simulations that have been performed in the past to guide the design of health care systems [53]:

- Simulating the use of hospital resources when treating patients with coronary heart disease.
- Simulating health expenditures under alternative insurance plans.
- Simulating the cost and effectiveness of screening for the early detection of a disease.
- Simulating the use of the complex of surgical services at a medical center.
- Simulating the timing and location of calls for ambulance services.
- Simulating the matching of donated kidneys with transplant recipients.
- Simulating the operation of an emergency room.

i) Applications to other service industries

Other service industries, such as health care, have proven to be fertile fields for the application of simulation. Government services, banking, hotel management, restaurants, educational institutions, disaster planning, the military, amusement parks, and many other industries fall into this category [53]. In many cases, the systems being simulated are, in fact, queueing systems of some type.

2.6. Literature review

As described in Section 2.2, floating offshore wind is yet to reach a commercial phase, with only a few pilot FOWFs currently in operation. Therefore, literature regarding the logistics of installing a FOWF is extremely limited. However, there have been a few studies concerning the installation logistics of conventional fixed-bottom offshore wind farms.

In the report of Dewan et al. [47], in the context of the “Innovation Project” of ECN Wind Energy, a discrete-event simulation tool is developed in order to model the installation of the components of a wind farm. Historical time series of site meteorological data are assumed to be representative for current and future operations of the wind farm, while delays caused by working hours and vessel weather limits are calculated by using a Monte Carlo time domain simulation. In the case of the semi-submersible floating concept where the model is applied, a fairly simplistic model is used for the installation process of 75 turbines, considering only the quayside assembly of the turbine, the wet-tow and the anchoring of the system, with deterministic task durations. Additionally, installation is supposed to begin on a pre-fixed date. Muhabie et al. [48] develop a high-level discrete-event simulation model for the installation phase of a fixed-bottom OWF, with just 10 different operations used to entirely model the installation of turbines and foundations. Weather uncertainty is taken into consideration using both the real historical data and a probabilistic approach. As a result, Muhabie et al. conclude that the two approaches (historical data and probabilistic approach) for the transport and installation of the wind turbines show a good agreement, considering the average mean lead-time for each month over a year. In Barlow et al. [49], a more advanced discrete-event simulation approach is, again, employed to model the logistics of the installation process and to identify the vessels and operations most sensitive to weather delays. A holistic two-stage approach is used to evaluate innovations to installation vessel design and operation, and innovative technological developments to the whole installation process. The first stage identifies the operations which are most susceptible to weather delays, while the second stage explores the impact on the installation process under a scenario where innovative developments were capable of reducing the weather sensitivity of these critical operations. A high-level schematic of relationship between OWF installation streams is developed and a Monte Carlo simulation of a Multivariate Auto-Regressive (MAR) weather model is used to generate many realisations of synthetic weather time-series. In the same context, Barlow et al. [44] used a similar discrete-event simulation approach in order to improve the understanding of the risks associated with logistical OWF installation decisions. The model enables evaluation of a given installation scenario considered over the entire planning-horizon, in addition to factors such as: the impact of changes to fleet size, fleet composition, vessel schedules, port selection and changes to installation costs including vessel, port and crew rates. The same MAR weather modelling approach is employed to capture weather uncertainty and a Monte Carlo simulation is used to generate synthetic weather time-series. In Öztürk et al. [50], two optimisation models are developed to schedule the installation operations that support key logistical decisions. The first model is a deterministic optimisation model, which results in an overall schedule for the installation operations minimising either the total cost or the total duration of the installation process. The second model is a robust optimisation model that finds the worst-case duration of the installation process for a given percentage of deviating tasks. Thus, both models are used to find an overall schedule for the whole installation process, and to find new schedules when deviations from the baseline schedule are present. The models developed by Barlow et al. [44] and Öztürk et al. [50] are later coupled into the paper of Barlow et al. [46]. In the context of the “LEANWIND” project, McAuliffe et al. [51] developed a suite of advanced logistics optimisation and financial simulation models, which can evaluate every stage of an OWF lifecycle and supply chain. The logistics optimisation models provide optimal solutions for the supply chain in the three primary lifecycle stages: prior to/post port, at port and supply to/from offshore site. For the installation of the OWF, the model determines the optimal mix and scheduling of vessels, helicopters and bases to support activities. The schedule can be used to provide an indicative plan for installation activities e.g., the number of components that could be installed per day. The total costs are calculated in the financial model, which uses a Monte Carlo simulation to consider stochastic elements such as weather and component failures. Finally, Altuzarra et al. [34], present a modelling tool of the anchoring and mooring system installation logistics for a floating offshore wind farm. A simulation tool is utilised provided by an external partner and the operations are simulated using a weather hindcast data base. The model gives a detailed representation of the mooring system installation and mooring and power cable hook-up campaigns and is capable of calculating the total duration and costs of the installation operations.

The fleet sizing problem, which is not unique to the OWF installation process, has also been studied widely in the oil and gas industry. Indeed, Shyshou et al. [52] developed a discrete-event simulation tool in order to model a sequence of rig move events and evaluate alternative anchor handling tug supply fleet size configurations. Each rig move event starts at a discrete point in time and, depending on its type, triggers a sequence of operations whose durations are sampled from respective probability distributions. Stochastic factors include weather conditions and durations of anchor handling operations. Durations of acceptable weather windows were generated by fitting theoretical probability distributions to historical meteorological data.

3. Objectives of this thesis

It should be noted that most of the literature used as a basepoint for writing the present thesis, some of which is mentioned in Section 2.6, concerns advanced academic research made in collaboration with various university partners and industry experts, including multiple interviews, workshops and validation sessions. That being said, the contribution of this study is to further expand the work made on conventional fixed-bottom OWF installation processes, in papers such as the ones described in Section 2.6, in order to develop an accurate model of a floating OWF installation, which, to the best of my knowledge, is yet to be studied extensively.

In particular, the objective of this thesis is to design and develop a discrete-event simulation model of the FOWF installation process, so as to provide decision support to OWF developers at the planning or bidding phase of an installation project. This simulation tool is purposefully designed to provide an accurate representation of the installation process and give an insight into the planning of the logistics activities, enabling the assessment and comparison of alternative logistical decisions, in the context of expected duration of each phase of the installation process and the influences on the overall project lead-time and costs. Such logistical decisions include: the number of vessels which are used to install each type of asset, the specific vessels which are chosen to install each type of asset and the benefits of choosing one vessel over another, if a single vessel should be used to install more than one type of asset, whether installation vessels are self-supplying or supported by supply barges and the number of supply barges used, whether vessels should operate over winter months, and the installation starting date and the scheduling of start-dates for every set of installation tasks. This tool is fully developed and implemented in Microsoft Excel.

Simulation is widely used in practice as a methodological approach to operational research problems where the complexity of the problem structure, the input and the output variables are such that an analytic approach would be difficult to achieve, as discussed in Section 2.5. The complexity of the FOWF installation problem considered in this work, is justified by the large number of operations which must be completed, the diversity of the tasks considered, and the necessity to gain a realistic understanding of the impact of uncertain weather conditions, task durations and vessel failures. Therefore, in order to successfully provide a means to assess and compare the numerous different logistical decisions considered during the planning phase of a FOWF installation project, a simulation approach is employed here.

4. Modelling considerations

4.1. Model scope

The installation model developed here is intended to cover all operations specifically related to the process of installing a FOWF and is centred on the key assets identified in Section 2.3. For each asset, the scope of the installation process model is focused on installation operations, and consideration is given to the natural, practical and contractual bounds to the installation which are outlined below. It is assumed that the manufacturer and model of each asset has been decided prior to the start of installation, and that the locations of each wind turbine, the paths of all cables, and the location of onshore substations are all known prior to installation. Management of the asset supply-chains is considered to be outside the scope of this project; however, the supply rate of some assets is identified as an important consideration in modelling the installation. Each category of asset is therefore assigned a fixed arrival rate which takes all aspects of the supply chain into consideration and assets can only be installed or assembled after arrival.

As a result, each asset installation is considered from the arrival of assets at port prior to final transit to the FOWF site. Installation vessels are considered from mobilisation at the vessel base port through to demobilisation. The installation operations are defined to cover all operations until an asset can be considered as completely installed, and all installation operations culminate when the WTGs go online. It should be noted that in the context of evaluating the model in this thesis, it is applied on a fictional case-study of a FOWF, designed to be representative of the current phase of large-scale FOWFs under development in Europe. Therefore, no offshore substation platform is considered, as it is not economically viable for current-scale FOWFs. The case-study is described in more detail in Section 6.

Other assumptions of the installation model include: (i) the minimum time-step of the analysis is one hour, (ii) the historical weather time series are representative of current and future weather conditions on the wind farm site, (iii) a given weather window can be fully exploited as appropriate, (iv) the supply rate of the floating platforms and WTGs, as well as storage space at the load-out port, are sufficient so that the installation will never be delayed by these factors, and (v) onshore pre-assembly operations are subject to no weather restrictions and are initiated prior to the mobilisation of the installation vessel so that these operations will not delay the installation vessel. Additional assumptions related to the installation operations, vessel use and costs are provided in Sections 4.2-4.4.

4.2. Installation operations

The FOWF installation process is partitioned into a number of installation operations, with each operation potentially comprising of a number of smaller tasks. An installation operation is defined as a key stage of the installation process, and subsequent operations should be characterised by different operational limits or considerations.

The flowchart for a standard asset installation process is displayed in Figure 15 [44], and of each of the key assets follows a similar approach. Each installation operation is defined in terms of duration and weather restrictions, and in cases where the operation can be completed in stages the minimum weather window required for each stage is included. Daylight restrictions are not taken into account in the context of the following case-study, meaning that the crew works in two shifts, so that the installation is carried out 24/7. However, even under perfect weather conditions there will be some natural variation in the duration of each installation operation. The triangle distribution has been recognised for many years as an appropriate probability distribution to model uncertain activity durations in project scheduling problems [54] and remains one of the standard methods used for this purpose in the Operations Research literature. This is the approach taken here, as only the minimum, mode and maximum durations are required, which have been elicited from relative literature, as discussed in Section 6.3.

Installation operations must be completed in the required order at each location, and installation of each category of asset proceeds from an activation date, subject to the completion of preceding operations. Where multiple vessels install the same type of asset, each vessel may be designated a unique set of operations for installation. To reflect operations which may be closed down over winter months there is the option to define seasonal downtime.

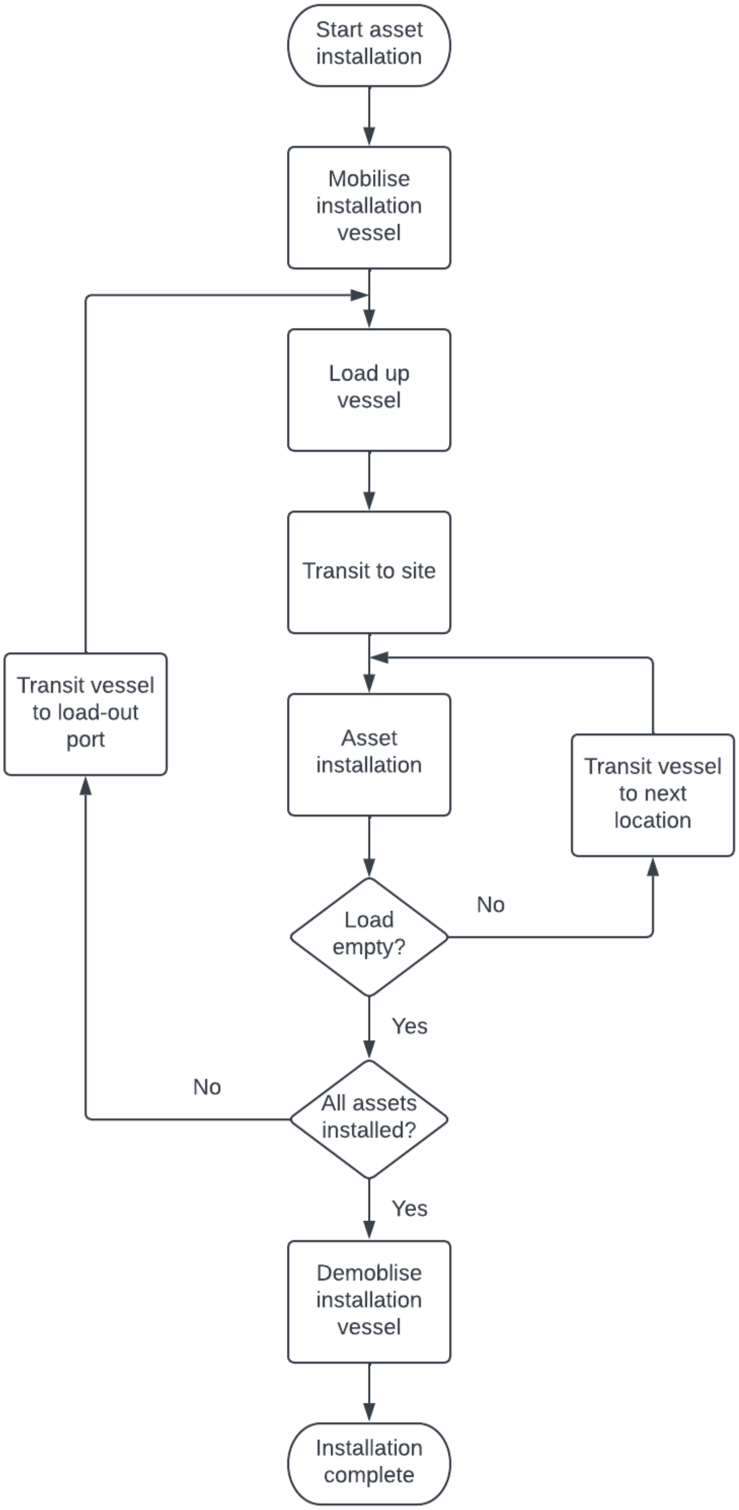
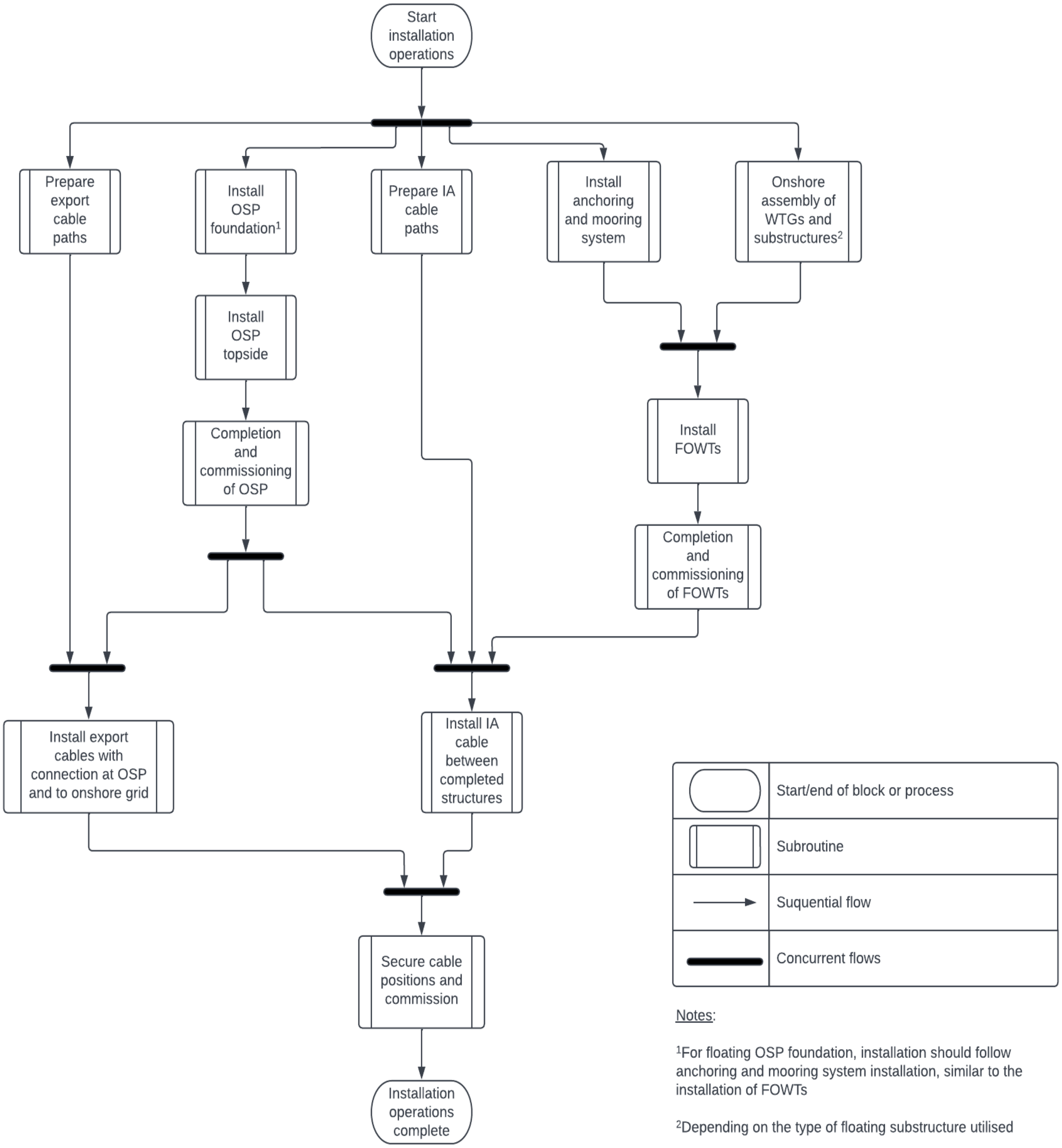


Figure 15: Flowchart for a standard OWF asset installation process [44].



Notes:

[1]For floating OSP foundation, installation should follow anchoring and mooring system installation, similar to the installation of FOWTs

[2]Depending on the type of floating substructure utilised

Figure 16: Schematic of relationship between the different FOWF asset category installation processes (adapted from [44] to consider the FOWF installation process).

An OWF installation process will adhere to a series of precedence relationships between the various categories of assets and within each category [44]. Many of these relationships are standard for OWF installation projects, both fixed-bottom and floating, and represent the logical order in which each asset is practically installed; these are displayed in Figure 16, which describes the generic framework of a FOWF installation process, including the installation of an OSP. Each subroutine shown in Figure 16 represents several installation operations, as defined previously, and in several cases, installation subroutines cover installation operations for multiple assets. The flow portrayed in Figure 16 defines the order in which operations must be completed for a single structure (WT, OSP, cable or mooring system), and in reality, all subroutines will be performed in parallel whilst preserving this order on each structure. Attention should be given to the type of supporting substructures for both the OSPs and the WTs. For example, as noted in Figure 16, for the case of a floating OSP foundation, the installation order should be altered, so that the OSP is installed after the mooring pre-lay campaign concerning the OSP's anchoring system is fully completed. In addition, for the case of spar-type foundation for the wind turbines, assembly is either done onshore, if the water depth at port is sufficient, or, most commonly, at sheltered coastal waters, due to the high draughts of spar-type substructures.

4.3. Installation and support vessels

The model enables the installation process of each category of asset to be performed by one or more installation vessels. This is representative of the realistic choices available to a decision maker, with the use of three installation vessels considered to be impractical in a real-world installation project [44]. Each installation vessel is uniquely defined in terms of operational capability – the time required to complete each task and the weather restrictions which would be associated with this, the cargo capacity, the sailing speed and an average charter day-rate (hire). An installation vessel is activated through its mobilisation date and will proceed to install all required assets subject to preceding operations, with transit between locations and reloading as presented in Figure 15. Upon installation of the final asset, the vessel will transit back to port before beginning demobilisation operations. Installation vessels are assumed to be capable of remaining offshore indefinitely, with factors such as the replenishment of water and fuel assumed to be addressed opportunistically as required, without affecting the installation schedule.

The installation of some assets, like the anchoring and mooring systems, can optionally be supported by supply barges, with any number of supply barges potentially utilised. For practical and safety considerations, supply barges can only be used for the installation of a specific subset of asset categories. Day-rates for supply barges include vessel and crew costs as well as the use of tugboats. Tugboats are also included in the towing of the FOWTs to site, assisting the main AHTS vessel during the towing itself and the hook-up operations, until the floater is storm safe [34]. Two tugs are considered per FOWT towing and hook-up operation.

Unexpected vessel and equipment breakdowns can be explicitly included by defining the probability of failure for each asset installation vessel and each supporting operation subroutine, or implicitly by defining a percentage increase to the expected duration of each installation operation. Additionally, by defining periods of vessel unavailability at the start of the installation, pre-scheduled maintenance operations can be included. It should be noted that similar considerations are not taken into account for the application of the model in the case-study.

4.4. Cost modelling

In general, the installation costs can be derived from a combination of the day-rates and mobilisation rates of all installation and support spread vessels used, the relative fuel consumption costs, all port costs and the costs of all installation technicians and vessel crews. All costs can be calculated directly from the installation durations. Vessel day-rates are highly volatile in practice; however, long-term vessel charters will typically agree fixed prices for the duration of the contract [44]. As the model presented here is intended to support planning decisions, the uncertainty in vessel day-rates is not captured explicitly, and costs for each vessel are assumed to remain constant throughout the installation project. The rate at which WTs come online and begin to generate energy and revenue offsets the capital expenditure on installation operations. It is imperative for an OWF developer to understand and exploit the expected relationship between expenditure and production over the period of the installation, with both factors dependent on the installation duration.

5. Methodology

5.1. Weather time-series modelling

In the present work, the real historical weather data approach has been implemented in order to model future weather conditions. As found in the paper of Muhabie et al. [48], the two approaches, real historical weather data and probabilistic approach, show a good agreement considering the average mean lead-time for each month over a year, having a correlation coefficient of 0.7. However, more accurate weather time-series modelling can be provided by using more complex methods, as the ones described in Section 2.4, but that is considered to be outside of the scope of the present work.

The weather conditions taken into consideration here are significant wave height and wind speed, which were identified by the literature ([44], [46], [48], [49], [50], [60], [61], [86]) as the most influential factors on offshore operations. Additional factors such as wave period and current speed will only impact specific operations, and to maintain tractable computation times these are not currently modelled.

The existing historical dataset is analysed to find the average and maximum significant wave height and wind speed in the wind farm site, for every time-step of the analysis which is one hour. Additional information about the specific historical weather data sets used in this case study are provided in Section 6.1.2.

5.2. Multi-threaded discrete-event simulation model

The simulation model developed in this work combines the logical model discussed in Section 4 with the synthetic weather time-series model discussed in Section 5.1 in a Microsoft Excel interface. Discrete-event simulation is a natural approach to model the FOWF installation process and is the method used here. Recent examples of applications of discrete-event simulation to dynamic systems in a renewable energy context include: managing electric vehicle charging [63], design and analysis of wood pellet supply chains [64], design and analysis of the supply chain for biocrude production [65], evaluation and management of smart grids [66],

[67], scheduling and control of distribution circuits with photo-voltaic generators [68], and operation and maintenance of OWFs [56], [58], [69], [86].

A multi-threaded discrete-event simulation model is developed to represent the FOWF installation process, as an extension of previous work made on fixed-bottom OWFs which is mentioned in Section 2.6. Each installation vessel, support vessel, and support operation is represented by a separate thread, and each thread of the simulation therefore models the progress of a unique sequence of operations. Threads may progress in parallel subject to various logical constraints defined through the installation model of Section 4; these logical constraints represent factors such as the practical order assets are installed in and the synchronisation of installation vessels and support vessels, where appropriate. Each thread maintains a clock which records the time transpired since the global start of the installation project. The state of the model represents the current clock for each thread, the current progress of the installation for each WTG, mooring system, and cable location, the location of each vessel, and the current number of assets carried by each vessel.

The FOWF installation is simulated by a series of distinct events, each of which represents a specific sequence of operations carried out by the same thread(s). Events are classified as pre-installation operations, in-port installation vessel operations, on-site installation vessel operations, and post-installation operations, with the partial or complete completion of each event resulting in some change to the state of the model. The first stage of the simulation completes the pre-installation operations for all assets, as these can be grouped according to asset-type and each group is then completed independently. The remainder of the simulation iteratively selects a thread associated with an installation vessel and completes the relevant operations. Selection is determined through a priority queue, where the level of priority is determined from the time of the thread clock and the satisfaction of various constraints to ensure the logical structure of the installation model is adhered to. Furthermore, priority is given to earlier operations in the sequence displayed in Figure 16. The specific sequence of operations completed in each iteration is determined by the vessel selected, its current location, current cargo, and the associated asset type. In the generic case, each port may be used by multiple vessels and barges installing various types of assets, and because each port has a maximum capacity of vessels or barges that can be loaded at the same time, the available capacity of a port must be updated after each set of in-port operations. The priority queue selection process for threads is necessary as a result of this factor, as otherwise each thread could be progressed independently. Following the completion of on-site operations, a series of post-installation operations is triggered, depending on the type of asset in question.

A specific installation scenario for a FOWF generates a unique set of installation operations and the precedence relationships between these, in addition to the defined durations, operational limits and sequencing of the required installation operations. The rate of progress of each thread in the simulation model is then calculated for the weather series generated, subject to uncertain task durations, with the minimum time-step of the analysis defined as one hour. A contingency-time factor can be included in order to increase the required duration of the weather window to complete a particular operation. The detailed breakdown of operations expressed through the model delivers an accurate assessment of the progress of each thread of the simulation and taken over a large number of weather series the simulation tool is therefore capable of providing an accurate measure of how a FOWF installation process may be expected to progress in practice.

Uncertainty in task durations is modelled through a Monte Carlo simulation. In particular, Monte Carlo simulation is used to generate many realisations of task durations, each of which is statistically representative of the relative triangular probability density function. As the simulation model is run, a resulting total installation duration and cost is provided, given the specific, random, sampling of task durations. This process is repeated again and again while assigning many different, random values to the task durations, with respect to their distributions. When the model simulation is complete, the results (e.g., installation durations and costs) are averaged to arrive at an estimate.

Each installation scenario considered is investigated over N simulation runs, where N is taken to be sufficiently large to provide a robust assessment of the scenario, subject to the modelled uncertainties, whilst providing a tractable computation time. It can be shown with 99.99% confidence that 98.83% of all potential simulated total durations lie within the range of durations obtained after 1000 simulations [70]. However, in the work of Muhabie et al. [48], where an OWF consisting of 60 wind turbines is studied, 200 to 400 iterations were found to be required in order to reach convergence of the simulation outputs. Therefore, in this case study FOWF consisting of 10 wind turbines, as described in Section 6, and in order to investigate many different installation scenarios, thus demonstrating this model's capability, while remaining within an acceptable computation time, the number of simulations, N, is set to 200.

5.3. Inputs and outputs of the simulation model

The simulation model developed in this thesis is fit for a specific FOWF, considered to be representative of current, large-scale, floating wind projects under development in Europe. However, it can be easily modified to cater for different offshore wind farm sites and FOWFs, varying the number of wind turbines and OSPs to be installed, along with their anchoring and mooring systems, and the wind farm layout itself.

As the model presented in Section 4 provides a detailed representation of an FOWF installation process, it is necessary to populate the simulation model with a detailed description of the FOWF characteristics and the entire installation process.

The initial, required inputs consider the basic FOWF parameters, such as: (i) the wind farm site location along with historical weather data (e.g., significant wave height and wind speed), (ii) the base port(s), (iii) the wind farm layout, (iv) the number of wind turbines and OSPs to be installed, (v) the size and power capacity of the WTs and (vi) the floating substructure design chosen along with its anchoring and mooring system.

Additional inputs to the model should include: (i) installation and support vessel characteristics (e.g., carrying capacity, deck cargo area, sailing and towing speeds), (ii) average day rates for port, vessels and crew, (iii) expected task durations, (iv) minimum and maximum operational durations and (v) weather operational restrictions for each installation operation (e.g., maximum allowable significant wave height and maximum allowable wind speed)

The nature of the simulation tool enables a wide variety of outputs to be produced, with detailed analysis of many aspects of the installation process possible. The outputs will generally originate from probabilistic measures which are calculated from the data generated across all simulations.

Probabilistic performance measures which can be used to evaluate an installation scenario include the mean and maximum cost and duration of installation and corresponding magnitudes of any delays experienced during installation. Each of these measures can be calculated for the entire installation process or calculated for a single asset category. In addition, these could be calculated for a specific category of asset installation operations, such as the operations performed by a particular installation vessel, to provide a detailed breakdown of operations. Delays are recorded as any time periods during which a specific category of asset installation operations is unable to proceed due to an incomplete preceding operation or inoperable weather conditions.

Besides from the total duration of an installation scenario, the model is capable of providing an accurate installation schedule. As discussed in Section 5.2, each thread of the simulation model maintains a clock which records the time transpired since the global start of the installation project and the state of the model is available in any time-step required. Therefore, the OWF developer has access to the progress of the installation for each WTG, mooring system, and cable location, the location of each vessel, and the current number of assets carried by each vessel.

Finally, additional outputs of the FOWF simulated installation scenario can include details on installation milestones such as first OSP activation, first WT activation and the progress of each asset installation. These outputs are an important consideration to an OWF developer for two reasons: firstly, an active wind farm produces profits through electricity generation, and so the sooner a site is partially or completely online the more profitable the lifetime costs of the site will be; secondly, a given OWF may have pre-defined obligations which are designated by government as part of the planning-approval process [44]. Targets such as the first date of exported power or the date of site completion must be satisfied or substantial fines are imposed, and it is therefore important to have an understanding of whether these obligations will be met.

6. Case study

To demonstrate the capability of the simulation model described in Section 5, a fictional FOWF installation campaign case study is investigated. The fictional FOWF is designed to be representative of the current phase of large-scale FOWFs under development in Europe. This case study was developed with the dual purpose of demonstrating the capability of the tool, and of evaluating the performance of the tool on a realistic problem. The input parameters were elicited from relative literature; however, they are entirely generic and do not correspond to any specific FOWF.

6.1. Case study floating offshore wind farm

6.1.1. Offshore Wind in Greece

Greece has 4.5 GW of wind energy installed today, all onshore, covering more than 18% of its electricity demand [71]. There are no offshore wind farms currently installed, neither fixed-bottom nor floating, but the potential for offshore wind in Greece is significant.

For that reason, in 2010, the Greek government proceeded to select twelve offshore areas across the country, mainly in the Aegean Sea, suitable for the installation of fixed-bottom OWFs [72]. These sites cover a total offshore area of 275 square kilometres with the average area to be 25 square kilometres. The selection of these areas was carried out given certain criteria:

- Exclusion of areas where potential OWF development would be incompatible with other interests (e.g., military, fisheries, tourism), in a zone of 6 nautical miles.
- For fixed-bottom OWFs, exclusion of areas with water depths greater than 50 metres.

- Exclusion of areas where potential OWF development could cause severe consequences to the marine environment.
- Exclusion of coastal areas where OWF development could cause visual nuisance.

These twelve areas were found to be located in the island of Agios Efstratios, Alexandroupoli, Karpathos, Corfu, Thasos, Kryoneri, Kimi, Lemnos, Lefkada, Petalious, Samothraki and Fanari Rodopis, and if exploited, are capable of producing 1.2 GW of green power. It should be noted that more than 50% of OWF considerations are gathered around Lemnos, Corfu and the coast of Thrace [72].

Much more research has been conducted since then in the context of both fixed-bottom and, primarily, floating Greek offshore wind [71]. The National Energy and Climate Plan (NECP) of Greece envisages a total of 7 GW of wind energy by 2030. With the NECP revision in 2023, this target will be raised. By that time, the government hopes to have built at least 2 GW of offshore wind. Offshore wind could play an important role in providing a clean and reliable energy supply to the more than 150 inhabited Greek islands, thanks to the good wind resource around the Greek peninsula.

In fact, in late July 2022, the Greek Parliament approved the country’s first Offshore Wind Law – an important step towards operating the first wind farms in Greek waters [71]. The Law appoints the State-owned exploration company Hellenic Hydrocarbon Resources and Energy Resources Management to lead site investigation, allocation and concession development. The national transmission system operator ADMIE will be responsible for providing the onshore and offshore grid infrastructure.

In the near future, the Greek Ministry for the Environment and Energy is expected to adopt a series of decrees. They will first commission Strategic Environmental Impact Assessments to identify larger offshore wind development areas. Within these areas, they will then assign specific installation zones. The decrees will also determine the specifics of offshore wind development in each installation zone. These zones will be established in collaboration with other societal interests such as the military, fishing, and tourism.

Developers will be able to apply for non-exclusive research permits for the broad offshore wind development areas. This will enable them to conduct resource assessments and sea space surveys. The first round of applications is expected within the next 1-2 years.

Only developers with a research permit will be eligible to bid in the upcoming offshore wind auctions. These first offshore wind auctions could take place as early as 2025-2026. The Government is opting for a sliding Feed-in-Premium scheme to support offshore wind development [71]. Successful bidders will be granted the exclusive right to develop, build, and operate the offshore wind farm in the designated installation areas. The sliding Feed-in-Premium revenue stabilisation scheme is very similar to Contract-for-Difference (CfD) auctions. CfDs have already proven their worth to society in a variety of European countries.

Given the characteristics of the Greek coastline with water depths of more than 50 metres, much of the 2 GW Greece aims to build by 2030 will be floating offshore wind [71]. The offshore wind technical potential in Greece is shown in Figure 17. The map shows the estimated technical potential for fixed and floating offshore wind in Greece in terms of installed power capacity in megawatts (MW) within 200 kilometers of the shoreline. It is provided by the Global Wind Energy Council (GWEC) with funding from the Ocean Renewable Energy Action Coalition (OREAC), to support the UN High Level Panel for a Sustainable Ocean Economy (Ocean Panel). Fixed and floating foundation datasets and methodology was developed by the Energy Sector Management Assistance Program (ESMAP). The wind resource data is sourced from the Global Wind Atlas and depicts the wind resource at 100 metres hub height at 250 metres resolution based on the latest input datasets and modeling methodologies.

The Greek Offshore Wind Law is therefore yet another push for Europe’s floating offshore wind industry. As discussed in Section 2.2, today Europe has just over 100 MW of floating wind across four projects operating in Scotland, Portugal and Norway. But the pipeline of new projects is growing. It is not unreasonable to expect that Europe will have over 10 GW of floating wind in operation by 2030.

Almost all Greek companies active in onshore wind have already expressed their interest in building offshore wind in Greece and there is also plenty of willingness from international offshore wind developers [71].

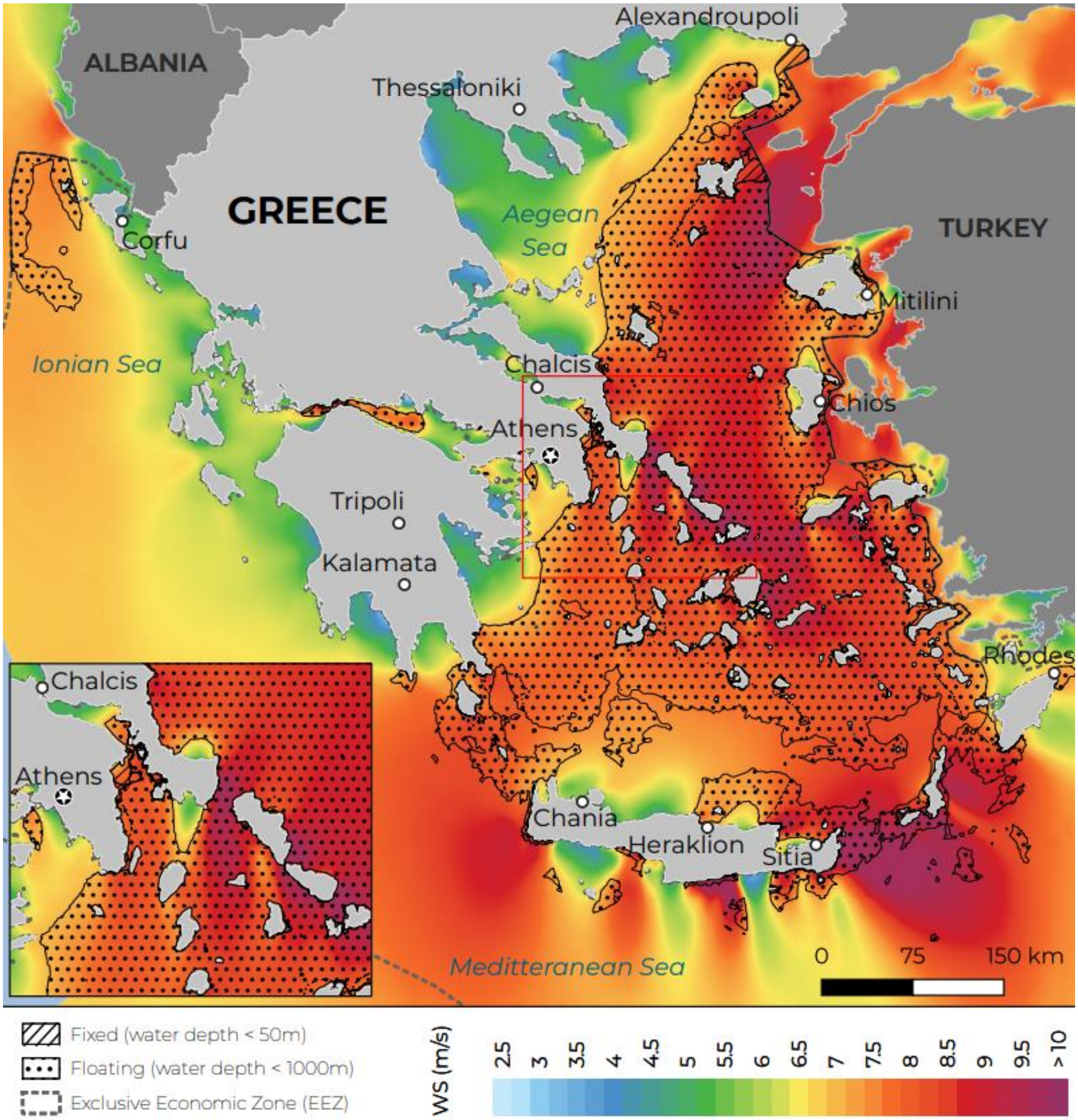


Figure 17: Offshore Wind Technical Potential in Greece [73].

6.1.2. Floating offshore wind farm characteristics

As depicted in Figure 17, the offshore areas with the most interest are the ones located south of Lemnos, east of Crete and near Andros, Tinos, Mykonos and Naxos. The site studied in this thesis is located approximately 10 kilometres off the South coast of Lemnos, with an average water depth of 100 metres. The base port for all installation operations and storage of structures and moorings for the construction of the wind farm is the port of Moudros.

Figure 18 depicts the location of the base port, the floating offshore wind farm, the four corner points with coordinates (39.50, 25.25), (39.75, 25.25), (39.75, 25.50) and (39.50, 25.25) from where available historical wind speed data were used and the on-site significant wave height historical data point with coordinates (39.696, 25.348). Hourly wind speed historical data for the period 2005-2020 were provided by the ERA5 dataset [74], while hourly significant wave height historical data for the period 2005-2019 were provided by Copernicus [75]. These data were used to generate the weather time-series for wind speed and significant wave height, enabling the capability of the simulation model to be demonstrated with realistic weather data.

The case study FOWF consists of ten Vestas V164-8.4 MW turbines, each installed on semi-submersible platforms, similar to the WindFloat Atlantic project. Each floating wind turbine is anchored to the seabed using three drag anchors and mooring lines. The total system capacity is 84 MW and the ten wind turbines are connected in a 4.8 kilometres-long inter-array cable network with a capacity of 66 kV, in agreement with the 88 MW Hywind Tampen project which is currently under construction. The wind farm will be connected to the onshore grid via two 25 kilometres-long export cables of the same type. The wind farm layout is advised from relative literature [76] and shown in Figure 19.

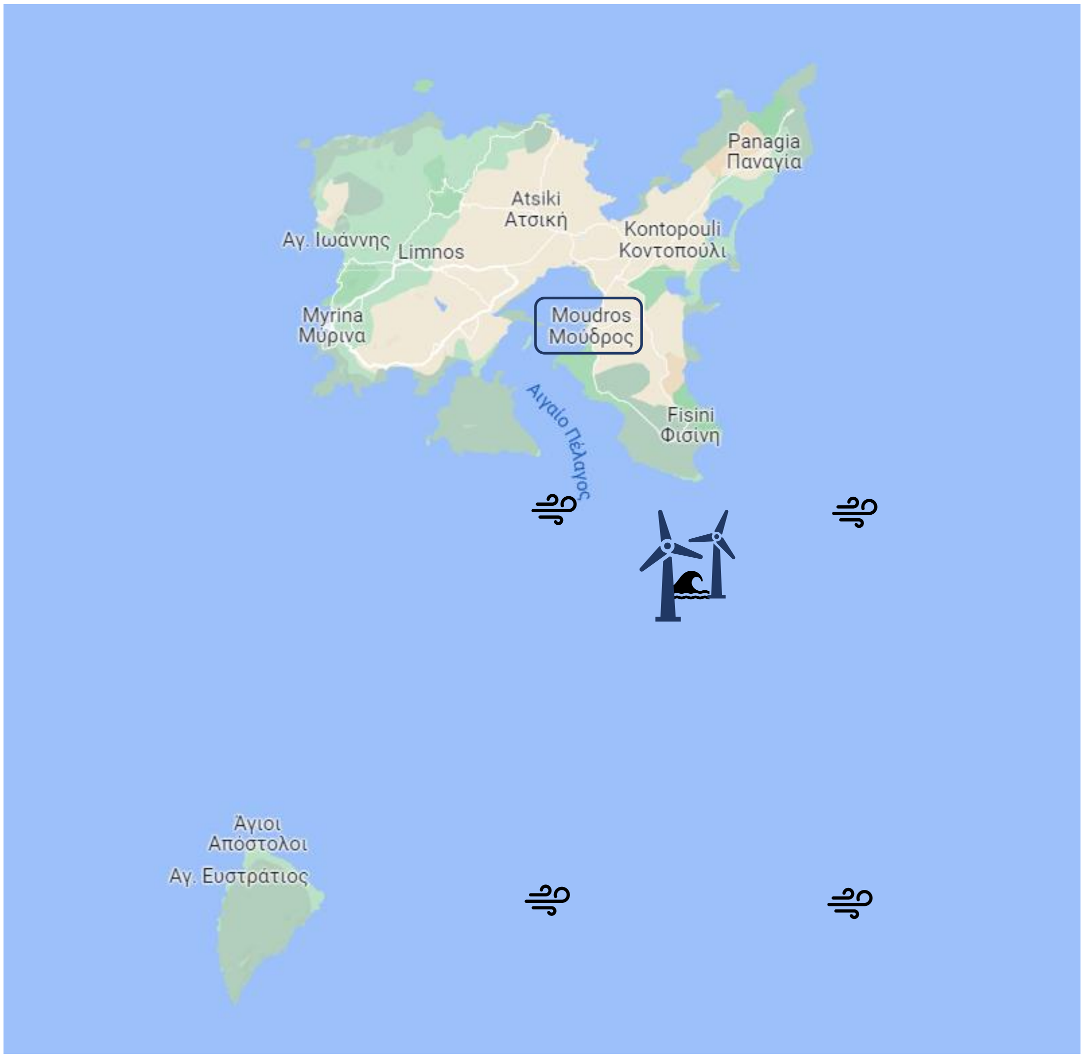


Figure 18: Floating offshore wind farm location and weather data points [Source: Google (2023) Lemnos. Available at: https://www.google.co.uk/maps (Accessed: 5 January 2023)].

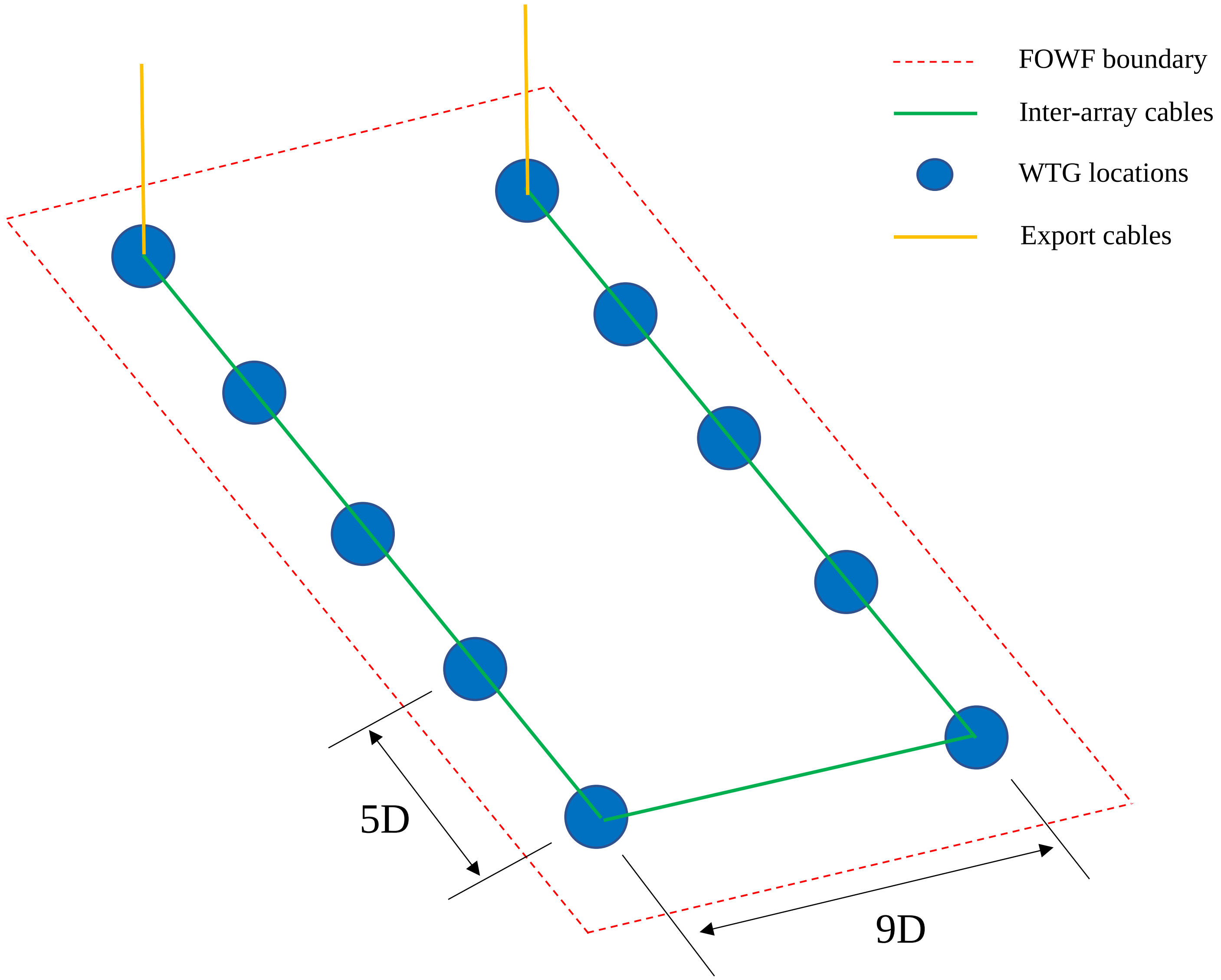


Figure 19: Floating offshore wind farm layout (D = 164 metres, the diameter of the turbine).

It should be noted that in order to properly design a wind farm layout, special attention should be given to the wake effect. Briefly, when wind passes through a wind turbine, the turbine extracts wind power that is later transformed into electricity. That means that the wind speed behind the wind turbine decreases, as it has lost a portion of its kinetic energy, and the wind direction changes due to the viscous action between the airflow and blades; this phenomenon is called the *wake effect* [77]. In the wake zone, because of the decrease in wind speed and increase in turbulence intensity, the power of the downwind wind turbine decreases and the fatigue damage increases. The wake effect adds additional fatigue damage to downwind wind turbines, which poses a serious threat to their power, reliability, and life. For that reason, wind turbines should be carefully located and sufficiently spaced. In general, for simple layout configurations like the one shown in Figure 19, the distance between two wind turbines of the same column can vary from 3D to 10D, while the distance between two columns can range between 5D and 18D [76].

6.2. Fleet description and costs

For the base case installation scenario, two installation vessels are considered in the simulation model: one cable laying vessel and one anchor handling tug supply vessel. Support vessels, such as tugboats, are also utilised to assist the main AHTS vessel during the towing for the floating wind turbines and the hook-up operations, until the floater is storm safe. Two tugs are considered per FOWT towing and hook-up operation.

As a cable laying vessel, the Boskalis Ndurance has been considered [78]. Of relevance to the application of the simulation model, it has a turntable capacity of 5000 tonnes, which considering a cable weight of approximately 57 kg/m [79] is more than enough to install the whole cabling system without the need of re-loading. It has a varying cable speed range of 0 to 1000 metres/hour and a maximum sailing speed of 11.5 knots.

For the AHTS vessel, the Bourbon Arctic has been considered [80], which is the vessel actually used for FOWT installation operations in the WindFloat Atlantic project. It has a cargo deck area of 780 square metres and a cargo deck load of 1000 tonnes, which translates into a carrying capacity of ten drag anchors, along with their mooring lines and connection components, per load. The anchors considered in this case study are the STEVSHARK®REX drag anchors, constructed by Vryhof and weighing 10 tonnes each [81], [82]. The vessel has a bollard pull of 280 tonnes and a service speed of 17 knots. However, during towing operations, the towing speed considered is 4 knots [83].

The weather limitations for each installation operation have been elicited from relative literature ([17], [34]) and are presented in Table 11:

Table 11: Vessel weather limitations [17], [34].

Vessel weather limitations		
Installation operation	**Max. sea state, Hs [m]**	**Max. wind speed, WS [m/s]**
Cable installation	3.5	15
Anchoring and mooring system installation	2.5	20
FOWT towing	1.65	14
Mooring and cable hook-up	2	20

As discussed in Section 4.4, for an accurate cost modelling, the charter day-rates, mobilisation and fuel consumption costs of vessels, port fees, and installation technicians and crew costs have to be taken into consideration for an accurate calculation of installation costs. All costs can be calculated directly from the installation durations. However, port costs for the use of port infrastructure, storage of components, quayside docking and crane use were not available for this study and are, therefore, not considered. In addition, an OWF installation requires in reality a lot of workforce in order to be completed. Examples of major roles in offshore wind installation operations include but are not limited to: (i) shipyard manager, (ii) crane operator, (iii) cable jointer, (iv) electrical technician, (v) ROV pilot, (vi) vessel Master and crew, (vii) vessel supervisor, (viii) marine coordinator, etc. [84]. This accuracy of cost modelling is considered to be outside of the scope of the present case study and is, therefore, not included.

Nevertheless, charter day-rates and mobilisation rates for all vessels are included in this study, which are also the main drivers of the FOWF installation logistics costs. These rates are presented in Table 12 ([10], [34]):

Table 12: Vessel rates [10], [34].

Vessel rates		
Vessel	**Mobilisation rate [EUR]**	**Day rate [EUR]**
Cable laying vessel	500,000.0	100,000.00
AHTS	500,000.0	40,000.0
Tugboat	-	15,000.0

It should be noted that the above rates include also include all necessary equipment to perform each installation operation (e.g., ROV, cable-handling equipment, cranes etc.).

6.3. Task durations

Installation operations have been already thoroughly described in Section 2.1.2 (cable installation operations), Section 2.2.2 (mooring system and FOWT installation operations) and Section 4.2 (Figures 15, 16). In this section a summary of the required installation operations in the context of the case study FOWF is provided, with additional information about expected task durations. As explained in Section 4.2, the triangle distribution has been recognised as an appropriate probability distribution to model uncertain activity durations in project scheduling problems [54] and is, therefore, the one used in this work. For its application, only the minimum, mean and maximum durations of a task are required. It should be noted that durations that do not result in integer values, are rounded up in order to remain in agreement with the simulation time step of one hour.

6.3.1. Cable installation

The wind farm installation procedure begins with the installation of cables. As discussed in Section 2.1.2, the use of a cable plough is considered which simultaneously inserts and buries the submarine cable into the seabed. For the dynamic cable, buoyancy modules and other components are included, as described in Section 2.2.2.

Firstly, the cable laying vessel is mobilised. The mobilisation is the preparation stage of the vessel and it takes place at the installation port. It equips the vessel with all the necessary equipment and paperwork in order to perform the required installation operations [84]. For the mobilisation duration of a vessel, the maximal and the most likely value is 24 hours, but occasionally it can be done faster [52]. The durations of mobilisation, loading and demobilisation of the cable laying and AHTS vessels are fixed across all investigations and not considered weather-sensitive, as these are assumed to have a straightforward impact on the duration installation operations [60].

After mobilising the cable laying vessel, it must be carefully loaded with the full length of export and inter-array cables. The cable loading process can be rather lengthy as it requires careful attention in order to properly store the cable in the ship's carousel. Large ships may have multiple carousels that each hold thousands of tons, or up to 3,000 kilometers of cable in total. This much cable means cable lay vessels commonly sit at port for weeks loading cable into the carousels [85]. In this study, two export cables of 25 kilometres each have been considered and a 4.8 kilometres-long inter-array cable network connecting the FWTs. A total loading duration of 72 hours is considered to be realistic.

Having loaded the vessel, the cable laying operations can begin. Starting from shore, the vessel installs the first export cable until the first FWT. Then, the inter-array cable network is installed, as shown in the wind farm layout (Figure 19). Last, the second export cable is installed as the vessel returns to shore. Installation durations for cable laying are considered to have a minimum value of 0.15 day per kilometre, a mean value of 0.30 day per kilometre and a maximum value of 0.60 day per kilometre [10]. Therefore, for a total cable length of 54.8 kilometres (including both export and inter-array cables), the cable laying installation can take from 197.3 hours to 789.2 hours, with a mean value of 394.6 hours.

Finally, having returned to shore, vessel demobilisation operations can begin, which, similarly to mobilisation, are considered to last 24 hours.

6.3.2. Anchoring and mooring system installation

While the wind farm's cabling system is being installed, the anchoring and mooring system can also be installed, as depicted in Figure 16. The mooring installation operations are described in detail in Section 2.2.2.

The AHTS vessel can be mobilised at the same time as the cable laying vessel, in order to properly equip the vessel for all anchoring installation operations. The AHTS vessel mobilisation duration is also considered fixed and equal to 24 hours.

After the vessel has been mobilised, it must be loaded with all required mooring components for the anchoring of ten FWTs. These components include: 30

mooring chains (3 for each WT), 30 unijoint and H-link connectors (3 for each WT) [34], 10 in-line tensioners (1 for each WT) and 30 drag anchors (3 for each WT). Given the vessel's carrying capacity, it will need to complete 3 loads in total, loading one third of the total mooring components each time. Each loading is considered to last 64 hours for the mooring chains and connectors and 32 hours for the anchors [34]. Therefore, the AHTS spends 96 hours loading each one of the three sets of mooring equipment.

When the vessel is successfully loaded, it transits to the wind farm site which is located approximately 25 kilometers from the base port. At a sailing speed of 17 knots, the vessel arrives at the site 48 minutes later. However, since the simulation time step is one hour, the transits to and from the wind farm sites are considered to last 1 hour. In addition, transits between WTs, which last much less, are not taken into account.

Having arrived at the farm site, the AHTS vessel begins the anchoring and mooring system installation, until it has installed all mooring components loaded. That means that it will fully install the mooring systems of the first three FWTs and only one third of the mooring components of the fourth WT. It must then return to port in order to load another ten mooring chains, connectors and anchors. After the second loading operation is complete, the vessel returns to site and continues installation. It installs the remaining two thirds of the mooring components of the fourth WT and then moves on to fully install the mooring systems the fifth and sixth WTs and the two thirds of the mooring components of the seventh WT. At that point it returns to the load-out port for the last loading operations and then, again, on site to finish installations in a similar manner. This procedure is also depicted in Figure 15.

The duration of a single mooring line installation is approximately 22 hours and the drag anchor tensioning operation duration is 12 hours [34]. That means that the average duration of the full installation mooring system per WT is 102 hours. Minimum and maximum durations of 72 and 144 hours, respectively, are considered to be realistic.

After the AHTS vessel finally installs the full mooring system of the tenth WT, it then returns to port in order to begin the WT towing and installation operations.

6.3.3. Floating offshore wind turbines installation

Following the relationship between the different FOWF asset category installation processes (Figure 16), the FOWTs can be installed after cable and mooring installation have been completed. The WT installation operations are also described thoroughly in Section 2.2.2.

First, the tug fleet arrives at the base port, but its mobilisation (or demobilisation) is not considered in this case study. As already discussed, tugboats are utilised to assist the main AHTS vessel during the towing for the floating wind turbines and the hook-up operations, until the floater is storm safe. Two tugs are considered per FOWT towing and hook-up operation. Before the FOWT can be towed to site, the floater must be safely connected to the AHTS vessel and tugboats [34]. The floater connection is considered to last 1 hour.

For the towing procedure, careful attention should be given to the towing speed in order to ensure the safe transport of the WT to the wind farm site. For that reason, a towing speed of 4 knots is considered in this work [83]. Thus, for a 25 kilometres-long trip, each towing operation is considered to take 4 hours.

After the WT reaches its designated installation location, it must be hooked-up to the mooring system and cables already installed. For the hook-up and tensioning operations of the mooring system, it has been assumed that the connection of the first two lines of each mooring system is performed on the deck of the AHTS, while the third line is connected utilizing an in-line tensioner, which is used for the final tensioning of the complete system. The floater will be held in position by the holding tugs until the last mooring line is connected and the floater is deemed to be storm safe. The duration of the mooring system hook-up operations per WT is approximately 40 hours. That is 10 hours for each mooring line connection and another 10 hours for the pre-tensioning of the last mooring line with the in-line tensioner [34]. Cable hook-up operations take about 6 hours each [34]. Therefore, the average duration of all hook-up operations per WT is 52 hours. Minimum and maximum durations of 26 and 64 hours, respectively, are considered to be realistic.

The AHTS vessel and tugboats must then return to the installation port, sailing at their service speed (1-hour transit), in order to repeat the same installation operations until all ten FOWTs are installed and commissioned.

Finally, after all FOWT installation operations have been completed, the AHTS vessel and tugboats return to port in order to begin demobilisation operations which are considered to last 24 hours. At that point, all vessels have been demobilised and the FOWF is fully installed and commissioned.

All task durations described above are summarised in Table 13:

Table 13: Task durations.

Installation operation	Task	Minimum duration [hours]	Mean duration [hours]	Maximum duration [hours]
Cable installation	Mobilisation	-	24	-
	Loading	-	72	-
	Asset installation*	197.3	394.6	789.2
	Demobilisation	-	24	-
Anchor and mooring system installation	Mobilisation	-	24	-
	Loading	-	96	-
	Transit to/from site	-	1	-
	Asset installation per WTG*	72	102	144
FOWT installation	Floater connection	-	1	-
	Tow to site*	-	4	-
	Asset installation*	26	52	64
	Transit back to installation port	-	1	-
	Demobilisation	-	24	-

*Operation considered as weather-sensitive in this case study

7. Results and discussion

To demonstrate the potential decision support provided by the simulation tool developed in this thesis, two different decision analysis problems are investigated. In Section 7.1, the scheduling of installation operations with consideration of seasonality is studied, in order to assess the variation of the expected costs and duration of the installation in different starting dates. In Section 7.2, four different installation strategies – with respect to fleet sizing – are investigated to obtain an understanding of the effect of fleet sizing to the project's total cost and duration.

7.1. Scheduling of installation operations with consideration of seasonality

For the base case installation scenario, where two installation vessels are utilised: one cable laying vessel and one anchor handling tug supply vessel, 200 simulations are performed for each start-date considered, with 200 simulations found to provide an acceptable level of statistical accuracy.

The start-date has been fixed to the first day of each month of the year and finally the average installation duration has been considered. Accordingly, Figure 20 depicts the average installation duration, in days, obtained after running the simulations, together with the first and third quartiles, the minimum, maximum and median value of the installation duration for each start-date. In Figure 20, the average values for the hourly historical weather time series have been considered.

Figure 20 indicates that there is little variability in terms of total installation duration, considering different start-dates and assuming that average past weather conditions re-occur. Indeed, the average values of historical weather data for significant wave height and wind speed, as described in Section 6.1.2, mostly restrict operability during January, February and December, given the vessel weather limitations listed in Table 11.

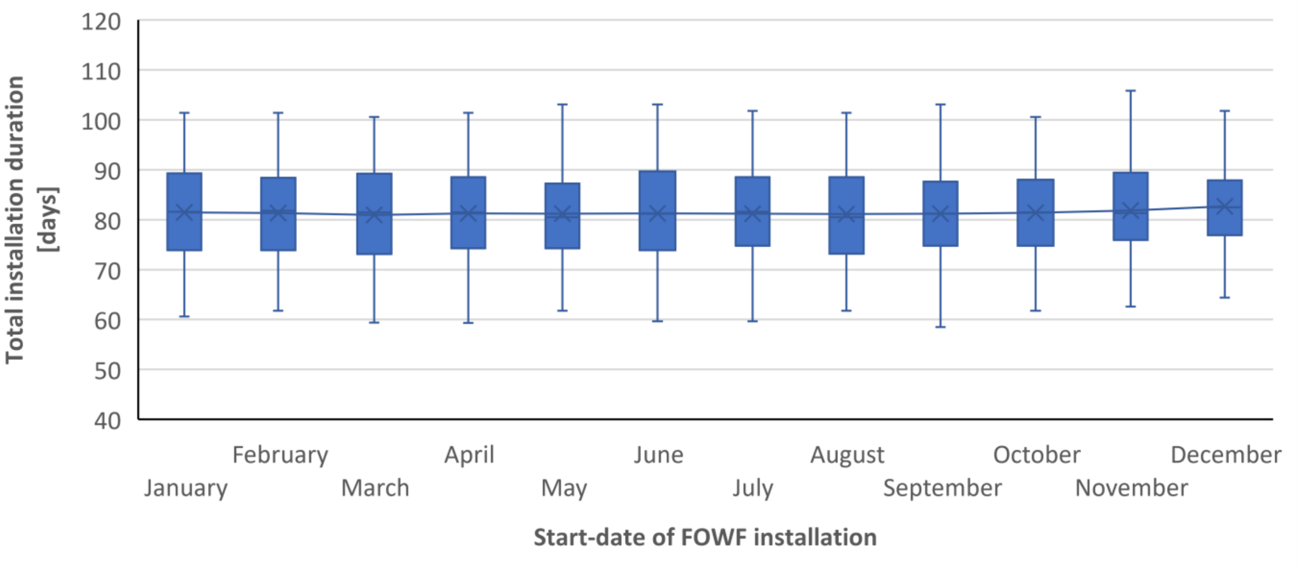


Figure 20: Scheduling of installation operations considering average weather conditions.

As a result, starting the installation operations on the 1st of March will provide a minimum total installation duration of 81.10 days and a total installation cost of 7,373,925 EUR. On the contrary, beginning installation on the 1st of December will result in a maximum total installation duration of 82.63 days and a total installation cost of 7,479,075 EUR. It should be noted, however, that since no weather restriction is present during the months of April to September, these start-dates are also capable of providing a minimal installation duration, with differences of less than 0.2% in comparison to March.

However, high variability is observed considering the worst-case scenario; that maximum past weather conditions re-occur. That variability is depicted in Figure 21, which gives an insight into the significant impact of weather conditions and vessel limitations on installation operations, as the delays occurred drive the total installation duration and cost up. According to Figure 21, a start-date on the 1st of June provides a minimum total installation duration of 88.15 days and a total installation cost of 8,592,596 EUR, while a start-date on the 1st of August results in a maximum total installation duration of 262.64 days and a total installation cost of 20,665,885 EUR. Comparing again March and December, the first results in a project lead-time of 113.27 days and a total cost of 10,776,828 EUR, while the second results in a project lead-time of 180.74 days and a total cost of 14,005,927 EUR.

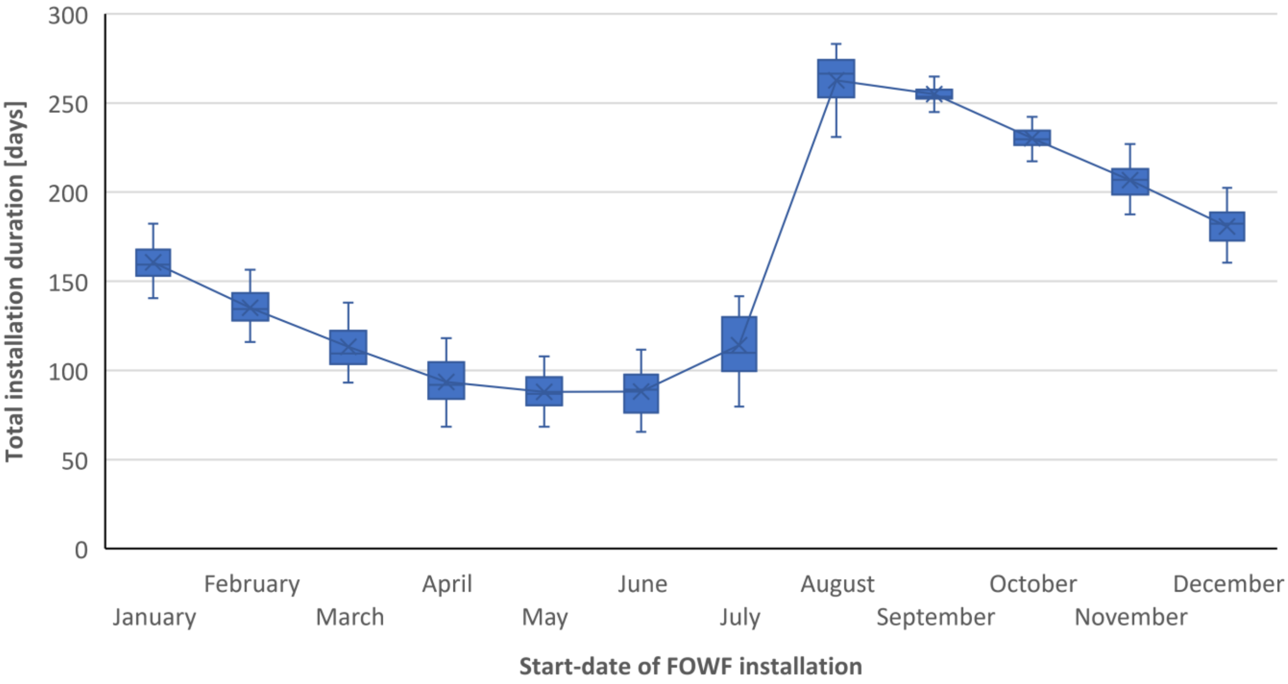


Figure 21: Scheduling of installation operations considering maximum weather conditions.

As mentioned above, start-dates from March to September, provide optimal, minimum, installation durations, assuming that average past weather conditions re-occur. However, in order to remain consistent with the results of the simulations and to evaluate different installation scenarios with respect to one start-date, March will be considered as the optimal approach, as starting installation operations in March will result, on average, in the commission of the wind farm at the earliest date. Different weather considerations can result in different optimal solutions, as shown in Figure 21, and the more accurate the weather model employed, the better are the results of the simulation tool developed in this thesis.

Since the simulation model runs on an hourly time-step, an accurate schedule for the whole installation process can be obtained. However, presenting the Gantt chart for the whole FOWF installation process would not be practical and would provide little clarification to the reader. In this setting, a sample Gantt chart is presented in Figure 22, depicting the cable installation operations and part of the anchor and mooring system installation, for the optimal start-date, considering average weather conditions, on the 1st of March. After 200 simulations, the total installation duration for cable laying was found to be approximately 463 hours or 19.3 days while the total duration for a wind turbine’s complete mooring system took 106 hours or 4.4 days, with no delays due to weather limitations observed. Therefore, given the rest task durations from Table 13, considered as deterministic in this work, the sample Gantt chart shown in Figure 22 can be obtained. The detailed installation schedule can also be seen in Table 14.

Table 14: Part of the installation schedule starting on the 1st of March (where M_{ij} means the installation of anchor and mooring line j for wind turbine i).

Task	Start date	Duration [hours]	End date
Cable laying vessel			
Mobilisation	1 March – 8 AM	24	2 March – 8 AM
Loading	2 March – 8 AM	72	5 March – 8 AM
Asset installation	5 March – 8 AM	463	24 March – 3 PM
Demobilisation	24 March – 3 PM	24	25 March – 3 PM
AHTS vessel			
Mobilisation	1 March – 8 AM	24	2 March – 8 AM
Loading	2 March – 8 AM	96	6 March – 8 AM
Transit to site	6 March – 8 AM	1	6 March – 9 AM
$M_{11,12,13}$	6 March – 9 AM	106	10 March – 7 PM
$M_{21,22,23}$	10 March – 7 PM	106	15 March – 5 AM
$M_{31,32,33}$	15 March – 5 AM	106	19 March – 3 PM
M_{41}	19 March – 3 PM	36	21 March – 3 AM
Transit to port	21 March – 3 AM	1	21 March – 4 AM
Loading	21 March – 4 AM	96	25 March – 4 AM

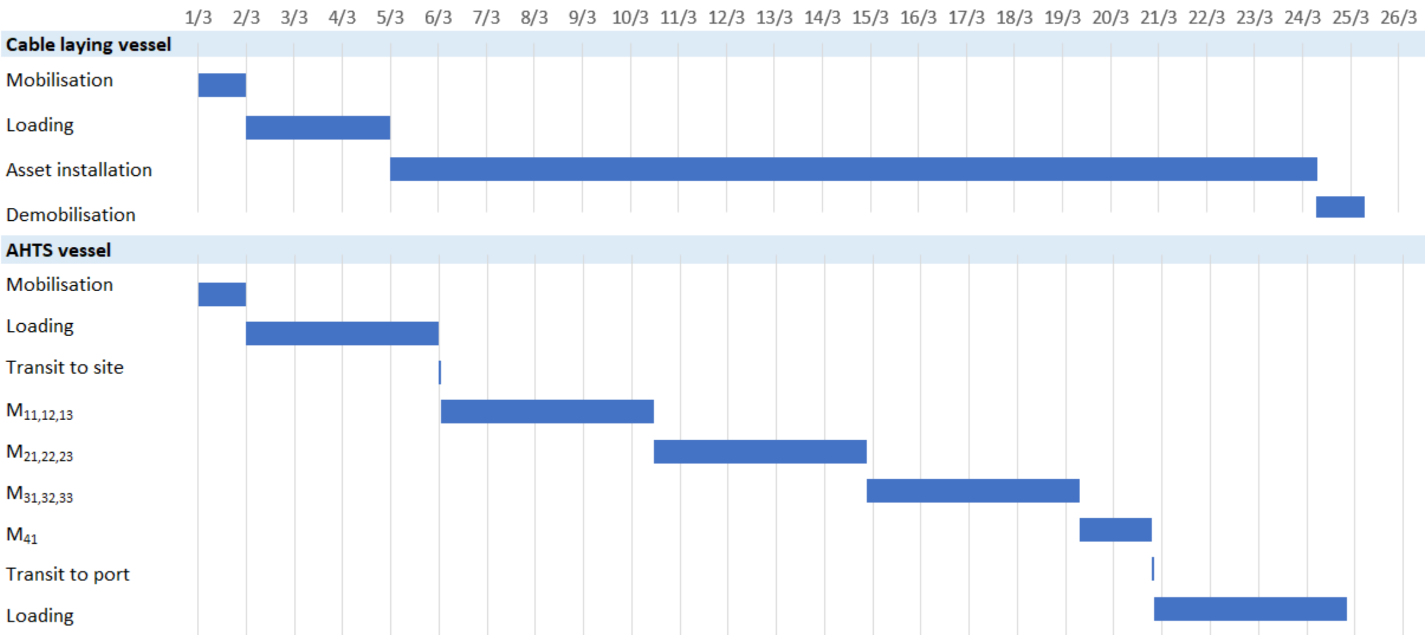


Figure 22: A sample Gantt chart for installation operations starting on the 1st of March.

7.2. Evaluation of different installation strategies with respect to fleet sizing

Having identified the optimal start-date of installation operations, considering average weather conditions, different installation strategies with respect to fleet sizing can be compared and evaluated. In this context, four fleet sizing variations are investigated in this section: (i) Scenario 1 considers the base case installation strategy, with two installation vessels employed, already studied in Section 7.1, (ii) Scenario 2 considers a total of three installation vessels consisting of two cable laying vessels and one AHTS vessel, (iii) Scenario 3 also assumes a total of three installation vessels consisting, however, of one cable laying vessel and two AHTS vessels, and (iv) Scenario 4 considers four installation vessels; two cable laying vessels and two AHTS vessels.

7.2.1. Scenario 2: Two cable laying vessels and one AHTS vessel

In this installation scenario, two cable laying vessels are employed for the cable installation, while all other installation operations concerning the anchor and mooring system installation and the FOWT installation remain the same. Therefore, both cable laying and mooring system installation operations continue to begin on the same day, with the difference that the cable loading operations as well as the cable laying process take half the time compared to the base case scenario (Scenario 1).

Thus, the two CLVs are mobilised which is considered to take 24 hours, they are then loaded, each one with half the total length of the cable to be installed, which takes 36 hours and then the cable laying operations begin with each CLV starting the installation from shore, laying one export cable and half the total length of inter-array cables. The vessels then return to port for demobilisation which is also considered to take 24 hours. The comparison of the duration of the cable installation operations between Scenario 1 and Scenario 2 can be seen in Table 15.

Table 15: Cable installation task durations for Scenario 1 and Scenario 2.

	Scenario 1			**Scenario 2**		
Task	Minimum duration [hours]	Mean duration [hours]	Maximum duration [hours]	Minimum duration [hours]	Mean duration [hours]	Maximum duration [hours]
Mobilisation	-	24	-	-	24	-
Loading	-	72	-	-	36	-
Asset installation	197.3	394.6	789.2	98.7	197.3	394.6
Transit back to installation port	-	0	-	-	1	-
Demobilisation	-	24	-	-	24	-

After performing 200 simulations for this installation scenario, the results regarding the total installation duration and the installation cost are listed in Table 16.

Table 16: Scenario 2: total installation duration and cost.

Scenario 2	**Average**	**Standard deviation**	**Maximum**	**Minimum**
Installation duration [days]	80.53	9.53	103.04	59.67
Installation cost [EUR]	8,010,613	994,332	10,468,333	5,933,333

Table 16 indicates that installation Scenario 2 provides practically no improvement in total installation duration compared to installation Scenario 1 which results in a duration of 81.10 days and a total cost of 7,373,925 EUR. This outcome was expected as the FOWF installation duration is mainly dependent on the mooring system installation and the FOWT installation and, thus, on operations of AHTS vessels, since: (i) the mooring system installation runs parallel to the cable installation and (ii) its duration is way more significant than the cable installation duration. Hence, the extra cost – approximately 650,000 EUR – of employing a second CLV is not in any way justified.

7.2.2. Scenario 3: One cable laying vessel and two AHTS vessels

In this case, one cable laying vessel and two AHTS vessels are employed for the installation operations. Therefore, while the cable installation operations do not change compared to Scenario 1, the mooring system and FOWT installation operations vary significantly.

Accordingly, both cable installation and mooring system installation begin on the same day. The two AHTS vessels are mobilised, which is considered to take approximately 24 hours, and are loaded, each one with 10 mooring components which takes 96 hours. They then transit to site in order to begin installations until 20 components are installed, which translates into the full mooring system installation for the first six WTs and the two thirds of the mooring system of the seventh WT. The vessels return to the installation port to re-load, now each one with 5 mooring components which require half the loading time. They then return to site in order to finish installing the mooring systems of the remaining four WTs which will also take half the time compared to Scenario 1, where only one AHTS vessel installs the remaining 10 mooring components.

Having finished all mooring system installation operations, the two AHTS vessels return to the installation port in order begin FOWT installation operations. Hence, all 10 FOWTs can be installed in half the time compared to Scenario 1. The vessels finally return to port for demobilisation which is also considered to take 24 hours.

After performing 200 simulations for this installation scenario, the results regarding the total installation duration and the installation cost are listed in Table 17.

Table 17: Scenario 3: total installation duration and cost.

Scenario 3	Average	Standard deviation	Maximum	Minimum
Installation duration [days]	41.80	4.61	51.33	30.71
Installation cost [EUR]	7,654,013	918,352	9,657,500	5,578,333

Table 17 indicates that installation Scenario 3 can achieve significant duration reduction – approximately 50% – in comparison to Scenario 1, with little increase in total installation cost, around 3.8%. This result demonstrates the impact of mooring system and FOWT installation operations on the total installation duration and cost and provides a viable alternative to the installation strategy employed in Scenario 1. This way, not only is the wind farm fully commissioned at an earlier date, but the first date of exported power also happens at an earlier stage. That is a major advantage for the wind farm developer as the wind farm can produce profit as soon as the first WT is activated and comply with potential pre-defined obligations designated by government, as explained in Section 5.3.

7.2.3. Scenario 4: Two cable laying vessels and two AHTS vessels

Finally, in Scenario 4, Scenarios 2 and 3 as described in Sections 7.2.1 and 7.2.2, respectively, are combined in order to investigate an installation strategy where four installation vessels are employed: two CLVs and two AHTS vessels. Installation operations in this case are explained in the sections above and the results provided by this installation scenario are listed in Table 18, for 200 simulations.

Table 18: Scenario 4: total installation duration and cost.

Scenario 4	Average	Standard deviation	Maximum	Minimum
Installation duration [days]	42.11	4.64	51.33	30.88
Installation cost [EUR]	8,417,979	923,895	10,361,667	6,312,500

Similar to the comparison between Scenario 1 and 2, Table 18 indicates that Scenario 4 provides practically no improvement with respect to total installation duration, compared to Scenario 3, which is an expected outcome. Once again, the extra cost required to employ a second CLV is not justified and does not represent an optimal installation strategy.

7.2.4. Comparison of all four different installation scenarios

In this section, all four different installation scenarios described above, are compared in order to obtain an understanding of the effect of fleet sizing to the project's total cost and duration. Results regarding total installation duration and cost for each scenario can be found in Table 19, while their variation can be seen graphically in Figures 23 and 24, which show the scenarios' total installation duration and cost, respectively.

Table 19: Total installation duration and cost for each scenario investigated.

		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Installation duration [days]	Average	81.10	80.53	41.80	42.11
	Standard deviation	10.08	9.53	4.61	4.64
	Maximum	101.75	103.04	51.33	51.33
	Minimum	61.38	59.67	30.71	30.88
Installation cost [EUR]	Average	7,373,925	8,010,613	7,654,013	8,417,979
	Standard deviation	1,054,306	994,332	918,352	923,895
	Maximum	9,633,333	10,468,333	9,657,500	10,361,667
	Minimum	5,401,667	5,933,333	5,578,333	6,312,500

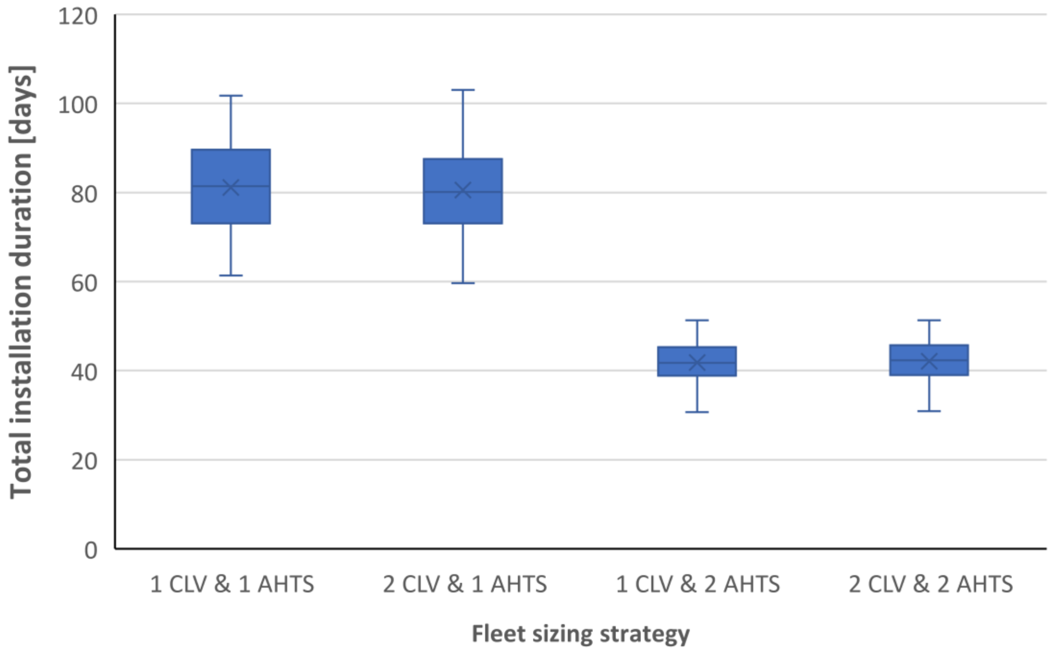


Figure 23: Total installation duration per fleet sizing strategy (installation scenario).

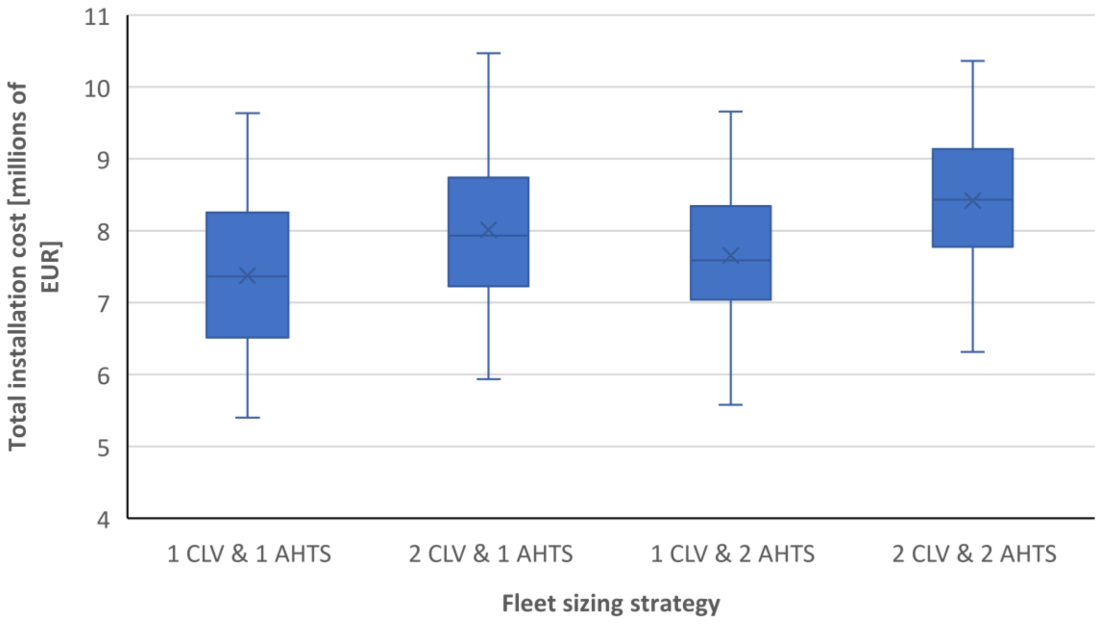


Figure 24: Total installation cost per fleet sizing strategy (installation scenario).

Table 19 and Figures 23 and 24 indicate that the two best fleet sizing strategies are to either employ one CLV and one AHTS vessels (Scenario 1) or to employ one CLV and two AHTS vessels (Scenario 3), with the employment of a second CLV providing no improvement in total installation duration.

In addition, one could argue that out of the two best solutions, the optimal approach is the one where two AHTS vessels are employed as the project's total lead time is significantly reduced by 50%, with just a slight increase in total cost of approximately 3.8%. However, that increase in costs can be justified by the advantages of an earlier wind turbine activation date and wind farm commission date, as already explained in Sections 5.3 and 7.2.2.

It should be noted that a variety of other installation strategies can be investigated and the ones presented in this study are only indicative of the capability of the simulation model developed here. For example, in Scenario 3, where 1 CLV and 2 AHTS vessels are employed, it is assumed that the FOWT installation process is triggered when all mooring systems are fully installed. However, a different approach would be to examine the expected cost and duration of the installation if after the first transit back to the load-out port, one AHTS vessel continues the installation of mooring systems, while the other begins installing the FOWT; thus achieving an even earlier first activation date.

8. Conclusions and further work

This thesis presented a discrete-event simulation tool designed to provide logistical decision-making support to FOWF developers at the planning or bidding phase of an installation project. The tool combined a realistic model of the installation process with a historical weather time series model, enabling the comparative risks and benefits of a wide variety of logistical installation decisions to be identified and assessed. The capability of the tool was demonstrated on a fictional case study, designed to be representative of the current phase of large-scale FOWFs under development in Europe. The simulation tool was used in order to explore various logistical installation decisions and strategies and identify their impact on the total installation cost and duration. The results were discussed and demonstrated that significant installation cost and duration reductions can be achieved by using the simulation tool in order to compare different installation scheduling and fleet sizing alternatives. In particular for the case study investigated, consisting of ten FOWTs, an optimal installation schedule was identified and a vessel fleet of one CLV and two AHTS vessels was found to reduce the total installation duration by 50%, while only increasing the total cost by 3.8%, compared to a fleet consisting of one CLV and one AHTS.

Throughout this work, several logistical decisions have been identified as critical to the FOWF installation process and various assumptions have been made. However, a major factor of the installation process is the infrastructure required to manufacture, transport, dry store, assemble, commission, wet store and deploy this technology. In practice various sources will be considered for each asset, with varying manufacturing and transportation costs, and the storage requirements for larger assets can be problematic. Additionally, there are a variety of considerations related to the layout of the FOWF which can have an impact on the installation process, including the geo-technical characteristics throughout the site and the design of the cable network. The project’s total lead time is also heavily dependent on port capabilities and delays while a more accurate cost modelling approach should further include port fees, vessel fuel consumption costs and all installation technicians and crew costs. Further, in reality, a rolling horizon installation schedule optimisation model is required, in order to generate new schedules when deviations from the initial schedule occur.

It would be desirable to include these considerations explicitly within a decision-making tool so that the whole supply chain can be optimally managed in conjunction with a robust installation schedule. Therefore, future work will extend the scope of the decision-support tool developed here, to incorporate these factors, coupled with a more complex weather time series modelling approach.

References

[1] Nalley, S. and LaRose, A., 2021, "International Energy Outlook 2021 (IEO 2021", Center of Strategic and International Studies, Washington, DC, USA

[2] Guo, Y., Wang, H. and Lian, J., 2022, "Review of integrated installation technologies for offshore wind turbines: Current progress and future development trends", Energy Conversion and Management 255 (2022), 115319

[3] GWEC, 2022, "Global Wind Report 2022", Global Wind Energy Council, Brussels, Belgium

[4] GWEC, 2022, "Global Offshore Wind Report 2022", Global Wind Energy Council, Brussels, Belgium

[5] LEANWIND, 2014, "WP Framework/Industry Challenges Report – supply chain and logistics", LEANWIND project, Work Package 5 – Deliverable number 5.1

[6] Kuo, Y. S., Abdel-Rahman, K., Wu, K. T., Huang, T. Y. and Achmus, M., 2014, "Suitability of a Pile Group Foundation for an Offshore Wind Turbine", Proceedings of the Twenty-fourth (2014) International Ocean and Polar Engineering Conference, Busan, Korea

[7] O'Kelly, B.C. and Arshad, M., 2016, "Offshore wind turbine foundations e analysis and design", Offshore Wind Farms – Technologies, Design and Operation, pp. 589-610

[8] Hensel, J., Ravi Sharma, M. S., Baxter, C. D. P. and Hu, S. L. J., 2012, "Development of a technology type factor for jacket structures for offshore wind turbines in Rhode Island", Journal of Renewable and Sustainable Energy 4 (063120)

[9] Rae, S., Raaberg, K. T. and Das, J., 2017, "Offshore Wind Foundations – A European Overview", The Renewables Consulting Group, London, UK

[10] Jalili, S., Maheri, A. and Ivanovic, A., 2022, “Cost Modelling for Offshore Wind Farm Decommissioning”, DecomTools

[11] Wikipedia, 2022, “List of offshore wind farms”, https://en.wikipedia.org/wiki/List_of_offshore_wind_farms, Accessed: 18 December 2022

[12] Ørsted, 2022, Hornsea 2 project, https://hornseaprojects.co.uk/hornsea-project-two, Accessed: 18 December 2022

[13] Ørsted, 2020, Hornsea 1 project, https://orsted.co.uk/energy-solutions/offshore-wind/our-wind-farms/hornsea1, Accessed: 18 December 2022

[14] EDPR, 2020, Moray East Offshore Wind Farm Project, https://www.morayeast.com/project, Accessed: 18 December 2022

[15] Ørsted, 2022, “Deeper waters, stronger winds – How floating offshore wind can be scaled”, Ørsted White papers

[16] WindEurope, 2018, “Floating offshore wind energy: a policy blueprint for Europe”, WindEurope Position papers

[17] Ramachandran, R. C., Desmond, C., Judge, F., Serraris, J. J. and Murphy, J., 2021, “Floating offshore wind turbines: Installation, operation, maintenance and decommissioning challenges and opportunities”, European Academy of Wind Energy, Open Access Wind Energy Science Discussions

[18] Iberdrola, “Floating offshore wind power: a milestone to boost renewables through innovation”, https://www.iberdrola.com/innovation/floating-offshore-wind, Accessed: 18 December 2022

[19] Crowle, A. and Thies, P. R., 2021, “Challenges during installation of floating wind turbines”, Open Research Exeter, University of Exeter, Exeter, UK

[20] Efthimiou, L. and Mehta, A., 2022, “Crash course: Floating offshore wind, a blog series”, World Forum Offshore Wind, https://wfo-global.org/crash-course-floating-offshore-wind-a-blog-series/, Accessed: 18 December 2022

[21] GWEC, 2022, “Floating Offshore Wind – A Global Opportunity”, Global Wind Energy Council, Brussels, Belgium

[22] Principle Power, https://www.principlepower.com/windfloat, Accessed: 18 December 2022

[23] Sant, T., Buhagiar, D. and Farrugia, R. N., 2018, "Evaluating a new concept to integrate compressed air energy in spar-type floating offshore wind turbine structures", Ocean Engineering, 166, pp. 232-241

[24] Speight, J. G., 2015, "Handbook of Offshore Oil and Gas Operations", Chapter 3 – Offshore Platforms, First Edition, Published by Gulf Professional, Laramie, Wyoming, USA

[25] Longridge, K., 2020, "Floating wind: What are the mooring options? – A Q&A with Kent Longridge", Acteon blog, https://acteon.com/blog/floating-wind-mooring-options/, Accessed: 18 December 2022

[26] Floating Wind Turbines, http://floatingwindfarm.weebly.com/anchoring-systems.html, Accessed: 18 December 2022

[27] Acteon, 2021, "Anchor types for floating wind", Acteon blog, https://acteon.com/blog/anchor-types-for-floating-wind/, Accessed: 18 December 2022

[28] Acteon, 2021, "How Suction Embedded Plate Anchors can reduce your project's footprint", Acteon blog, https://acteon.com/blog/how-suction-embedded-plate-anchors-can-reduce-your-projects-footprint/#:~:text=The%20SEPLA%20system%20uses%20a,to%20install%20additional%20plate%20anchors., Accessed: 18 December 2022

[29] ABC Moorings, "Mooring Anchors", http://abc-moorings.weebly.com/mooring-anchors.html, Accessed: 18 December 2022

[30] American Bureau of Shipping, 2018, "Guidance notes on: Design and installation of drag anchors and plate anchors", American Bureau of Shipping, Houston, Texas, USA

[31] Equinor, Hywind Scotland, https://www.equinor.com/energy/hywind-scotland, Accessed: 18 December 2022

[32] Offshore Wind Design AS, Gravity Anchors, https://www.offshorewinddesign.com/gravity-anchors/, Accessed: 18 December 2022

[33] Ma, K. T., Wu, Y., Bello, L., van der Horst, M., Stolen, S. F. and Luo, Y., 2021, "MOORING DESIGNS FOR FLOATING OFFSHORE WIND TURBINES LEVERAGING EXPERIENCE FROM THE OIL & GAS INDUSTRY", Proceedings of the ASME 2021 40th International Conference on Ocean, Offshore and Arctic Engineering, OMAE 2021

[34] Altuzarra, J., Herrera, A., Matías, O., Urbano, J., Romero, C., Wang, S. and Soares, C.G., 2022, "Mooring System Transport and Installation Logistics for a Floating Offshore Wind Farm in Lannion, France", Journal of Marine Science and Engineering, 10, 1354

[35] Equinor, Hywind Tampen, https://www.equinor.com/energy/hywind-tampen, Accessed: 18 December 2022

[36] Tanikoki, R., Abe, K., Sukegawa, T., Azuma, D. and Nishikawa, M., 2017, "Dynamic Cable System for Floating Offshore Wind Power Generation", SEI Technical Review, Number 84

[37] Avinash, A., 2021, "Optimisation of Offshore Wind Floater from Dynamic Cable And Mooring Prospective", Diploma Thesis, University of Liège, Liège, Belgium

[38] Peritus, 2021, "Dynamic Cable Systems", ORE Catapult Subsea UK Webinar

[39] Acteon, 2020, "Benefits of floating offshore wind", Acteon blog, https://acteon.com/blog/benefits-of-floating-offshore-wind/, Accessed: 19 December 2022

[40] Principle Power, 2021, "KOWL: World's largest floating windfarm fully operational", https://www.principlepower.com/news/kowl-worlds-largest-floating-windfarm-fully-operational, Accessed: 19 December 2022

[41] Principle Power, https://www.principlepower.com/projects/windfloat-atlantic, Accessed: 19 December 2022

[42] Vestas, 2022, “Vestas selected as preferred supplier for the 1.3 GW MunmuBaram floating offshore wind project in South Korea”, News release from Vestas Asia Pacific, Singapore

[43] Shell Global, 2021, “ ‘MunmuBaram’ Joint Venture established by Shell and CoensHexicon for floating wind project in South Korea”, https://www.shell.com/energy-and-innovation/new-energies/new-energies-media-releases/munmubaram-joint-venture-is-formally-established-by-shell-and-coenshexicon-for-floating-offshore-wind-project-in-south-korea.html, Accessed: 19 December 2022

[44] Barlow, E., Tezcaner Öztürk, D., Revie, M., Akartunali, K., Day, A.H., & Boulougouris, E., 2016, “On using simulation to model the installation process logistics for an offshore wind farm”, Technical Report, https://strathprints.strath.ac.uk/60880/

[45] Rippel, D., Jathe, N., Becker, M., Lütjen, M., Szczerbicka, H. and Freitag, M., 2019, “A Review on the Planning Problem for the Installation of Offshore Wind Farms”, International Federation of Automatic Control, PapersOnLine 52-13 (2019), pp. 1337-1342

[46] Barlow, E., Tezcaner Öztürk, D., Revie, M., Akartunalı, K., Day, A.H., and Boulougouris, E., 2017, “A mixed-method optimisation and simulation framework for supporting logistical decisions during offshore wind farm installations”, European Journal of Operational Research, 264 (2018), pp. 894-906

[47] Dewan, A., Asgarpour, M. and Savenije, R., 2015, “Commercial Proof of Innovative Offshore Wind Installation Concepts using ECN Install Tool”, ECN Wind Energy, Innovation Project

[48] Muhabie, Y. T., Caprace, J. D., Petcu, C. and Rigo, P., 2015, “Improving the Installation of Offshore Wind Farms by the use of Discrete Event Simulation”, Proceedings of the 5th World Maritime Technology Conference

[49] Barlow, E., Tezcaner Öztürk, D., Revie, M., Akartunalı, K., Day, A.H., and Boulougouris, E., 2015, “Exploring the impact of innovative developments to the installation process for an offshore wind farm”, Ocean Engineering, 109 (2015), pp. 623-634

[50] Tezcaner Öztürk, D., Barlow, E., Revie, M., Akartunalı, K., Day, A.H., and Boulougouris, E., 2016, "Robust Rolling Horizon Optimisation Model for Offshore Wind Farm Installation Logistics", Technical Report, https://strathprints.strath.ac.uk/60955/

[51] McAuliffe, F. D., Lynch, K., Sperstad, I. B., Nonås, L. M., Halvorsen-Weare, E. E., Jones, D., Akbari, N., Wall, G., Irawan, C., Norstad, I., Stålhane, M. and Murphy, J., 2018, "The LEANWIND suite of logistics optimisation and full lifecycle simulation models for offshore wind farms", LEANWIND project, Journal of Physics, Conference Series 1104 (2018) 012002

[52] Shyshou, A., Gribkovskaia, I. and Barceló, J., 2009, "A simulation study of the fleet sizing problem arising in offshore anchor handling operations", European Journal of Operational Research, 203 (2010), pp. 230–240

[53] Hillier, F. S. and Lieberman, G. J., 2010, "Introduction to Operations Research", Ninth Edition, Published by McGraw-Hill, New York, NY, USA

[54] Williams, T. M., 1992, "Practical Use of Distributions in Network Analysis", Journal of the Operational Research Society, 43:3, pp. 265-270

[55] Catterson, V. M., McMillan, D., Dinwoodie, I., Revie, M., Dowell, J., Quigley, J. and Wilson, K., 2014, "An economic impact metric for evaluating wave height forecasters for offshore wind maintenance access", Wind Energy, 19 (2), pp. 199-212

[56] Dinwoodie, I. and McMillan, D., 2013, "Operational strategies for offshore wind turbines to mitigate failure rate uncertainty on operational costs and revenue", Renewable Power Generation, IET 8(4), pp. 359–366

[57] Hill, D. C., McMillan, D., Bell, K. R. W. and Infield, D., 2012, "Application of Auto-Regressive Models to U.K. Wind Speed Data for Power System Impact Studies", IEEE Transactions on Sustainable Energy, Vol. 3, No .1

[58] Dalgic, Y., Lazakis, I., Dinwoodie, I., McMillan, D. and Revie, M., 2015, "Advanced logistics planning for offshore wind farm operation and maintenance activities", Ocean Engineering, Vol. 101, pp. 211-226

[59] Billinton, R. and Allan, R. N., 1983, "Reliability evaluation of engineering systems", Plenum press, New York, NY, USA

[60] Barlow, E., Tezcaner Öztürk, D., Revie, M., Akartunalı, K., Day, A.H., and Boulougouris, E., 2014, "An assessment of vessel characteristics for the installation of offshore wind farms", International Conference on Marine Technology ICMT 2014, Glasgow, UK

[61] Barlow, E., Tezcaner Öztürk, D., Revie, M., Akartunalı, K., Day, A.H., and Boulougouris, E., 2014, "A support tool for assessing the risks of heavy lift vessel logistics in the installation of offshore wind farms", Proceedings of the 2014 RINA marine heavy transport and lift conference IV

[62] Taha, H. A., 2007, "Operations Research: An Introduction", Eighth Edition, Published by Pearson Prentice Hall, Upper Saddle River, New Jersey, USA

[63] Palensky, P., Widl, E., Stifter, M., and Elsheikh, A., 2013, "Modeling intelligent energy systems: Co-simulation platform for validating flexible-demand EV charging management", IEEE Transactions on Smart Grid, 4, pp. 1939–1947

[64] Mobini, M., Sowlati, T., and Sokhansanj, S., 2013, "A simulation model for the design and analysis of wood pellet supply chains", Applied Energy, 111, pp. 1239–1249

[65] Ekşioğlu, S. D., Palak, G., Mondala, A. and Greenwood, A., 2013, "Supply chain designs and management for biocrude production via wastewater treatment", Environmental Progress & Sustainable Energy, 32, pp. 139–147

[66] Al-Agtash, S., 2013, "Electricity agents in smart grid markets", Computers in Industry, 64, pp. 235–241

[67] Brown, J., and Khan, J. Y., 2013, "Key performance aspects of an LTE FDD based smart grid communications network", Computer Communications, 36, pp. 551–561

[68] Jung, J., Onen, A., Russell, K., Broadwater, R. P., Steffel, S., and Dinkel, A., 2015, "Configurable, hierarchical, model-based, scheduling control with photovoltaic generators in power distribution circuits", Renewable Energy, 76, pp. 318–329

[69] Endrerud, O. E. V., and Liyanage, J. P., 2015, "Decision support for operations and maintenance of offshore wind parks", Proceedings of the 2015

engineering asset management-systems, professional practices and certification, pp. 1125–1139

[70] Conover, W.J., 1980, “Practical nonparametric statistics”, Published by John Wiley & Sons, New York, NY, USA

[71] WindEurope, 2022, “First Greek Offshore Wind Law seeks 2 GW by 2030”, https://windeurope.org/newsroom/news/first-greek-offshore-wind-law-seeks-2-gw-by-2030/, Accessed: 3 January 2023

[72] Syridou, T., 2018, “Study of Offshore Wind Farm Installation in Alexandroupoli”, Diploma thesis, School of Engineering, Department of Mechanical Engineering, Technological Educational Institute of Crete, Heraklion, Crete, Greece

[73] GWEC, 2021, “Discover the potential for offshore wind around the world”, https://gwec.net/discover-the-potential-for-offshore-wind-around-the-world/, Accessed: 3 January 2023

[74] Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D. and Thépaut, J. N., 2018, “ERA5 hourly data on single levels from 1959 to present”, Copernicus Climate Change Service (C3S) Climate Data Store (CDS), https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview, Accessed: 28 December 2022

[75] Zacharioudaki, A., Ravdas, M., Korres, G. and Goglio, A. C., 2022, “ Mediterranean Sea Waves Reanalysis”, Copernicus Climate Change Service (C3S) Climate Data Store (CDS), https://data.marine.copernicus.eu/product/MEDSEA_MULTIYEAR_WAV_006_012/description, Accessed: 28 December 2022

[76] Mytilinou, V., Lozano-Minguez, E. and Kolios, A., 2018, “A Framework for the Selection of Optimum Offshore Wind Farm Locations for Deployment”, Energies Journal, 11(7): 1855, https://strathprints.strath.ac.uk/65686/

[77] Zhao, L., Xue, L., Li, Z., Wang, J., Yang, Z. and Xue, Y., 2022, "Progress on Offshore Wind Farm Dynamic Wake Management for Energy", Journal of Marine Science and Engineering, 10, 1395

[78] Boskalis, "Cable-laying vessels", https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/cable-laying-vessels, Accessed: 3 January 2023

[79] Bowie, M., Parry, A., Giles, J. and West, A., 2018, "Cable plan – Kincardine offshore windfarm project", Cobra KOWL, Doc. No.: KOWL-PL-0004-009

[80] Bourbon, https://www.bourbonoffshore.com/en/services/marine-%26-logistics/our-fleet/AHTS, Accessed: 3 January 2023

[81] Delmar Systems and Vryhof, https://delmarvryhof.com/products/anchors/stevshark-rex/, Accessed: 3 January 2023

[82] Vryhof, 2015, "Vryhof Manual – The guide to anchoring", Fight Edition

[83] Le, C., Ren, J., Wang, K., Zhang, P. and Ding, H., 2021, "Towing Performance of the Submerged Floating Offshore Wind Turbine under Different Wave Conditions", Journal of Marine Science and Engineering, 9, 633

[84] Davies, C., Logan, A. and Roberts, A., 2020, "Job Roles in Offshore Wind", Green Port Hull and BVG Associates brochure

[85] Whiteford, S., 2021, "How do cable lay vessels work", Onestep Power, Houston, Texas, USA, https://www.onesteppower.com/post/cable-lay-vessels, Accessed: 3 January 2023

[86] McMorland, J., Collu, M., McMillan, D. and Carrol, J., 2022, "Operation and maintenance for floating wind turbines: A review", Renewable and Sustainable Energy Reviews, 163 (2022) 112499