Commercial Proof of Innovative Offshore Wind Installation Concepts using ECN Install Tool

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Abstract

Installation of offshore wind farms contributes approximately 15-20% to the life cycle costs of an offshore wind farm. Moreover, because of its high dependency on weather conditions, it is associated with high risk. The high installation costs of offshore wind can be reduced significantly by innovative installation methods. In this report, first an introduction to the offshore wind installation is given and then the installation effort for a reference wind farm is described. Later on, three innovative installation concepts are described.

Additionally, using the “ECN Install” tool the installation of the reference wind farm and three innovation concepts are modelled. ECN Install is a planning and logistics tool developed by ECN for installation planning of offshore wind farms. As a result of the ECN Install calculations, the total installation time and all possible delays for the installation of the reference wind farm and three innovative concepts are presented. It is seen that as compared to baseline modelling, the innovations can save up to 1.5-2 days of time per turbine or foundation installation.

Contents

Summary

The offshore wind industry has seen a significant growth in recent years. In 2014 itself, 408 new offshore turbines were fully grid connected, adding 1,483 MW to the European system. Besides Europe, emerging markets like South and East Asia and the US are having a definite and promising plan for installation of offshore wind farms.

The sudden stride in the installation of these wind farms led to the development of ECN Install. The software was built within the Far and Large Offshore Wind Programme (FLOW) with due consultation with IHC Merwede and Van Oord. Besides conventional methods of installation, the market requires innovative concepts to make the installation cost low and more importantly reduce the risk. To encourage such concepts, three ideas are proposed as part of an ”Innovation Project” within ECN.

To demonstrate the modelling by ECN Install, firstly, installation for a near Gemini offshore wind farm location is simulated. The offshore wind farm is considered as the reference wind farm which is located 85 km from shore. Moreover, only the foundation and turbine installation are analysed within the scope of the project. The electrical infrastructure is not accounted in the modelling. It is seen that the average installation time per foundation and per turbine equals more or less 3 days.

As part of the three innovations, the first innovation proposes to build an offshore harbour, where components are transported by a feeder vessel and are assembled there itself. Also, the concept of single lift installation is introduced with this innovation. It is seen that the average duration per turbine installation is thereby reduced to merely 0.78 days. The second innovation introduces the concept of breakwaters. These structures act as wave attenuators and stabilise the weather conditions in and around the wind farm for installation. The model resulted with nearly 1.5 days for the average duration of foundation and turbine installation time. The last innovation corresponds to floating offshore turbines. Initially, modelling for a reference wind farm following the Hywind installation methodology is prepared. And later, as part of the third innovation, installation through an onshore assembly of turbines is completed. Moreover, a different concept of towing and installation is followed. The difference in the methodology of the two concepts (baseline and innovation) is around 1.9 days per installation of turbine.

1

Introduction

1.1 Offshore Wind

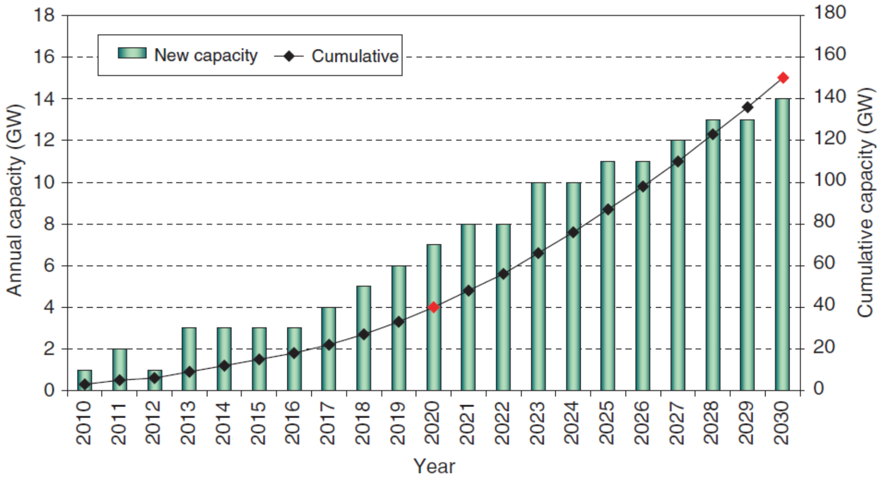
Offshore wind energy observed a substantial increase in terms of installation of offshore wind farms. Europe alone in 2014 added 1.5 GW of offshore wind capacity to the grid amounting to a total of over 8.7 GW (fully grid connected) [1]. An offshore wind farm typically consists of large multi-megawatt wind turbines clustered together at an offshore location some kilometres from the coast, feeding the high voltage grid on an onshore connection point through cables that are carefully buried in the seabed [2].

Offshore wind energy is a key pillar for the European energy transition. The European countries are aiming to cover 35% of their energy consumption from renewables by 2020, which sets a target of 40 GW installed offshore capacity by 2020 [3]. **Figure 1** illustrates the projected targets for offshore wind farm installations in Europe. Therefore, to reach the ambitious European climate and energy targets, more than 30 GW offshore capacity should be installed by 2020. This means that the required effort for installation of offshore wind farms will be significant in the coming years. Furthermore, because of environmental laws and limited space near shore, future wind farms will be located further offshore and consequently in deeper water, encountering harsher weather conditions. Hence, in order to reduce the installation time and costs, it is essential to develop robust long term installation planning concepts that can be used by a variety of users such as installation contractors, wind farm developers, harbour authorities and OEMs.

1.2 Offshore Wind Farm Installation

As discussed above, the planned installation of offshore wind farms in Europe in the coming 2-3 years is in the range of 300-600 MW. These wind farms require thorough planning before the actual implementation process. The entire installation process is conducted over several phases or steps. These steps can be in sequence or in parallel. There are several factors that can turn this process into a challenge. These factors can either be due to offshore site conditions or the technical limitations of the installation vessels. Each project has its own characteristic parameters and requires a unique optimum solution. In this report, some possible innovations have been explored. Some of the innovations have been tested with prototype and some are under scrutiny. However, using the modelling approach developed in-house by ECN, these innovations have been validated in terms of benefit achieved by lowering the total installation time. A detailed discussion about the offshore wind farm installation is discussed in Chapter 2.

Figure 1: Projection of Europe's offshore wind farm Installation (source: GWEC)



1.3 Outline of the Report

The report has been distributed over various chapters. Chapter 2**Fout! Verwijzingsbron niet gevonden.** presents the explanation to the offshore wind installation, discussing the installation of various components of an offshore wind turbine including turbines, foundations, cables, high voltage station, etc. Moreover, an explanation is provided of ECN Install, the tool developed in-house at ECN to model planning of offshore wind farm installation. Chapter 3 introduces the reference wind farm chosen for the simulation and comparison. The installation model developed using ECN Install is described and corresponding results are highlighted. Further, Chapter 4**Fout! Verwijzingsbron niet gevonden.**, Chapter 5 and Chapter 6 introduce the three innovations proposed for the installation of offshore wind farm. The report is completed with Chapter 7 providing the conclusions and future work.

2

Offshore Wind Installation

The installation of offshore wind farms is influenced significantly by weather conditions. The initial planned timeline might not be valid while undertaking the real implementation of the installation steps. In general, it is observed that support structures can be installed in more adverse weather conditions compared to the blades and nacelle. The installation of the latter requires more reliability of the weather, logistics and working conditions. This implies that installation planning is quite critical for the overall success of the process. Moreover, an actual indication of the date of commissioning and associated installation cost is necessary. Another aspect critical for the successful realisation of the project is spare part and resource management. For instance, if the capability of the vessel is to transport six piles, it is necessary that the same number are available at the harbour for loading. These small optimisations of resources can highly influence the installation costs and hence mitigate project risk. With larger and far-offshore wind farms planned in future, the efficiency and the reliability of the entire installation process is quite relevant.

2.1 Installation of Electrical Infrastructure

Cable arrays, offshore electrical infrastructure, and medium and high voltage transmission cables make up roughly 14% of offshore wind's levelised cost of energy [4]. The components installed as part of electrical infrastructure are: Offshore High Voltage Sub-station (OHVS), in-field array cables, export cable and grid connection.

On-site offshore substations are used to reduce electrical line losses and improve the overall electrical efficiency by increasing the voltage level (e.g., to 100–220 kV) from the collection system and then exporting the power to shore. Apart from locating the lines from the collection system at a central point and transforming the energy produced to high voltage, the substation contains the necessary switching panels and other electrical facilities (e.g., power factor correction systems). The substation normally rests on a monopile or gravity-based foundation and may be also used as a service platform for the wind power plant with a boat docking facility and a helicopter landing station.

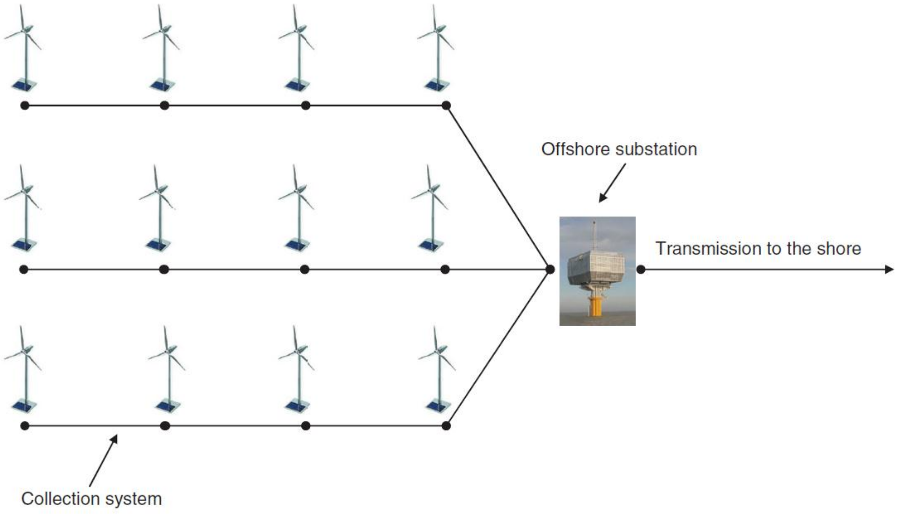
Typically, an offshore substation is installed in cases where the project is in the range of tens of megawatts, located quite far from shore, and the connection to the electric grid is not at the collection voltage. The OHVS is normally assembled onshore and can take several months before the same is constructed [7]. OHVS installation is done in parallel with other wind farm installation. **Figure 2** below shows the different stages of OHVS installation.

Figure 2: Different phases of OHVS Installation [5][6]


Construction Phase
Loading Phase
Travelling & Installation Phase

The power output of the wind farm is delivered to the offshore substation through interturbine (array) cables (or collection system).The cables are typically rated at 30–36 kV and are designed to connect multiple wind turbines by forming a string (collection circuit) before feeding the project's offshore substation. Then, the transmission of the power to the mainland grid is achieved with export cables of similar design with the collection system but with higher voltage (usually 100–220 kV). Typically, each collection and export circuit may be rated up to 3 and 150–200MW, respectively. A typical layout of the wind farm with inter- array cables is shown in **Figure 3.**

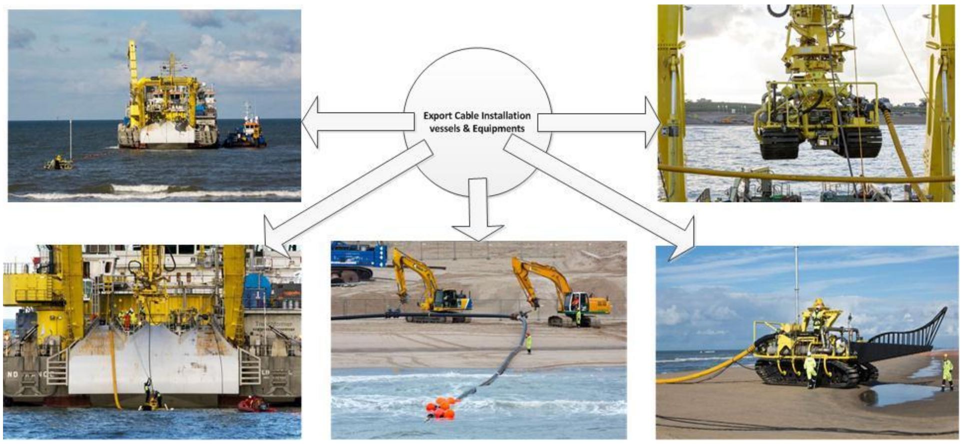
Figure 3: Layout of wind farm illustrating the inter-array cables [4]



Different types of inter-array cables are used in offshore wind projects. Offshore wind power cable is usually buried in the seafloor. Also, there are several methods for installation of these cables, but in most cases, the cable is simultaneously laid and buried by either an underwater plough or remotely operated vehicle (ROV). The plough, or ROV, operates a water jet which fluidizes sediment and creates a trench into which the cable is laid; the fluidized sediment then buries the cable. Alternatively, cable may be pre-laid on the seafloor and an ROV may later bury the cable. For monopiles, a J-tube is attached to the outside to serve as a conduit for the electrical cable. The J-tube extends from above sea level down to or below the mud line and the cable must be fed up through the J-tube via a winch. The process of feeding the cable usually requires divers and/or an ROV and is sensitive to tidal, wave and current windows [9].

Export cables may be either high voltage (above 110 kV) or medium voltage (20e40 kV) depending on the capacity of the plant and the length of the export cable. All OWFs operational today, are radially connected to the onshore electric grid through use of high voltage alternating current or high voltage direct current submarine cables. **Figure 4** shows the installation steps for setting up the export cables from the shore to the OHVS location.

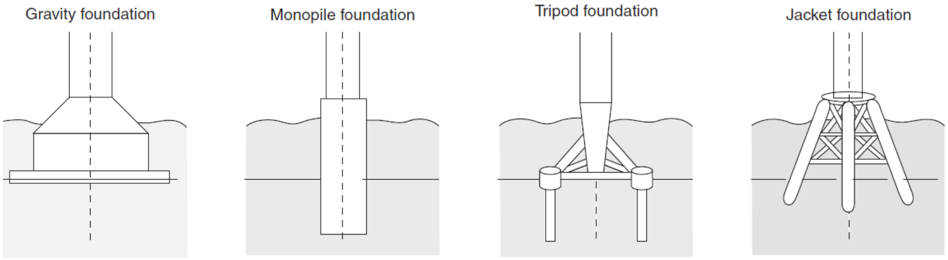
Figure 4: Export Cable Installation Procedure [8]



2.2 Installation of Foundations

Foundation installation is one of the initial part of installation performed for the wind farm. The selection of the offshore wind turbine support structure (foundation) is based on site-specific conditions. Water depth, wind/wave conditions, currents, seabed properties (i.e., natural or man-made obstructions, slopes, stability, composition, etc.), and access requirements are the basic parameters affecting the design of the foundation type to be used [7]. Some of the available and commonly installed foundations are shown in **Figure 5.**

Figure 5: Different types of sub- structures



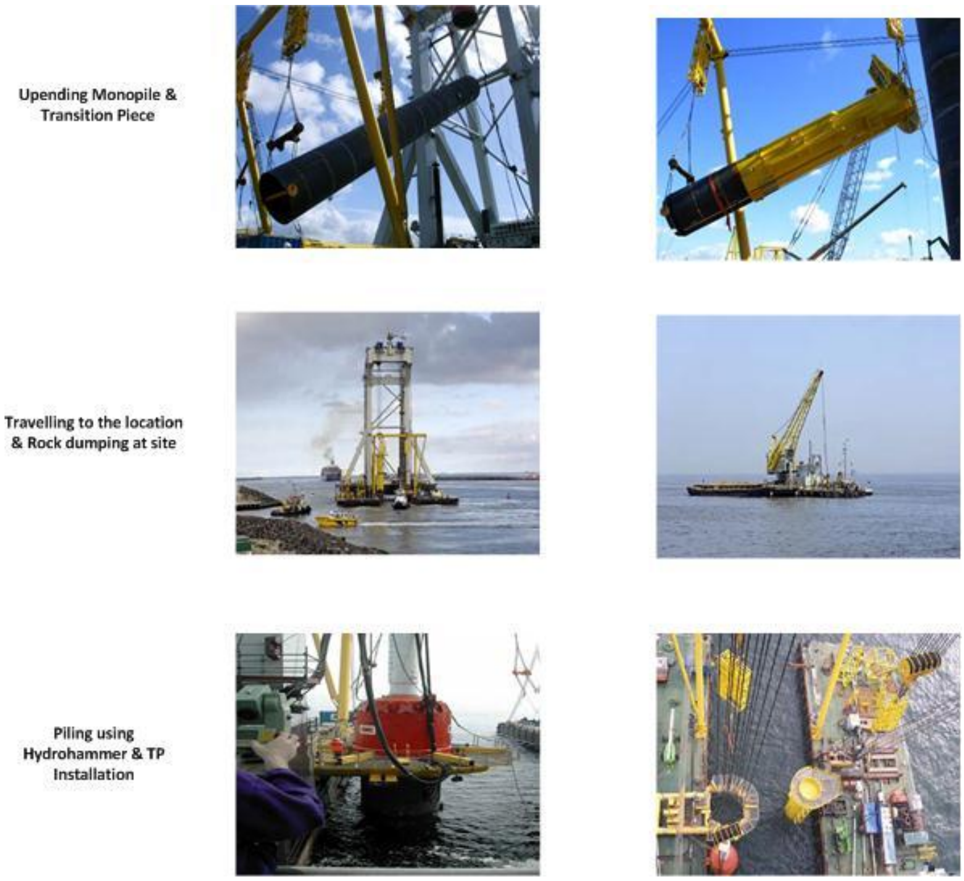
In this report, only monopiles are considered as support structures for installation. It comprises the simplest and the most commonly employed foundation solution up till now mainly due to its low cost, the minimal footprint on the seabed, and low design requirements for transition from onshore to offshore. Monopile foundations consist of a large cylindrical steel pile and a steel structure (transition piece) placed over and grouted onto it [9]. Monopile installation consists of sea-bed preparation, piling, scouring, transition piece (TP) installation, grouting and J-tube installation.

Firstly, the seabed is prepared by dumping rocks (scour protection) and making the surface even. Further, from a pre-assembly site in the harbour, each monopile is transported to the site by an installation vessel. The installation generally takes place with either a jack-up barge or a floating crane vessel, which ideally needs to have sufficient height, storage capacity, and ability to operate in a wide range of water depths, wave heights, and currents. The crane must be capable of lifting the structures, with hook heights being greater than the level of the nacelle to enable the tower and wind turbine assembly [8].

The pile is upended by a crane and/or a specialized pile gripping device and a hydraulic hammer drives the pile into the seabed to a predetermined depth. The time to drive the piles depends on the soil type, diameter and thickness of the piles, burial depth and the weight of the hammer. After the monopile is secured, a transition piece is grouted onto the pile. The transition piece is typically installed immediately after piling by the same vessel that drove the pile, but if two vessels are employed in installation, a separate vessel may follow behind the foundation installation. The area around the monopile may need to be protected with rocks to guard against erosion (scour protection). This is accomplished by side dumping barges or other less expensive vessels.

Figure 6 illustrates the steps involved in the installation process of support structures at OWEZ wind farm. Said farm was the earliest offshore wind farm installed in Netherlands.

Figure 6: Sub- Structure Installation at OWEZ wind farm [10]



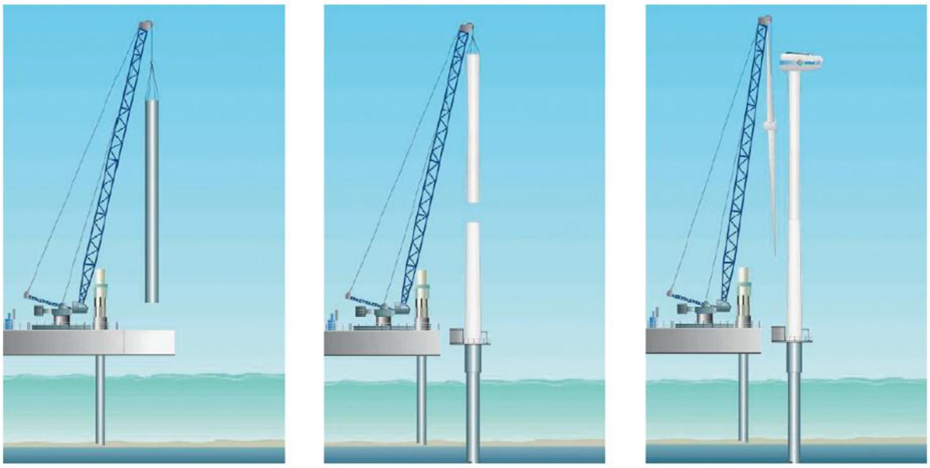
2.3 Installation of Wind Turbines

Wind turbine installation components primarily consist of three blades, tower and nacelle. **Figure 7** depicts the common steps involved in the wind turbine assembly installation. However, there are various concepts through which wind turbines can be installed. Some of the concepts are [11]:

- “Bunny Ear” with a Tower in Two Pieces
- “Bunny Ear” with a Tower in one Piece
- Pre-assembled Rotor (All three blades pre-assembled)
- Five Pieces separately (Tower, Nacelle with hub, 3 Blades)
- Six Pieces separately (Tower in two pieces, Nacelle with hub, 3 Blades)

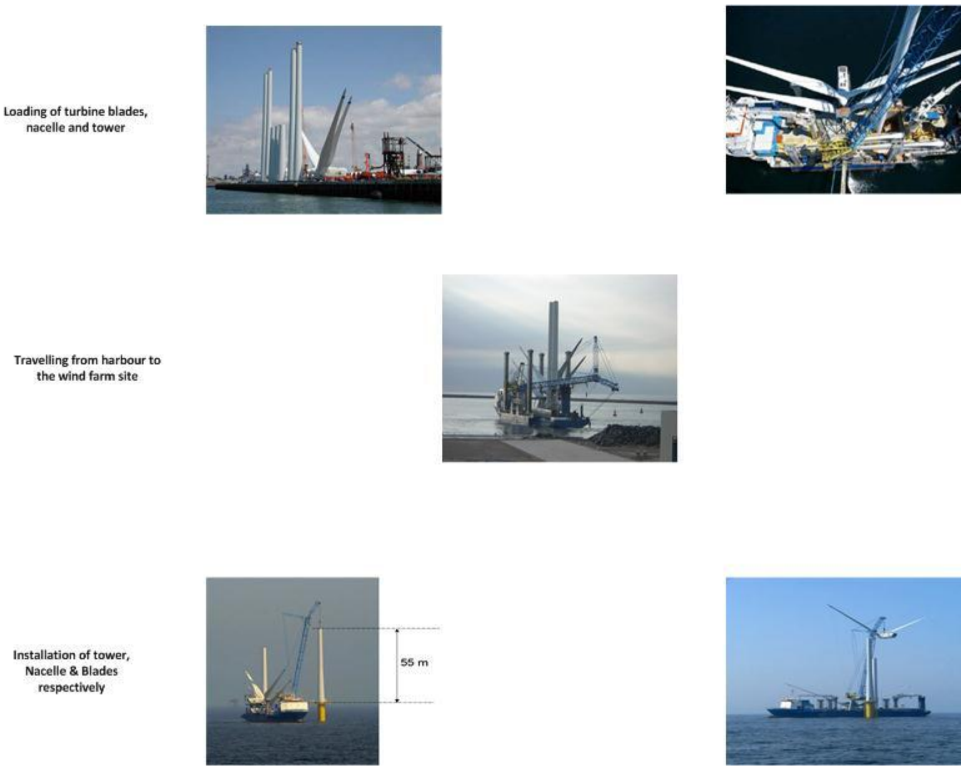
Difference in the approach followed for installing the turbine will lead to the selection of an appropriate vessel. Moreover, Offshore lifts are risky and are susceptible to delay in operations due to wind speeds, so the preference is usually to minimize offshore assembly. In most cases, onshore assembly reduces the number of lifts from seven to three or four per turbine. This is accomplished either by assembling the rotor onshore (the three blades and the hub) or using a bunny-ear configuration in which the nacelle and hub are attached to two blades [9].

Figure 7: Illustration of Wind Turbine Installation [9]



In the case of OWEZ wind farm, strategy 2 from the above list was chosen. Two complete sets of turbines were loaded on the vessel, which were finally installed at the site. The complete flow of turbine installation is illustrated in **Figure 8.**

Figure 8: Illustration of Wind Turbine Installation [10]



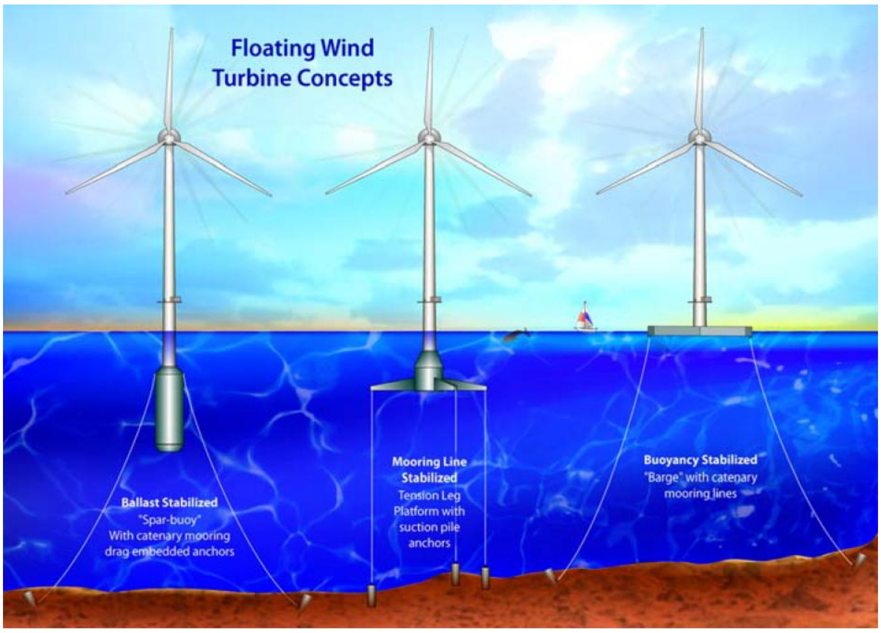
Besides the conventional bottom founded wind turbines, floating wind turbines have also been in development for a while. Fixed bottom foundation concepts are suitable to a certain water depth. But with water depths of more than 40 metres, the above discussed structures will experience increased cost and this shall require larger fixed bottom structural dimensions which are economically nonviable. In this context, a floating concept (i.e., mounting a wind turbine's tower on a floating platform) instead of a fixed bottom foundation may be a better choice [7]. For that reason, a lot of research effort has been put on developing a feasible concept, with a number of possible offshore wind turbine platform configuration permutations in terms of available anchors, moorings, buoyancy tanks, and ballast options being under investigation by the offshore industry.

Typically, floating wind turbines are held in place by wires or chains anchored on the ocean floor with piles or suction anchors. However, the final design of a floating configuration and the selection of the most appropriate solution may vary significantly depending on a large number of parameters (e.g. mooring system cost and deployment complexity, on-site installation requirements, soil conditions, maintainability, and related costs). In general, one may classify floating structures into three main types based on the strategy used to ensure static stability:

- Ballast stabilized
- Mooring line stabilized
- Buoyancy stabilized

These concepts are illustrated in **Figure 9**. Detailed discussion of the floating turbines and the installation concepts will be done in Chapter 6.

Figure 9: Floating Turbine concepts [12]



The next section introduces the ECN Install software in brief to model the installation process mentioned in this section.

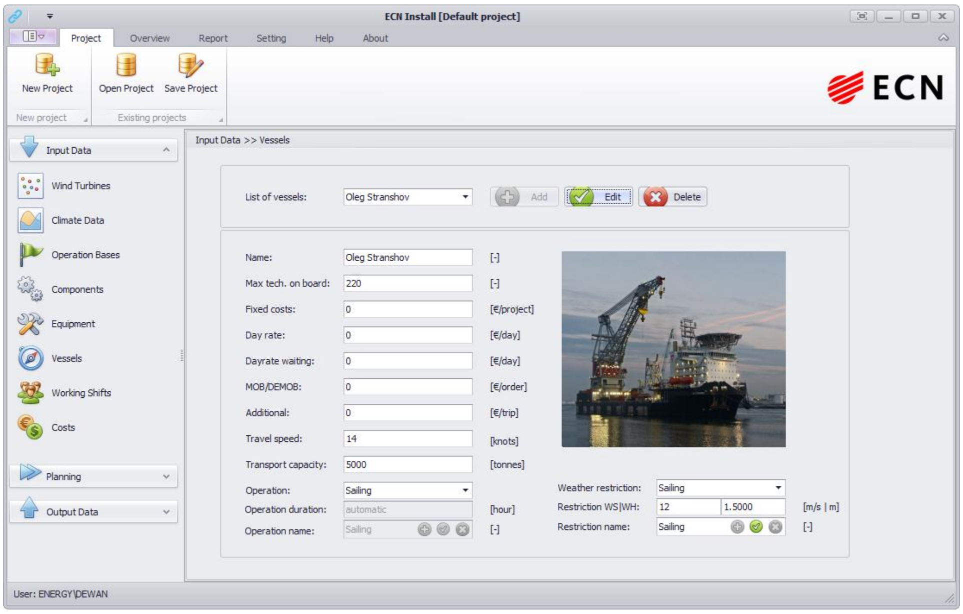
2.4 ECN Install Tool

The installation of the components of wind farm discussed above can be modelled using an ECN developed software. The Installation model, named ECN Install provides the user a tool to simulate the proposed plan of installation in the form of 'steps'. In order to have a generic model only three types of steps are considered:

- Loading step, which describes the set of activities to load the components from the harbours to the vessel;
- Traveling step, which describes the traveling of the vessels to and from the harbours and the farm;
- Installation step, which is used to describe all installation activities being performed with vessels and equipment; e.g. piling or vessel positioning.

Besides the above set of steps defined as an initial plan by the user, general inputs of the wind farm installation like working patterns of the crew, climate information, vessels and equipment used, harbours and turbine data, etc. are obtained as well. A screenshot of the interface with vessel inputs is shown in **Figure 10.**

Figure 10: Graphical Interface sample for ECN Install



List of vessels: Oleg Stranshov

Name: Oleg Stranshov [-]
Max tech. on board: 220 [-]
Fixed costs: 0 [€/project]
Day rate: 0 [€/day]
Dayrate waiting: 0 [€/day]
MOB/DEMOB: 0 [€/order]
Additional: 0 [€/trip]
Travel speed: 14 [knots]
Transport capacity: 5000 [tonnes]
Operation: Sailing
Operation duration: automatic [hour]
Operation name: Sailing [-]
Weather restriction: Sailing
Restriction WS|WH: 12 1.5000 [m/s | m]
Restriction name: Sailing [-]

User: ENERGY\DEWAN

While defining each of the steps, the user can select the corresponding vessel, equipment, weather thresholds and the components to be installed. The steps are initially processed to compile without any delays. Additionally, the weather information provided by the user is used to create accessibility vectors for performing each particular step. By using a Monte Carlo simulation in the time domain, delays caused by working hours and vessel weather limits are calculated. A working example of the implementation of such steps is described in **Table 1.**

In **Table 1**, an activity termed as pre-piling is performed. In this example, three lines of parallel activities are executed, with each box representing one step. The step could either be loading, traveling or installation.

Table 1: Sample Installation of Piles

1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	…	1.n
			2.1	2.2	2.3	2.4			
		3.1	3.2	3.3	3.4	3.5	3.6	…	3.n

For instance, step 1.1 could be loading a component to the jack-up barge at the harbour, step 1.2 could be defined as traveling to the farm, and steps 1.3 to the end of the sequence could be vessel positioning, vessel jacking up, placing the template, placing the pile and then hammering. The second line could be a parallel activity like feeding new piles to the jack-up barge with a support vessel and the third line could be an independent parallel activity like installation of balance of plant.

Additionally, it’s possible to cluster a few steps together to use the same weather window. For instance, steps for placing the template and pile could be clustered together to ensure that, during installation the necessary weather window to perform both activities exists. In order to simplify the definition of installation activities it is also possible to repeat several activities, like repeating all piling steps for the number of wind turbines in the farm.

ECN Install has been used for modelling the case of the reference wind farm and all three proposed innovation concepts. The results are a summary of the outputs obtained from the software. The next chapter introduces the reference wind farm, the modelling approach and the equivalent results.

3

Reference Wind Farm

The installation of the reference wind farm is modelled corresponding to current existing installation methods. Components of multiple foundations and turbines are loaded in a harbour to large installation vessels and are subsequently transported to the wind farm where the complete turbine is assembled. The installation of scour protection and electrical infrastructure is not modelled in this study.

This chapter presents the installation steps of the reference wind farm, model results and analysis.

3.1 Wind Farm Location

This reference wind farm has a rated capacity of 300 MW and consists of 75 4MW wind turbines. The wind farm is located north of the isle Schiermonnikoog at a distance of 85 km from shore. The closest port is Eemshaven, which is also accessible for large vessels (f.i. jack-up barges). The water depth inside the wind farm varies between 28 and 36 meters. The wind farm is connected to the grid via an onshore substation which is subsequently connected to two offshore substations.

A real farm representative for these characteristics is either Gemini or a cluster of Gode Wind I+II+III. **Figure 11** gives an illustration of the reference wind farm.

Figure 11: Location of reference wind (near Gemini location)

For the simulations, time series of meteorological data have been used. ECN obtained 20 years (1992-2011) of 3-hourly time series of wind and wave parameters close to the location of the wind farm. The data is obtained by ECN from BMT ARGOSS using satellite data. Water depths at the model points are estimated. These historical time series are assumed to be representative for current and future operations of the wind farm.

The figures on the next page give an overview of the historical meteodata at the site of Gemini. A clear distinction can be made between the conditions in summer and winter. The average wave height (significant)and wind speed in the seasons are listed in **Table 2.**

Table 2: Average wind speed and wave height at Gemini (for different seasons)

Season	Wave height (av.)	Wind Speed (av.)
Winter	1.97m	9.17m/s
Spring	1.39m	6.98m/s
Summer	1.14m	6.07m/s
Autumn	1.70m	8.35m/s

Figure 12: Average significant wave height per season at offshore site of wind farm Gemini. One can see large variations in wave height depending on the season.

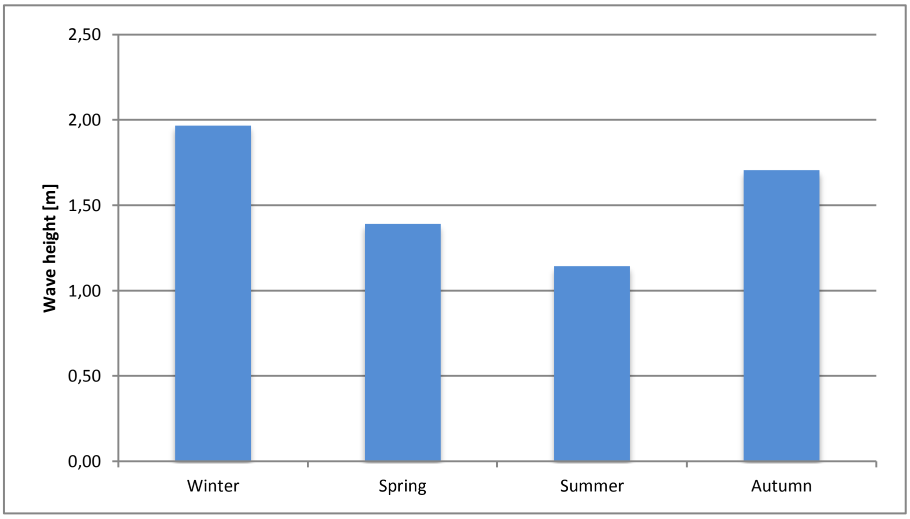
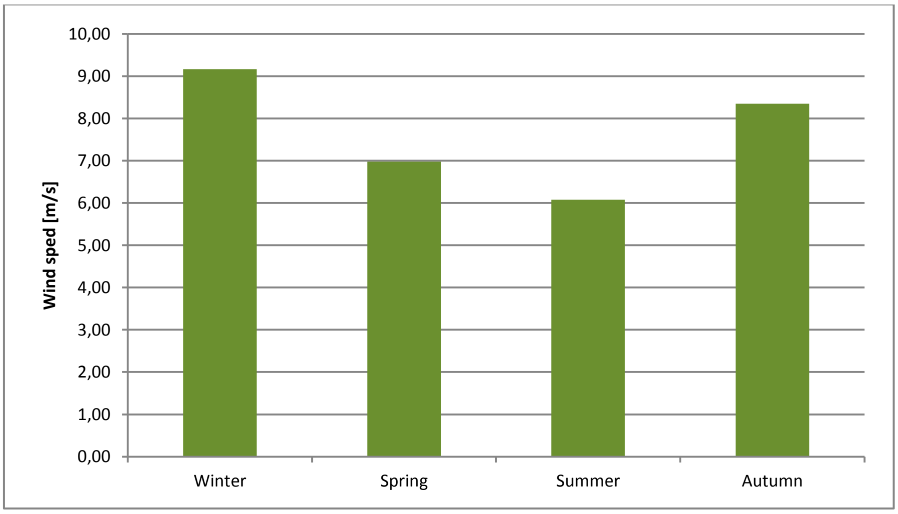


Figure 13: Average wind speed per season at offshore site of wind farm Gemini. One can see large variations in wind speed depending on the season



The average wind speed and wave height over different seasons give us an indication of the accessibility to the wind farm. This in-turn helps in planning the right season and period for installation.

Figure 14: Significant wave height with simultaneous wind speeds in all seasons over 20 years of data.

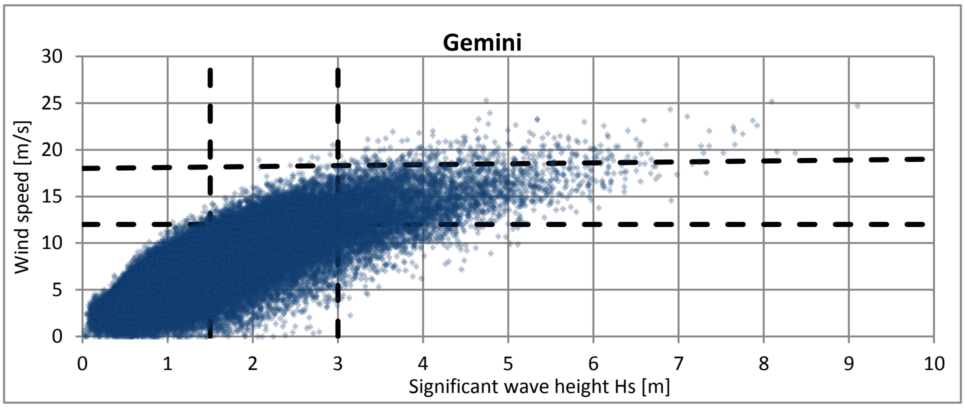


Figure 15: Significant wave height with simultaneous wind speeds in winter season over 20 years of data.

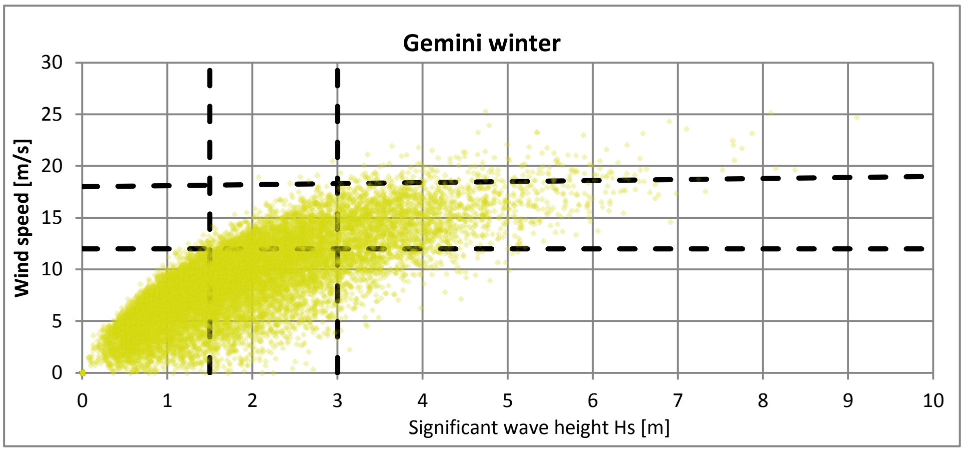
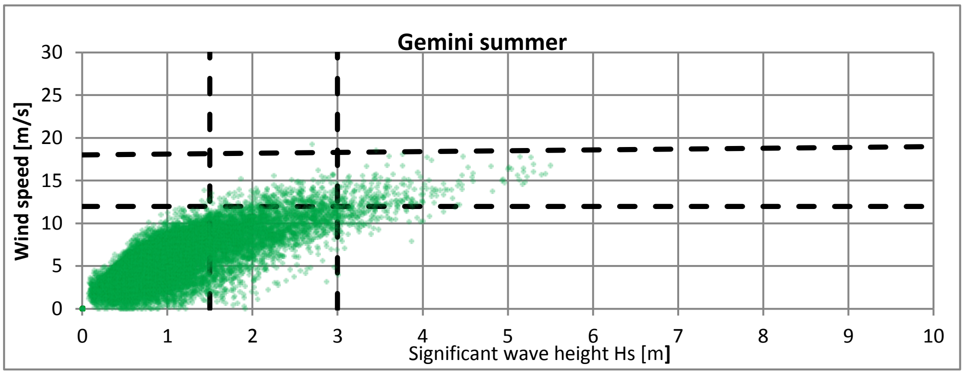


Figure 16: Significant wave height with simultaneous wind speeds in summer season over 20 years of data.



3.2 Wind Farm Components

Wind farm installation consists of three parts, namely: foundations, turbines and Electrical infrastructure (including scour protection). Each of them follow different installation techniques, procedures and equipments. As mentioned before, only the first two installation parts (foundations and turbines) are modelled using ECN Install as part of this report.

The foundations are assembled offshore from the following components:
- Monopile
- Transition piece
- J-tube set

The turbines are assembled offshore from the following components:
- Tower bottom
- Tower top
- Nacelle
- Three blades

Other components are:
- Scour protection
- BOP
  - Inter turbine cables
  - Offshore substation
  - Shore connection cables
  - Onshore connection to grid

Furthermore, an independent analysis has been performed for foundation and turbine installation. This was done mainly due to the difference in the installation technique required for foundations and turbines. Moreover, some of the innovations only affect parts of the installation strategy.

3.3 Installation Model

An introduction to the modelling software- ECN Install, was given in section 2.2. Input parameters were indicated in brief in the said section, which included wind turbine data, climate information, operation bases, components, equipments and vessels to be used for the installation, the working shift patterns and planning steps.

3.3.1 Basic Inputs

The detailed explanation for the inputs entered are as follows:

- *Wind Turbines*: Seventy-Five 4 MW machines are considered for installation. A power curve for the same turbine is saved in the project structure. The hub-height selected is 100 meters.
- *Climate Data*: Weather information of a location in North Sea is used. Specifically, the data is corresponding to the near Gemini location (satellite data) for offshore location and EWTW weather data for onshore harbour. Both the weather data are available with 3 hours of resolution.
- *Operation bases*: Eemshaven is used for the entire installation process and is the sole harbour. Wind farm (near Gemini location) is the other operation base for the installation process.
- *Components*: Five components are considered to be installed for each of the 75 Siemens turbines. They are – Monopiles, Transition Piece, Tower, Nacelle and Blades. For each of the component, the material cost and weight is entered.
- *Equipment*: The Hydraulic hammer f.i. IHC S-1200, is considered for the foundation installation process. For the equipment items used, the corresponding costs, operations and weather restrictions are entered. For a given pieces of equipment, various operations and weather restrictions may apply.
- *Vessel*: Two vessels are used for the entire installation process. One for the foundation installation and the other for turbine installation. Vessels with comparable operational capability are Oleg Strashnov (foundation installation) and MPI Discovery (turbine installation). Similar to the equipment input, the corresponding costs, operations and weather restrictions are entered for the vessels. Additionally, the transport capacity is also entered for each of the vessels. Moreover, for every vessel, more than one operations and weather restriction are defined.
- *Working shifts:* The default work shifts defined in the software are used. In case of regular working shift, different working patterns are pre-defined for each of the 4 seasons.

3.3.2 Planning

Besides the inputs common for the entire project, the planning steps are defined for both the foundation and turbine installation. E.g. 75 turbines are installed in more than 550 steps. The steps vary from as small as 1 or 2 hours to as big as 20 hours. In general, the following phases are considered for the entire installation process. The steps are mentioned in order of installation (both foundation and turbine):

- *Foundation :* Loading of 3 monopiles, 3 J-tube, 3 Transition piece (T.P.) on an installation vessel and finally installing them using hydrohammer. Complete set of foundation are loaded in a single loading operation. Moreover, the installation steps for foundations are summarized in **Table 3**.
- *Tower, Nacelle & Blades:* The three components of the wind turbine (blades, nacelle and tower) for 6 turbines are loaded and installed with a subsequent visit to the wind farm. The structures are assembled offshore with the vessel crane. Similarly as foundations, **Table 4** summarizes the steps for installing turbines.

Table 3: Installation steps of the foundations. The components of three foundations are loaded on the installation vessel. The starting date is 29th March.

Step Number	Step Description	Duration [hrs]	Wind Speed limit [m/s]	Wave Height limit [m]
1.1	Loading 3 foundations (monopiles, transition pieces and J-tube sets) to vessel	12	17	10
1.2	Travelling to the offshore wind farm	auto(3.3)	17	4
1.3	Anchoring and positioning vessel	6	17	2
1.4	Upending and positioning MP	3	17	2
1.5	Piling MP	7	17	2
1.6	Installing J-tube set	4	17	2
1.7	Lifting and stabilizing TP	2	17	2
1.8	Grouting	4	17	2
1.9	Taking in the vessel anchors	2	17	2
1.10	Travel to next turbine	1	17	4
	go back to step 1.3 and repeat 2 times			
1.11	Travel back to harbour	auto(3.3)	17	4
	go back to step 1.1 and repeat 24 times			

Table 4: Installation steps of the turbines. The components of six turbines are loaded on the installation vessel. The starting date is 5 August.

Step Number	Step Description	Duration [hrs]	Wind Speed limit [m/s]	Wave Height limit [m]
2.1	Loading 6 turbines (6 tower assemblies bottom, 6 tower assemblies top, 18 blades) to vessel	12	17	10
2.2	Travelling to the offshore wind farm	auto(3.9)	17	4
2.3	Jacking up vessel	4	14	1.4
2.4	Upending tower bottom and bolting to TP	3	17	2
2.5	Upending tower top and bolting to TP	3	17	2
2.6	Installing nacelle	5	17	2
2.7	Installing 3 blades	7	17	2
2.8	Jacking down vessel	4	14	1.4
2.9	Travel to next turbine site	1	17	4
	go back to step 2.3 and repeat 6 times			
2.9	Travel back to harbour	auto(3.9)	17	4
	go back to step 2.1 and repeat 50 times			

It should be noted that the vessel, upon completing one set of loaded foundations/turbines, must return back to shore . Also, the turbine installation is done in parallel with foundation installation. To be specific, the starting date of turbine installation is chosen only after 7 complete foundation installations are completed.

3.3.3 Model Assumptions

Besides the general description of the steps, the listed points summarize some of the other considerations for the entire project.

- Multiple shift[1] pattern is considered for all the Installation *step type* and Regular single shift for Loading *step type.*
- In general, the steps are considered *splittable.* Only the Installation step (travelling) with "Sailing" as vessel operation is considered as "No, in one go".
- The step duration and step weather duration are considered the same for all the steps.
- The installation is supposed to begin on 29th March (for foundation) and 5th August (for turbine), i.e. the starting of the sequence or the first step.
- All the vessels and the equipments mentioned in the *Input Data* have been used while defining the *Planning Steps.*

3.4 Installation Model Results

The modelling was performed for both foundation and turbine installation. The table below presents the duration and delays of installing the 75 turbines and foundations. It should be noted that the outputs are generated by averaging 20 years of analysis.

Table 5: Results are in days average per turbine

	Start Date	End Date	Duration Total [days]	Duration work [days]	Delay total [days]	Delay weather [days]	Delay shift [days]	Delay harbour [days]
Foundations	29-Mar	27-Aug	2.02 ±0.57	1.45	0.57 ±0.57	0.36 ±0.51	0.17 ±0.05	0.04
Turbines	5-Aug	7-Mar (next year)	2.86 ±2.09	1.26	1.60 ±2.09	1.41 ±2.00	0.19 ±0.09	0.00

The installation of the foundations can take between 109 and 194 days with on average 28% caused by delays. The turbines take between 58 and 371 days with on average 56% caused by delays. It can be concluded that the variation in weather conditions per year is significant.

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[1] This implies that the crew works in two shifts. The timings are fixed from 06.00 hrs. to 18.00 hrs. and then 18.00 hrs. to 06.00 hrs. In short, the installation is carried out 24*7.

The sub-sections below give the average time taken by each foundation and turbine. Moreover, the total time is divided between the actual duration of work, weather delay, shift delay and harbour lock.

3.4.1 Foundations

Figure 17 illustrates the installation time of each of the 75 foundations. The weather delay is relatively constant throughout the installation of the foundations from March to August. Again, the results are based on 20 year weather data.

Figure 17: Duration and delays for installing 75 foundations over time

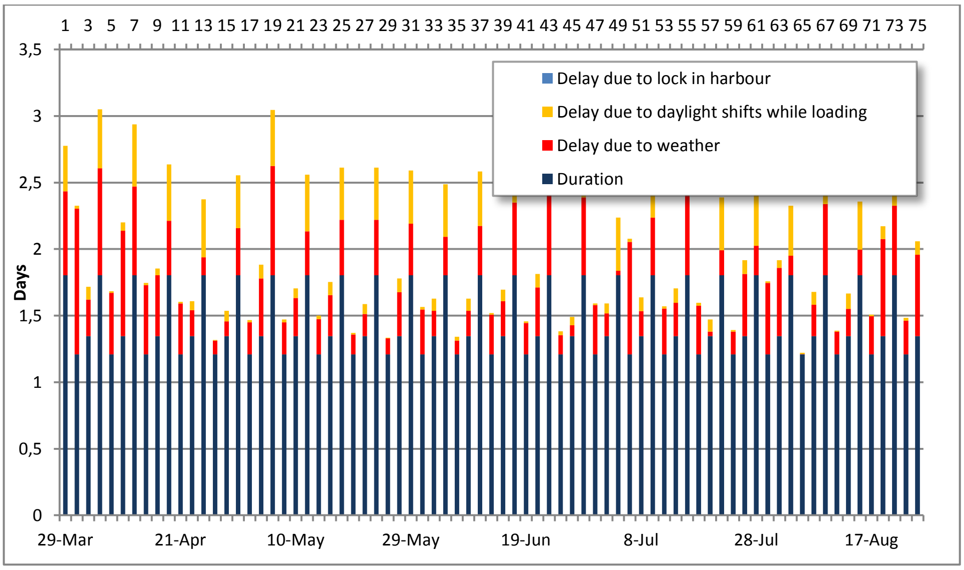


Figure 18 below depicts the average duration per step including delays. Each of the step mentioned in **Table 3** are highlighted below. The piling of the monopile has the highest weather delay due to stringent weather restrictions to perform this step. When loading the vessels with components in the harbour, shift delay occurs since loading is only done during daylight.

Figure 18: Average duration and delay per step

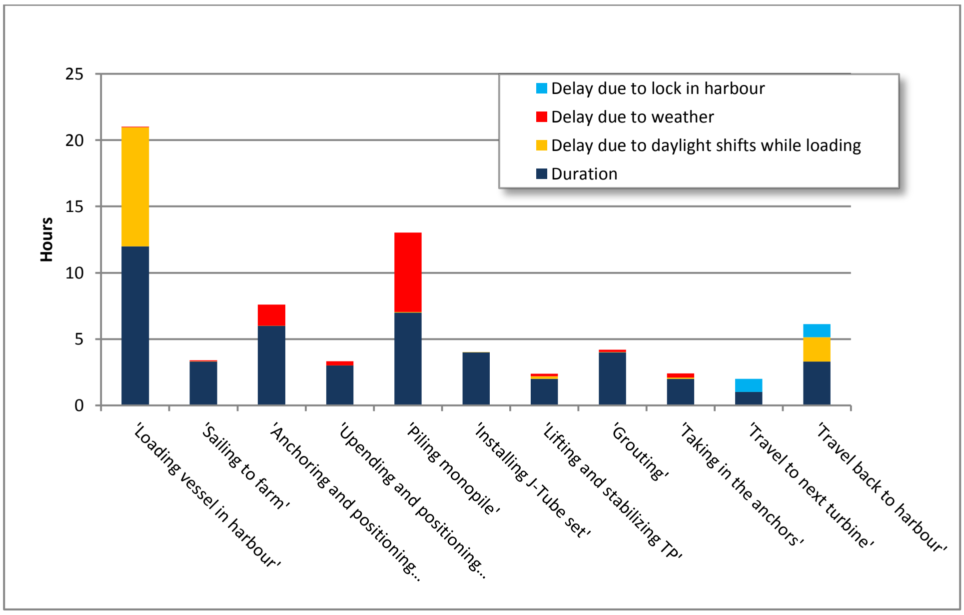


Figure 19: Planning of first two foundations including duration and delays

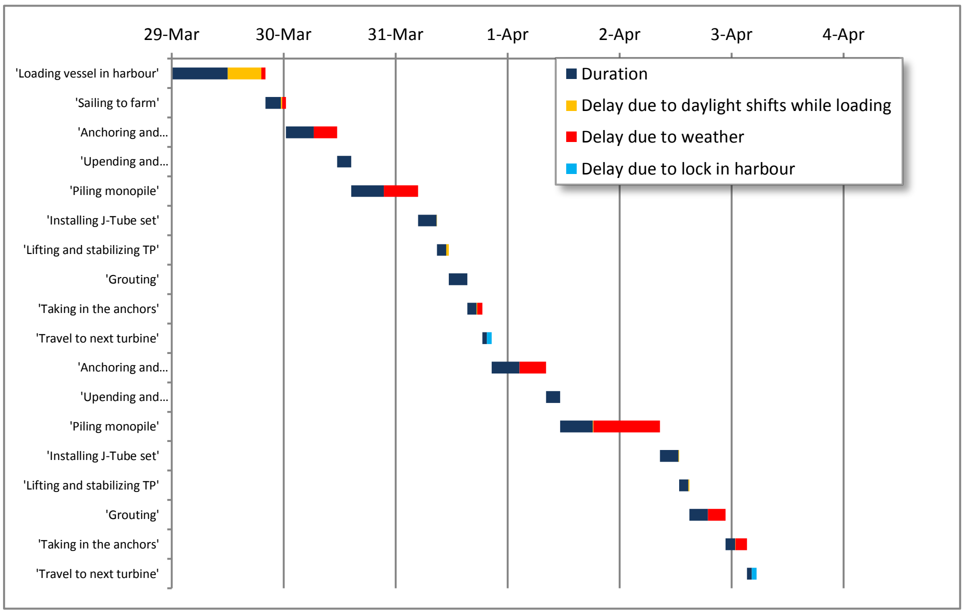


Figure 19 demonstrates the Gantt chart for each of the first 18 steps. These steps account for the installation of 2 foundations. A similar chart can be prepared for the entire 75 installation of foundations.

3.4.2 Turbines

As illustrated for foundations, installation for 75 turbines (including nacelle, blades and tower) based on 20 year weather data are shown in **Figure 20**. Clearly it can be seen that the weather delay increases in the winter season.

Figure 20: Duration and delays of 75 turbines over time

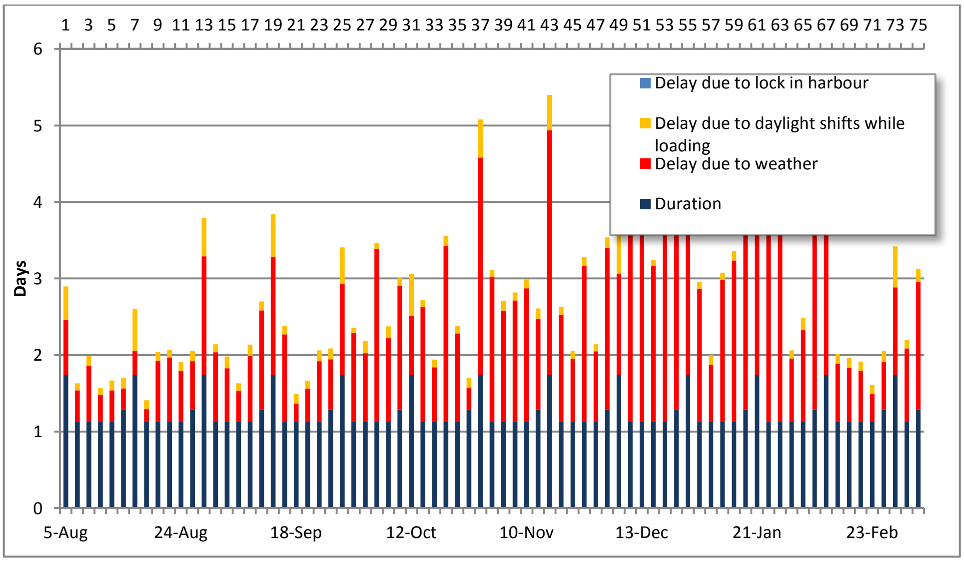


Figure 21 below depicts the average duration per step including delays. Each of the steps mentioned in **Table 4** are highlighted below. Jacking up/down operation contributes significantly to the weather delay because of high weather restrictions. Installation of blades is also an operation requiring good weather conditions.

Figure 21: Average duration and delay per step (for turbine installation)

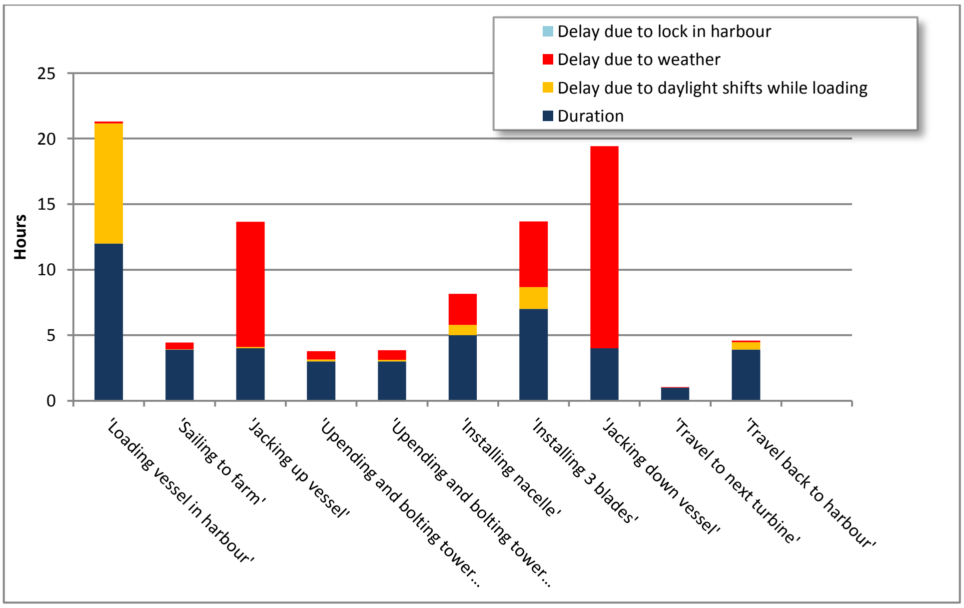


Figure 22: Planning of first three turbines including duration and delays

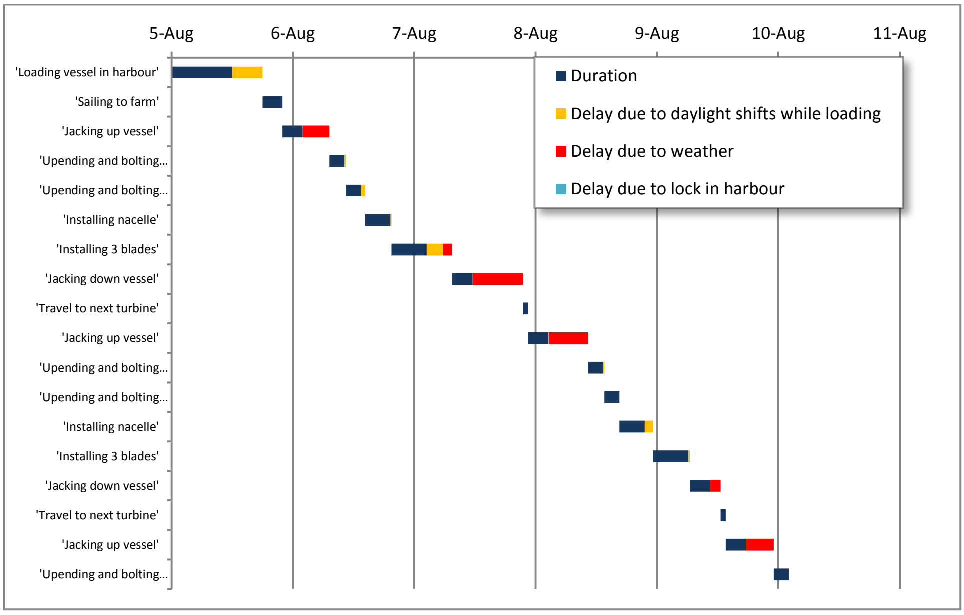


Figure 22 demonstrates the Gantt chart for each of the first 18 steps. These steps account for the installation of 3 turbines. Similar chart can be prepared for the entire 75 installation of turbines.

3.5 Discussion

The installation procedure followed for the reference wind farm is a conventional way followed currently by the industry. Although latest vessels and equipment have been considered for the installation, still the methodology or the planning process is standard. For e.g. in the above case, the foundations were installed in a better weather period leading to low risk and standard deviation. For the installation of 75 turbines, it took nearly 5 months (considering marginal risk). However, for turbine installation, the weather is more unpredictable leading to high risk. The installation time can take around 7-8 months. It should be noted that the total time (including delays) estimated is only corresponding to the steps considered as part of the installation.

In general, the time and risk involved in installation of turbine is substantial. Innovation in assembly and installation is really important to reduce the time of installation of wind farms. The next three chapters introduces some innovative concepts. These concepts demonstrate the ways in which overall installation time can be reduced. It should be noted that these concepts and innovations are ideas which may not be completely developed, but are in advanced phases of their research. Some projects have been developed with these concepts introduced in the next chapters.

4

Innovation: Offshore Assembly Harbour

The turbine in the reference wind farm is assembled offshore, installing component by component from the installation vessel. The assembly time increases the installation time and therefore also the delays. If the turbine assembly is done elsewhere, in an onshore or offshore harbour, and the complete turbine is picked up from this harbour and installed in a single lift, this would potentially reduce the installation time and costs.

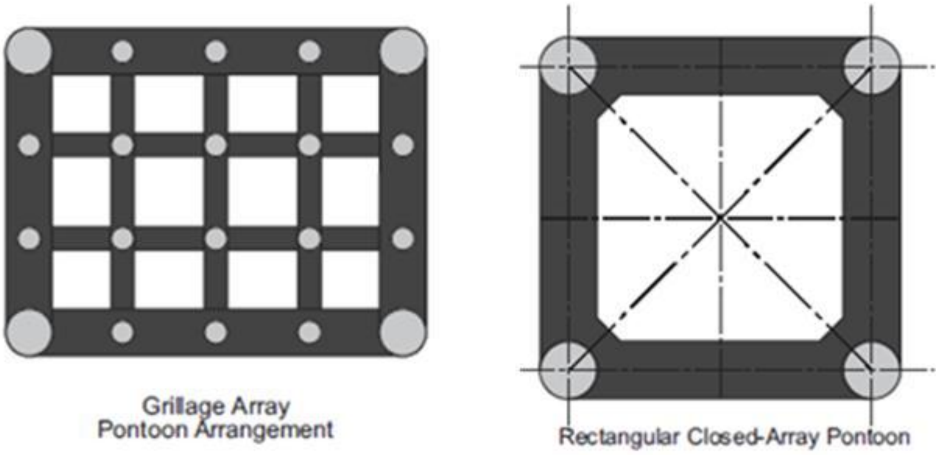
4.1 Innovation Concept

In the reference wind farm discussed above, the installation process is carried out from the onshore harbour. This is a standard approach followed by every wind farm developer and contractor. An illustration of the harbour is shown in **Figure 23**.

Figure 23: Example of an onshore harbour with different components placed for installation [13]

This innovation introduces the concept of building an offshore harbour similar to as shown above, which could be a floating pontoon structure. The design of the structure could be as shown in **Figure 24**. The turbine components are transported to this offshore assembly harbour by feeder vessels. The offshore harbour (floating or island) stores these components and turbines are assembled one by one. Parallel to the assembly works, the installation vessel picks up complete turbines and installs them in sets of two. It should be noted that the foundations are installed similar as done in the reference wind farm.

Figure 24: Different structure of an offshore harbour [14]



Further, together with the innovation of the offshore harbour, a different approach of installing turbines is proposed. Instead of assembling the turbine on the turbine location, the turbines are assembled at the offshore harbour. These turbine structures can then be transported to the exact site location and placed on the transition piece in a single lift application. One such vessel, possessing the capabilities of carrying two turbines at a time and installing them one by one, is shown in **Figure 25**.

Figure 25: Huisman Shuttle vessel with a capability of single lift installation of turbines [15]

4.2 Installation Model

The installation model for the offshore harbour is developed in ECN Install. Individual models for the foundations and turbines are prepared. Moreover, for the turbine installation, single-lift installation with a vessel similar to Huisman Shuttle is employed. The sub-sections below only discuss the turbine planning steps and the model assumptions corresponding to it.

4.2.1 Planning

The steps for installing the turbines are the result of both strategies- offshore harbour assembly and single life installation. **Table 6** summarizes the steps of installing the turbines. Note that the starting date of installation is 5th August.

Table 6: Installation steps of the turbines. In sets of two turbines are installed from the offshore assembly harbour. The starting date is 5 August.

Step Number	Step Description	Duration [hrs]	Wind Speed limit [m/s]	Wave Height limit [m]
2.1	Travel to offshore harbour	auto (3.3)	17	4
2.2	Loading 2 completely assembled turbines to vessel	2	14	2.5
2.3	Travelling to the wind farm	1	17	4
2.4	Single lift installation of turbine (with floating vessel)	5	14	2
2.5	Travel to next turbine site	1	17	4
	go back to step 2.4 and repeat 1 time			
2.6	Travel back to offshore harbour	1	17	4
	go back to step 2.2 and repeat 37 times			
2.7	Travel back to harbour	auto (3.3)	17	4

4.2.2 Model Assumptions

- Travelling of single lift installation vessel to offshore harbour is only considered once. For the consecutive delivery, a feeder is employed. It is always assumed that there is zero delay time in delivering the parts at the offshore harbour.
- There is zero assembly delay time. The turbine assembly is always up to date and the vessel is ready for installation.
- The weather limits and step duration are considered in line with the specifications of the Huisman vessel. These values are only indicative of reality. However, sensitivity analyses are done for different step durations and weather limits.

4.3 Installation Model Results

Table 7 presents the average duration and delays for installing 75 turbines and foundations. For the baseline, turbine installation is done 85 km from shore with a single lift operation. The installation step of single lift installation takes 5 hours.

Table 7: Results are in days average per turbine

	Start Date	End Date	Duration Total [days]	Duration work [days]	Delay total [days]	Delay weather [days]	Delay shift [days]	Delay harbour [days]
Turbines	5-Aug	4-Sep	0.78 ±0.14	0.69	0.09 ±0.14	0.069 ±0.12	0.024 ±0.02	0.00

The table above shows the difference it can make when performing turbine installation with an offshore harbour placed and the turbines being completely assembled and placed in a single lift. For installing 75 turbines, it shall take 58 days on average. Noticeably, the risk or the standard deviation has reduced significantly with the change in strategy. It should be noted that foundation installation can also be done with an offshore harbour in place. The only difference is that the foundations have to be piled according to the conventional way and the Huisman vessel cannot be applied in this case.

4.3.1 Turbines

The installation of turbines includes tower, nacelle and blades. In this case of installation, the complete turbine assembly was lifted and placed on the transition piece in a single lift. This definitely resulted in a significant reduction in total actual duration of the work. On average, it takes just 75% of a day to compete a turbine installation. The results for 75 turbines, individual step and Gantt chart for some starting steps are illustrated in **Figure 26**, **Figure 27** and **Figure 28** respectively.

Figure 26: Duration and delays of 75 turbines over time

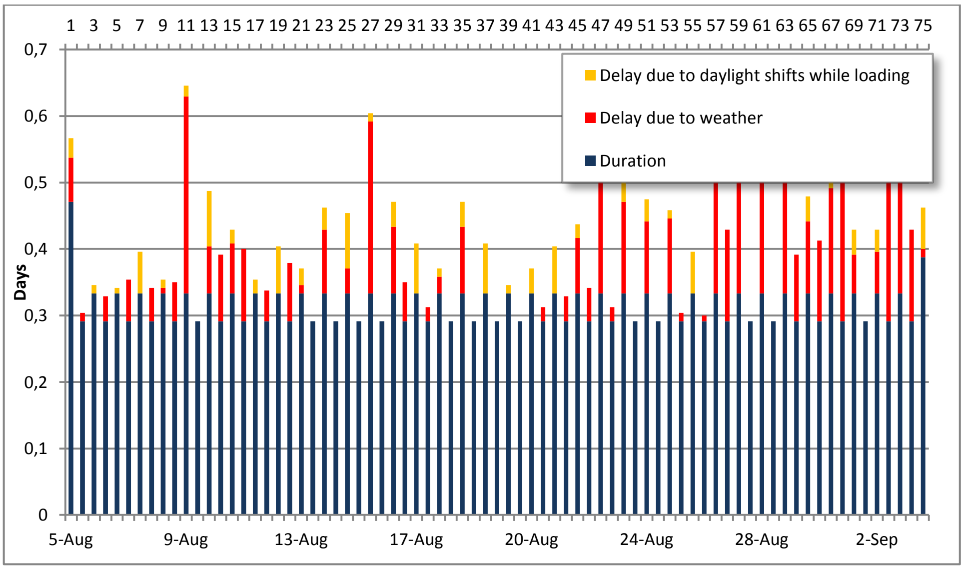


Figure 27: Average duration and delay per step

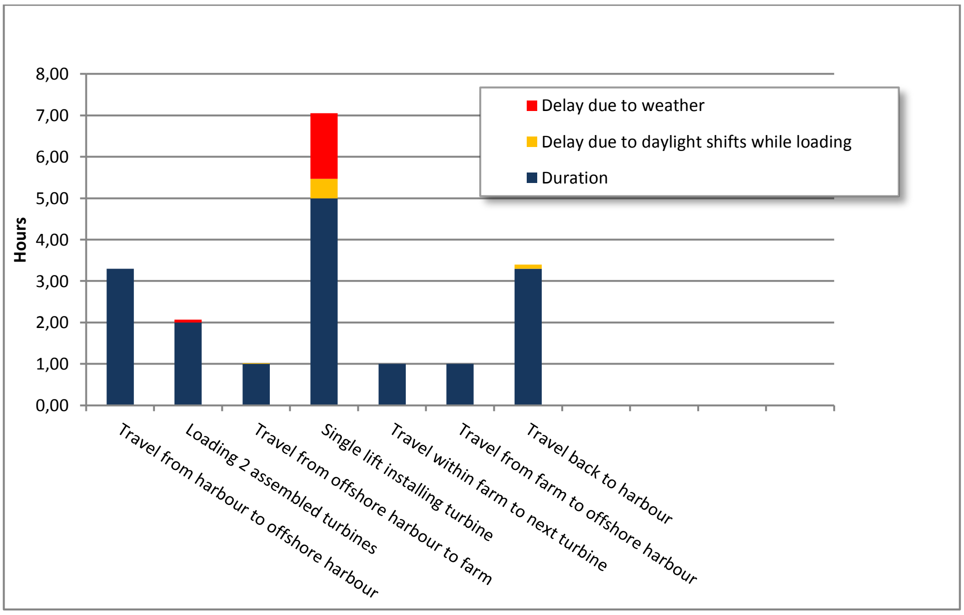
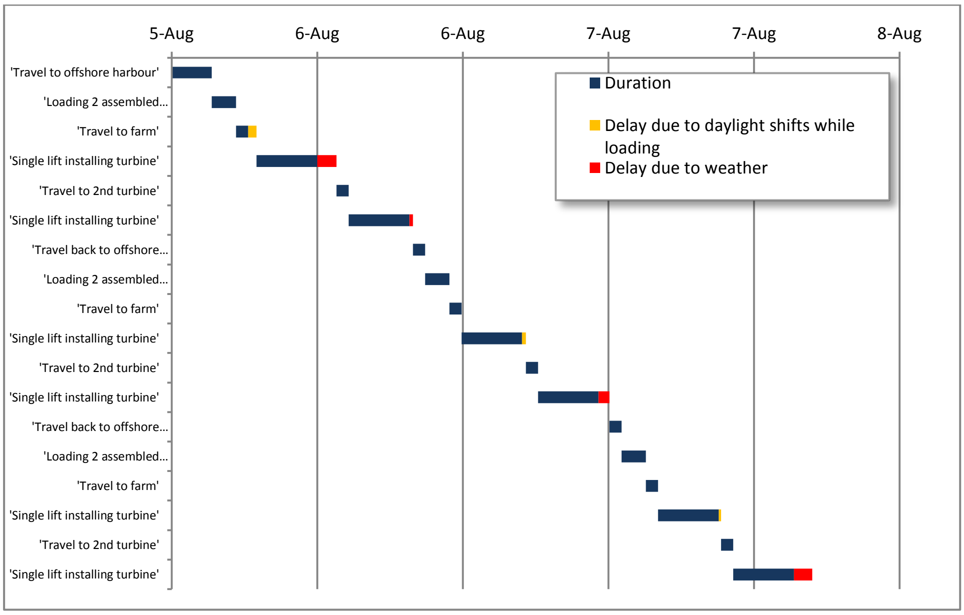


Figure 27 evidently shows the weather delay is caused only in the case of the actual single lift installation. For the rest of the steps, the weather restrictions are quite high and shall result in negligible weather delay. Also, there is hardly any shift delay as the crew is working following a 24*7 strategy. Gantt Chart in **Figure 28** shows the repeated weather delays accounted three times for the installation steps shown.

Figure 28: Planning of first turbines including duration and delays



4.3.2 Sensitivity Studies

The following inputs are varied to study the sensitivity of the results.

- Distance from onshore harbour to offshore harbour is varied in steps of 35, 85 and 150 km.
- The wave height limit of the single lift installation is varied in steps of 1.5, 2.0, 2.5, 3.0 and 3.5 m.
- The duration of the single lift installation is varied in steps of 3, 5, 7 and 9 hours.

The results for the analysis is tabulated below in **Table 8**.

Table 8: Results for offshore harbour innovation (days average per turbine)

Reference wind farm: Turbines

Distance [km]	Start Date	End Date	Duration Total [days]	Duration work [days]	Delay total [days]	Delay weather [days]	Delay shift [days]
35	5-Aug	7-Mar (next year)	3.90	1.77	2.13	1.421	0.710
85	5-Aug	8-Mar (next year)	3.91	1.95	1.96	1.439	0.524
150	5-Aug	14-Mar (next year)	4.25	2.19	2.06	1.491	0.571
Innovation Turbines: Single lift with Hs=2 m T=5 hrs							
35	5-Aug	4-Sep	0.62	0.53	0.09	0.069	0.025

85	5-Aug	4-Sep	0.78	0.69	0.09	0.069	0.024
150	5-Aug	5-Sep	0.99	0.90	0.09	0.069	0.087

Innovation Turbines: Single lift with D=85km and T=5 hrs

Wave Height limit [m]	Start Date	End Date	Duration Total [days]	Duration work [days]	Delay total [days]	Delay weather [days]	Delay shift [days]
1.5	5-Aug	11-Sep	0.87	0.69	0.18	0.162	0.032
2	5-Aug	4-Sep	0.78	0.69	0.09	0.069	0.024
2.5	5-Aug	1-Sep	0.75	0.69	0.05	0.033	0.029
3	5-Aug	1-Sep	0.74	0.69	0.05	0.031	0.033
3.5	5-Aug	1-Sep	0.74	0.69	0.05	0.032	0.029

Innovation Turbines: Single lift with D=85 km Hs=2 m

Duration [hrs]	Start Date	End Date	Duration Total [days]	Duration work [days]	Delay total [days]	Delay weather [days]	Delay shift [days]
3	5-Aug	26-Aug	0.67	0.61	0.06	0.038	0.038
5	5-Aug	4-Sep	0.78	0.69	0.09	0.069	0.024
7	5-Aug	21-Sep	1.01	0.78	0.23	0.137	0.096
9	5-Aug	23-Sep	1.03	0.86	0.17	0.141	0.140

The results for each of the sensitivity analysis mentioned above are discussed as follows:

- With an increase in distance, the average duration of travelling from shore to harbour will increase (**Figure 29**). This shall result in a higher of step duration and have a marginal effect on the total installation time. It is important to note is that the weather data (Gemini) used for all three locations is the same, i.e. the weather data is not entirely representative of the distance from shore. Hence, there is little difference in the weather delay at different distances. However, the application of such an offshore harbour would be more advantageous for higher distances.
- The wave height restrictions assumed in the baseline innovation is 2m. However, the vessel manufacturer proposes that the installation can be carried out even in 3.5 m wave height. From **Figure 30**, it is clear that even with 2m

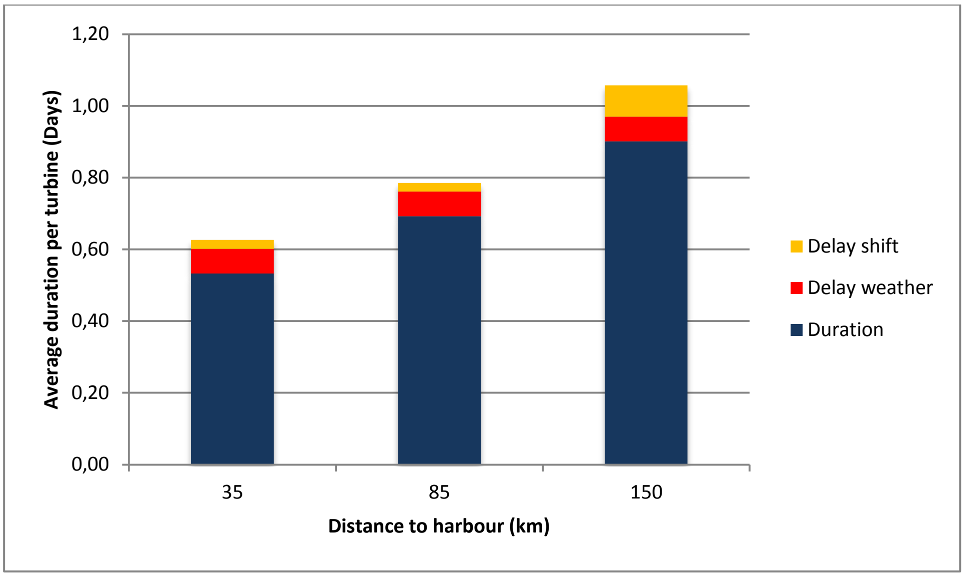
operability of the vessel for single-lift operation, the turbine installation can be done at a significant pace[2] with minimum weather delay.

- In the baseline innovation scenario, 5 hours is considered for the single lift turbine installation. However, the vessel operator again estimates the value to be less (3 hours). The sensitivity analysis is done with the variation from 3 hours (minimum) to 9 hours (maximum). The difference in installation time of 75 turbines between the minimum (3 hours) and maximum (9 hours) is 27 days **Figure 31**. Most of the actual difference is because of the increase in the step size of installation. The weather delay is not much between the two extremes (3 hours and 9 hours).

From the sensitivity analysis, it is clear that with an offshore harbour in combination with an innovative single lift installation vessel, the installation time can be significantly reduced. The graphs for each of the sensitivity analysis are placed in **Figure 29**, **Figure 30** and **Figure 31**.

Direct comparison between the baseline reference wind farm and the innovation is done in the next section .

Figure 29: Innovation Turbines: Single lift with Hs=2 m T=5 hrs. Distance to the onshore harbour is varied by 35, 85 and 150 km.



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[2] There is only 3 days of difference between the completion time of installing 75 turbines at Gemini location with the vessel being able to operate at 2m or 3.5 m.

Figure 30: Innovation Turbines: Single lift with D=85km and T=5 hrs. The wave height limit of the single lift installation is varied by 1.5, 2.0, 2.5, 3.0 and 3.5 m

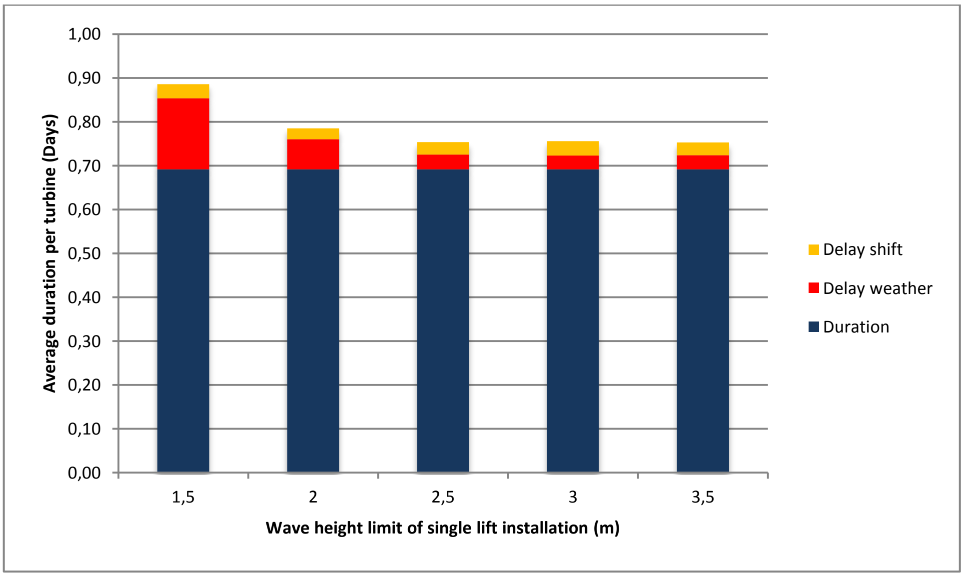
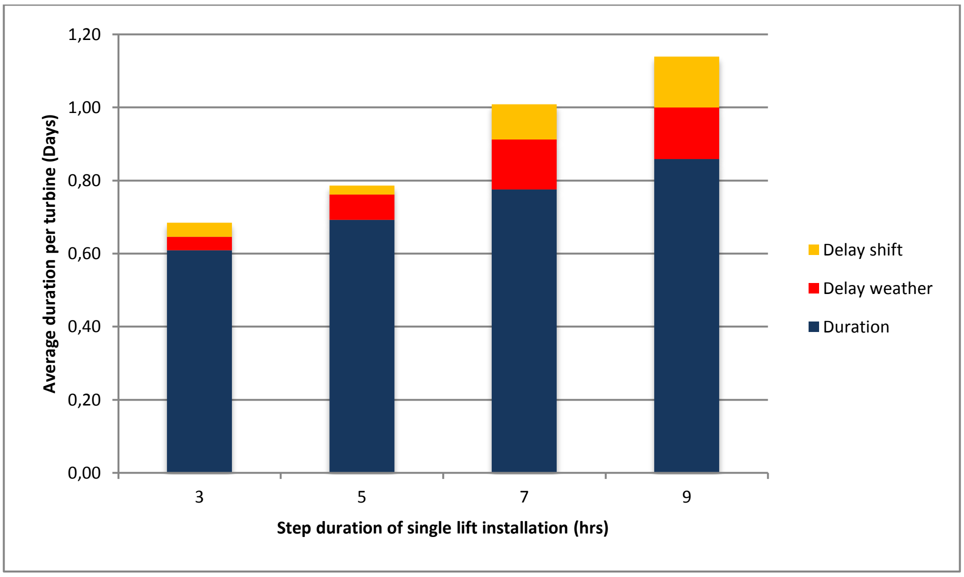


Figure 31: Innovation Turbines: Single lift with D=85 km Hs=2 m. The duration of the single lift installation is varied by 3, 5, 7 and 9 hours



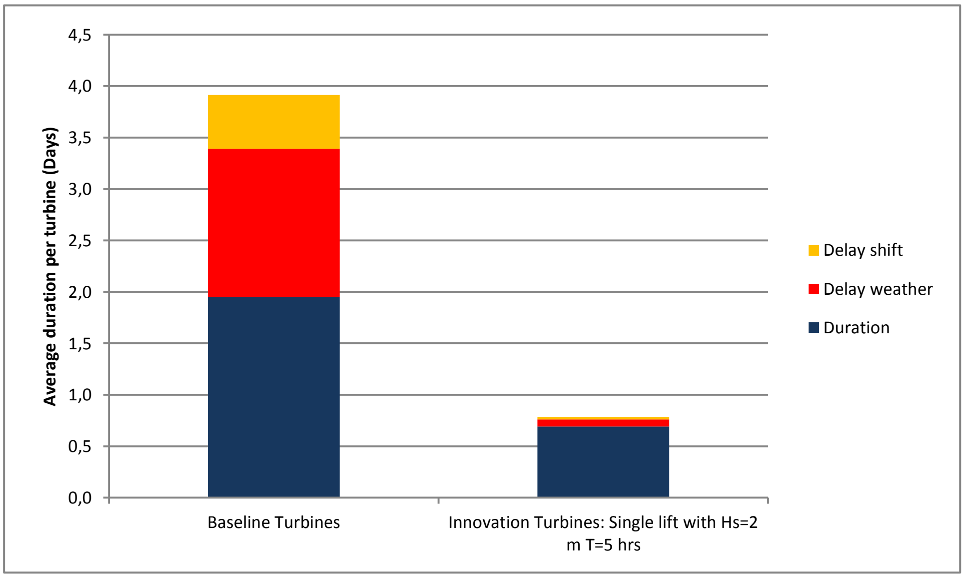
4.4 Discussion

The concept of an offshore harbour is unique and shall require some technical expertise and financial back up before such structures can be developed offshore for wind energy purpose. Additionally, the use of innovative single lift installation vessels like the Huisman Shuttle will make the offshore wind industry reach greater heights. On one hand, the use of offshore structures reduce the travelling time for the vessel, the

Huisman vessel will significantly reduce the actual installation time. Moreover, the latter shall also provide an opportunity to work under harsh weather conditions.

A general comparison between the baseline reference wind turbine installation and the installation with offshore harbour together with Huisman vessel is made in **Figure 32**. One can clearly see more than 3 days (per turbine installation) of difference between the two methods. With such a significant difference, innovative concepts as introduced above will reduce the overall risks of the project . Additionally, it should be noted that such an offshore harbour is useful even in the operational phase of the wind farm.

Figure 32: Average duration and delay per turbine of installing turbines.



5

Innovation: BreakWaters

The installation time observed in the case of the reference wind farm was quite high. Also, there was high risk or standard deviation seen in the implementation of the installation. The high risk is mainly due to the weather conditions prevalent near the wind farm. With our reference wind farm situation 85 km from the shore, the wind and wave limits affect the installation process. This chapter introduces the concept of installing breakwaters, structures, which can help limit the waves in and around the wind farm. This shall help carry out the installation work under much harsher conditions, which would potentially reduce the installation time and costs.

5.1 Innovation Concept

Conventionally, a breakwater is a structure constructed for the purpose of forming an artificial harbour so as to attenuate waves to an acceptable level or eliminate their effects altogether. It creates a sheltered region in order to prevent damage to shorelines, harbours, and other natural or man-made structures [16] [23]. Some of the examples of installation of breakwaters are the Elmer Beach in UK [18], submerged breakwaters used for coastal protection in china, detached breakwaters in ports, etc.

Although there are several types of breakwater structures, one can mainly categorize it in three main types [23]:

- *Conventional (mound) type of breakwaters*
  Mound types of breakwaters are actually no more than large heaps of loose elements, such as gravel and quarry stone or concrete blocks.

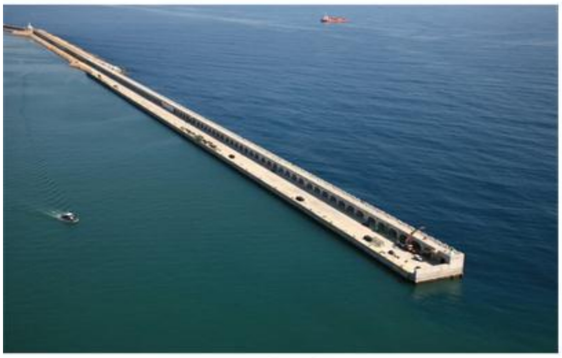
- *Monolithic type of breakwaters*
  Monolithic types of breakwaters have a cross section designed in such a way that the structure acts as one solid block. In practice, one may think of a caisson, a block wall, or a masonry structure. Generally this kind of structure is used when space is scarce and local water depths are relatively large.

- *Composite type of breakwaters*
  A composite type of breakwater is a combination of the conventional and monolithic type of breakwater. When water depths get larger, this kind of structure is often preferred from an economical point of view.

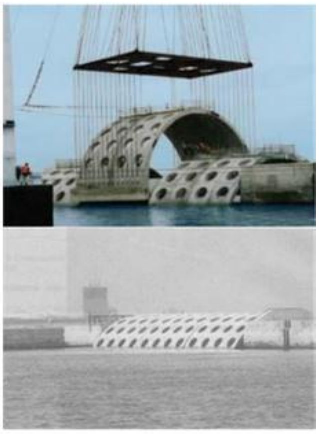
The above mentioned type of breakwaters are illustrated in **Figure 33**.

Figure 33: Standard types of breakwater structures

Conventional breakwaters



Composite breakwaters



Monolithic breakwaters

Besides the above standard breakwaters, floating breakwaters have always generated interest. A lot of theoretical and practical research has been done in this field. Floating breakwaters represent an alternative solution to protect an area from wave attack, compared to conventional fixed breakwaters [21]. The advantage of using a floating breakwaters are deep water applications, minimum visual impact, minimum interference with water quality and ease of rearrangement of breakwater layout.

Four fundamental factors which greatly influence the design of floating breakwaters are the following: (1) buoyancy and floating stability, (2) wave transmission, (3) mooring forces, and (4) breakwater and structural integrity [22].

Floating breakwaters are commonly divided into four general categories [21]:

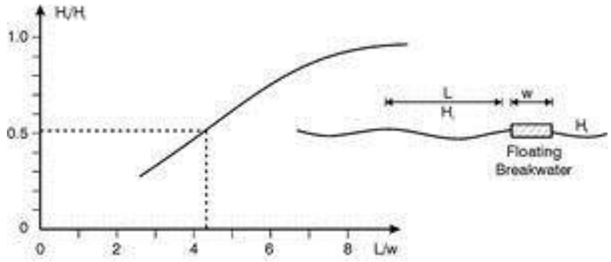
1. Box
2. Pontoon
3. Mat
4. Tethered float

One such example of a floating breakwater is shown in **Figure 34**.

Figure 34: Example of Box floating breakwater (Fezzano,SP-Italy; courtesy of INGEMAR srl)

Floating breakwaters work by dissipating and reflecting part of the wave energy. No surplus water is brought into the sheltered area in this situation. They are especially suited for areas where the tidal range is high, as they follow the water-level. The rough relation between the transmission coefficient H_t/H_i and the ratio *L/w* between the wavelength *L* and the width of the floating structure *w* can be seen in **Figure 35** .

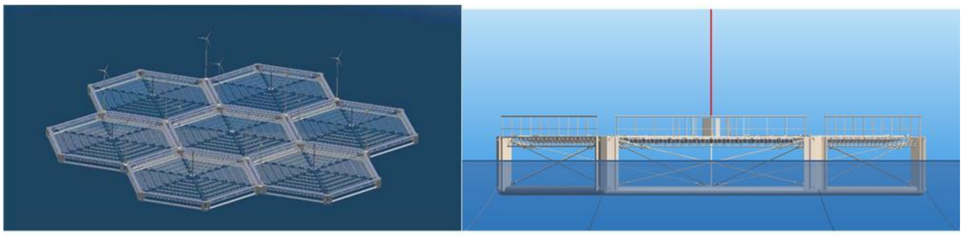
Figure 35: Relation developed for installing floating breakwaters [21]



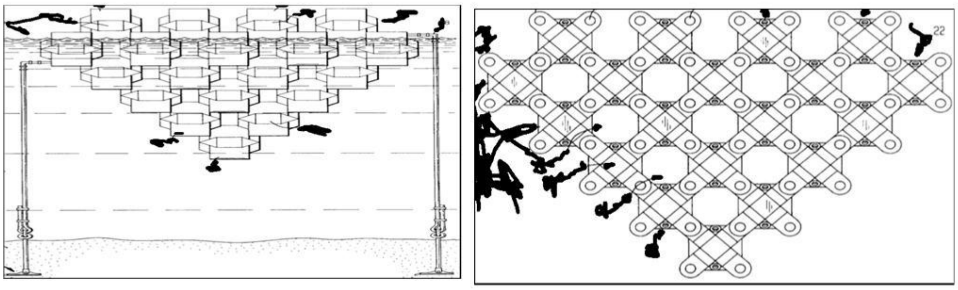
The wave transmission coefficient H_t/H_i, i.e. the ratio between the height of the transmitted wave and the height of the incoming wave, depends very much on the ratio L/w between the wavelength L and the width of the floating structure w. As a rule-of-thumb the transmission varies between $H_t/H_i = 0.3$ for L/w = 3 and $H_t/H_i = 0.9 – 1.0$ for L/w = 8.

Some of the patented floating breakwater structures are shown in **Figure 36**.

Figure 36: Innovative concepts of Floating breakwater structures [22]



Hexifloat
Top View (left) & Side View(right)



Modules Breakwater
Top View (left) & Side View(right)

With respect to the above figure, the Hexifloat is a huge floating system which integrates four different types of energy generators: wind, wave, tidal and solar. Originally designed as an offshore energy production platform, its shape, size and modularity make it a very attractive concept for seasteading. By redesigning the underwater part of the platform and integrating a controllable ballasting system, the whole apparatus may also work as an efficient floating breakwater in addition to its exceptional energy generator. In addition, the combination of multiple Hexifloats would produce a huge structure (approximately 60 meters wide) with an improved wave damping capacity.

Secondly, the modules breakwaters consists of two floating walls/pontoons connected by a device absorbing energy from the displacement of the two structures relative to one another when hit by waves.

One of the commercial example of a semi-floating breakwater, designed to defend a large harbour, is the pier extension of Port Hercule in Monaco. In 2002 ‘La digue semi-flottante’ was installed as a pier extension in Monaco, in approximately 55 m of deep water. An enormous caisson, 352 meters long, with a main body 28 m wide, a total depth of 19 m and a draft of 16 m was installed. It is multifunctional and, as a permanent structure, it has to withstand design storm conditions during its expected lifetime of 100 years. Although the water depth was quite high, the wave conditions were quite moderate.

Figure 37: Pier extension at Port Hercule, Monaco [23]

In this report, it is assumed that the thickness of the floating structure shall affect the wave attenuation. Later in the model analysis, these percentages of wave attenuation are discussed.

5.2 Installation Model

The installation model for the water breakers is similar to the reference wind farm. Only the weather time series at the site location (offshore) are altered and specifically the wave height limit is scaled down to demonstrate the wave attenuation because of breakwaters. The sub-sections below list the planning steps followed and the model assumptions for this innovation.

5.2.1 Planning

The use of breakwaters affects the wave height level around the wind farm area. There is no difference in the procedure of installation which is similar to reference wind farm. Only the weather conditions (specifically wave height) are changed to a certain level. Hence, **Table 3** and **Table 4** (Chapter 3) are used as steps for the installation of wind farm.

5.2.2 Model Assumptions

Following are some of the assumptions considered specifically for this innovation:

- The wave height at the offshore location (from the weather data) is scaled evenly for the entire length of the weather data. Note that the weather conditions at the harbour do not change.
- The starting date of the foundation installation is same as the reference wind farm. However, the turbine installation starts at a different date. The consideration is that the turbine installation starts when 7 foundations are completely installed. The same assumption led to a different starting date for the reference wind farm.
- Three different percentages of wave attenuation have been considered. They are 40%, 60% and 80% of wave attenuation. In physical sense of breakwaters, the percentage depends on the number of rows or the thickness and the length of the breakwater. I.e. the more thickness and length of breakwater, the higher the wave attenuation. 60 % wave attenuation has been considered as an innovation baseline and the corresponding results are described in the section below.

5.3 Installation Model Results

The table below presents the duration and delays of installing the 75 turbines and foundations with 60% wave reduction for the near Gemini location. Note the starting dates for foundations and turbines.

Table 9: Results are in days average per turbine

	Start Date	End Date	Duration Total [days]	Duration work [days]	Delay total [days]	Delay weather [days]	Delay shift [days]	Delay harbour [days]
Foundations	29-Mar	1-Aug	1.67 ±0.04	1.45	0.22 ±0.04	0.008 ±0.02	0.211 ±0.02	0.00
Turbines	22-Apr	10-Aug	1.48 ±0.11	1.26	0.22 ±0.11	0.02 ±0.04	0.20 ±0.07	0.00

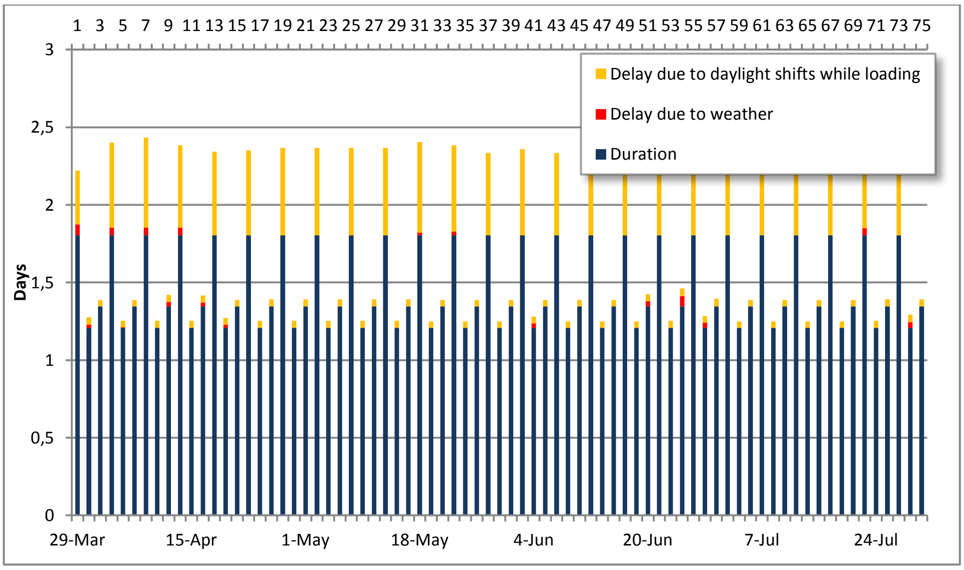
The results above highlight that for foundation installation, it shall take around 125 days and for turbine installation, around 111 days. These values are with respect to the average duration (in days) per turbine. The most striking feature in the above innovation is the reduction of standard deviation, which is mainly due to the reduction in the wave height limits around the wind farm area. The low standard deviation leads to the overall decline in the risk of the project. Moreover, the installation above was performed in the summer period and lead to even lower average duration of installation.

The next sub-sections summarize the graphs individually for foundations and turbines respectively.

5.3.1 Foundations

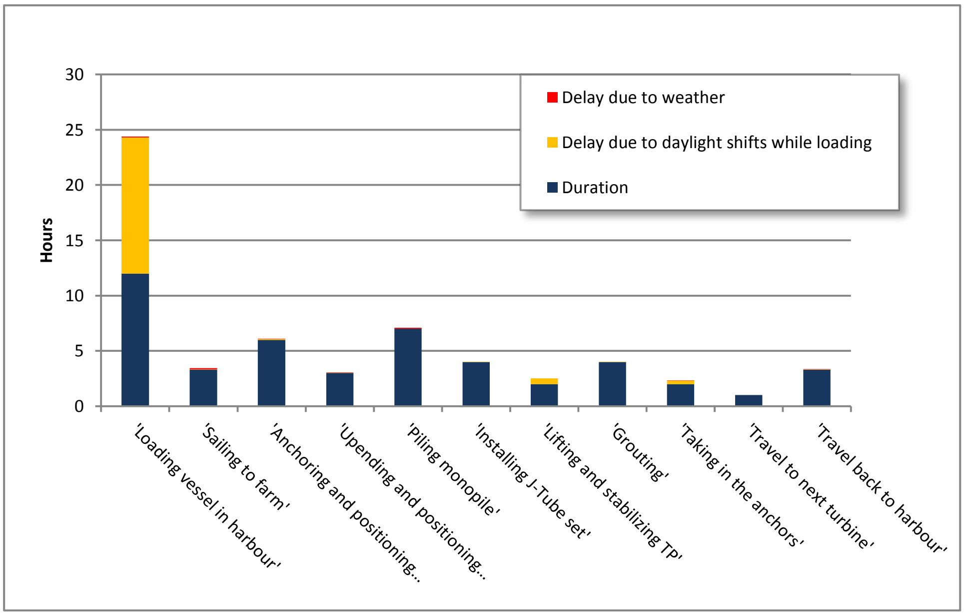
Foundation installation comprises of the installation of monopile, transition piece and J-tube. The installation commences on 29th March (as was done in the case of reference wind farm). The results below (in **Figure 38**) show the average duration and delay per turbine for installing 75 foundations. 60% attenuation is considered with the use of breakwaters.

Figure 38: Average duration and delay per turbine for installing foundations.



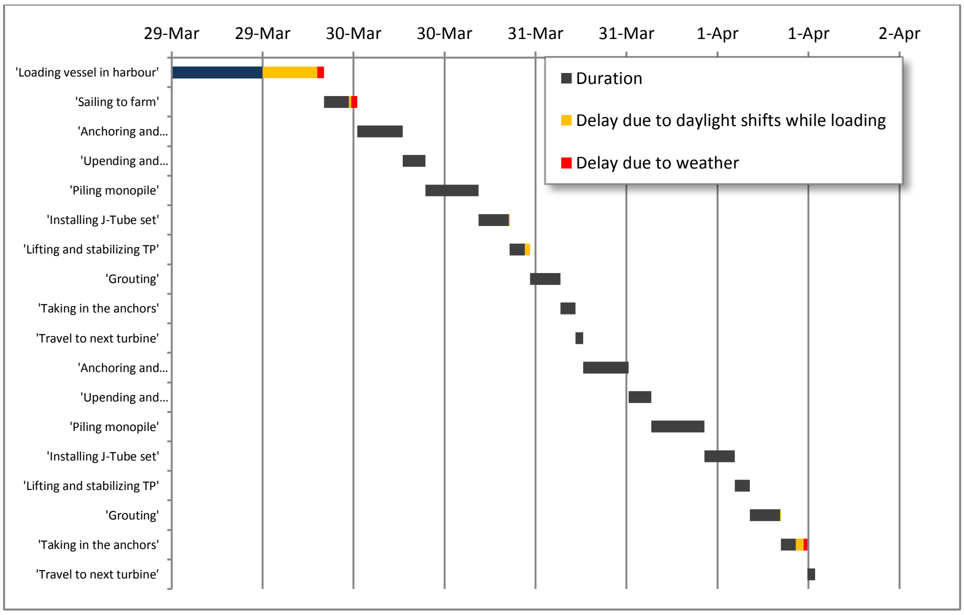
Since the weather is not a major limiting factor now, there is a repeated trend in the installation of each foundation. After every three foundations, there is a shift delay due to the loading being performed only in the day (regular shift). The other steps are performed with minimum weather and shift delay. This can be clearly observed in **Figure 39**.

Figure 39: Average duration and delay per step



Further, **Figure 40** illustrates a Gantt chart for the installation 2 foundations. The chart reconfirms the reduction in the weather delay because of application of breakwaters.

Figure 40: Average duration and delay per turbine for installing foundations.



5.3.2 Turbines

The installation of turbines include tower, nacelle and blades. A similar installation strategy as implemented in reference wind farm is followed for the installation. The trend is similar to the foundations, where the weather delay has been limited to lower values. Moreover, only the shift delay is predominant during the loading of the 6 turbines for each round of installation. **Figure 41**, **Figure 42** and **Figure 43** show the average duration and delay of 75 turbines, duration and delay per step and Gantt chart for installing the initial turbines respectively.

Figure 41: Duration and delays of 75 turbines over time

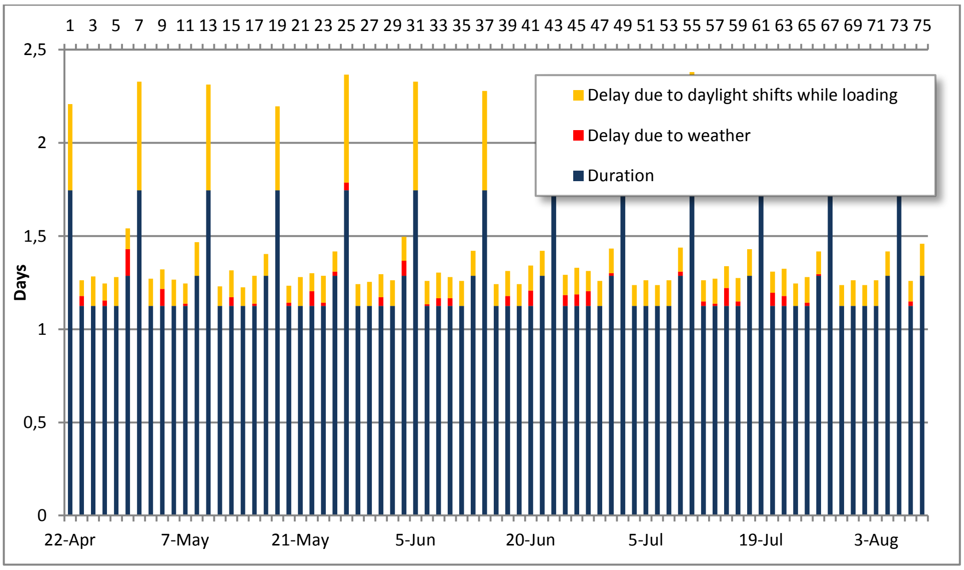


Figure 42: Average duration and delay per step

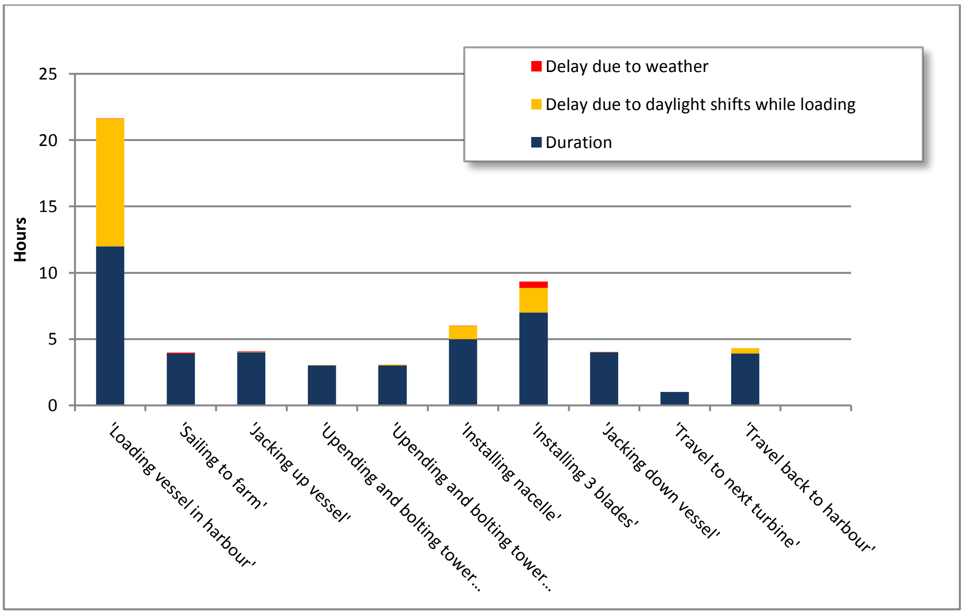
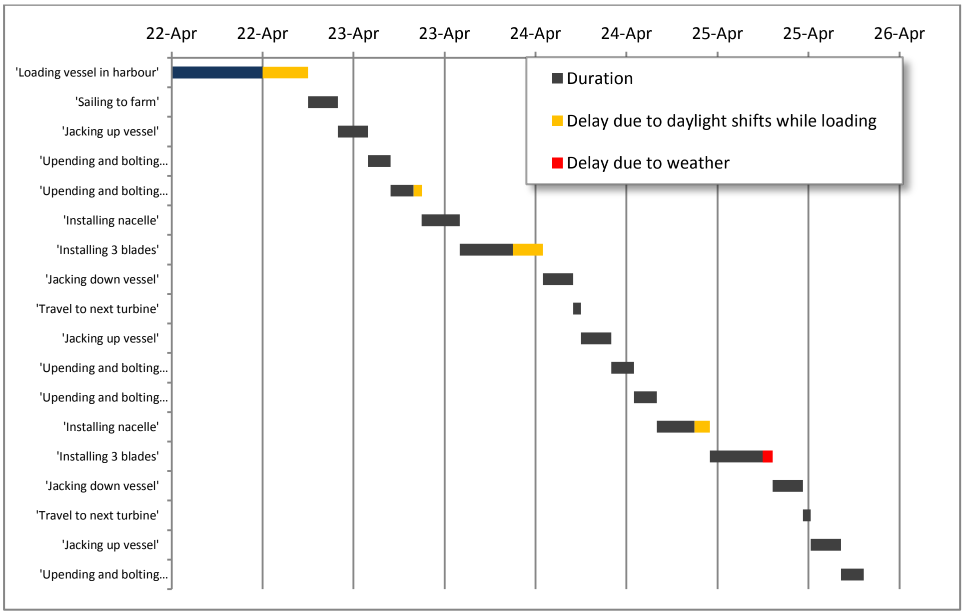


Figure 43: Planning of first turbines including duration and delays



5.3.3 Sensitivity Studies

The following inputs are varied to study the sensitivity of the results:

- Difference in the wave percentage reduction for the baseline location (foundations and turbines). The percentage has been varied in steps of 0%, 40%, 60% and 80%.
- Different locations for installing wind farm. Three locations have been chosen in all. Besides Gemini, YM6 and GodeWindII offshore wind sites have been selected for sensitivity analysis.
- Different starting dates for installation. Three dates (seasons) have been selected for both foundation installation. The starting dates chosen are 29th March, 29th September and 29th January (the next year). Also, the percentage wave reduction are varied for all the three dates.

The results for sensitivity analysis are tabulated below in **Table 10**.

Table 10: Results for breakwater innovation(days average per turbine)

Innovation Foundations: Gemini location with different % wave reduction

% wave reduction	Start Date	End Date	Duration Total [days]	Duration work [days]	Delay total [days]	Delay weather [days]	Delay shift [days]
40%	29-Mar	3-Aug	1.71	1.45	0.25	0.048	0.206
60%	29-Mar	1-Aug	1.67	1.45	0.22	0.008	0.211
80%	29-Mar	1-Aug	1.67	1.45	0.22	0.004	0.215

Innovation Turbines: Gemini location with different % wave reduction							
40%	23-Apr	15-Aug	1.52	1.26	0.26	0.065	0.195
60%	22-Apr	10-Aug	1.48	1.26	0.22	0.023	0.196
80%	22-Apr	10-Aug	1.48	1.26	0.22	0.021	0.196
Innovation Foundations: Gemini location with different starting date							
0%	29-Jan-	17-Jul	2.26	1.45	0.81	0.625	0.184
60%	29-Jan	6-Jun	1.71	1.45	0.26	0.046	0.211
0%	29-Mar	27-Aug	2.02	1.45	0.57	0.357	0.168
60%	29-Mar	1-Aug	1.67	1.45	0.22	0.008	0.211
0%	29-Sep	2-May (next year)	2.88	1.45	1.43	1.246	0.181
60%	29-Sep	7-Feb (next year)	1.76	1.45	0.31	0.101	0.205
Innovation Foundations: YM6 location with different starting dates & % wave reduction							
0%	29-Mar	6-Aug	1.74	1.39	0.34	0.15	0.19
40%	29-Mar	27-Jul	1.60	1.39	0.21	0.015	0.193
60%	29-Mar	26-Jul	1.59	1.39	0.19	0.003	0.191
80%	29-Mar	26-Jul	1.59	1.39	0.19	0.003	0.190
0%	29-Sep	19-Mar (next year)	2.29	1.39	0.90	0.718	0.181
60%	29-Sep	28-Jan (next year)	1.62	1.39	0.23	0.033	0.193
0%	29-Jan	20-Jun	1.90	1.39	0.51	0.32	0.19
60%	29-Jan	29-May	1.61	1.39	0.21	0.019	0.194
Innovation Foundations: GodeWindII location with different starting dates & % wave reduction							
0%	29-Mar	16-Aug	1.88	1.40	0.47	0.27	0.20
40%	29-Mar	30-Jul	1.65	1.40	0.24	0.048	0.196

60%	29-Mar	26-Jul	1.59	1.40	0.19	0.005	0.186
80%	29-Mar	26-Jul	1.59	1.40	0.19	0.003	0.186
0%	29-Sep	11-Apr (next year)	2.59	1.40	1.19	0.98	0.21
60%	29-Sep	31-Jan (next year)	1.66	1.40	0.25	0.059	0.194
0%	29-Jan	6-Jul	2.12	1.40	0.72	0.514	0.202
60%	29-Jan	30-May	1.62	1.40	0.22	0.027	0.190
Innovation turbines: YM6 location with different % wave reduction							
0%	24-Apr	23-Aug	1.61	1.23	0.39	0.20	0.19
40%	21-Apr	8-Aug	1.45	1.23	0.23	0.034	0.195
60%	21-Apr	7-Aug	1.45	1.23	0.23	0.029	0.196
80%	20-Apr	4-Aug	1.42	1.23	0.20	0.027	0.199
Innovation turbines: GodeWindII location with different % wave reduction							
0%	26-Apr	11-Sep	1.85	1.23	0.62	0.38	0.24
40%	22-Apr	15-Aug	1.54	1.23	0.31	0.055	0.254
60%	21-Apr	12-Aug	1.51	1.23	0.28	0.023	0.259
80%	21-Apr	12-Aug	1.51	1.23	0.28	0.020	0.260

The results for each of the sensitivity analysis mentioned above are discussed as follows:

- It is observed that there is not much difference with the level of attenuation (only three percentages) for the average installation days for 75 foundations/turbines. The difference between 40% and 60% (or 80%) wave reduction is only 3 days installation time. Hence, even a breakwater with a capacity of 40% wave attenuation will be suitable for installing foundations and turbines.
- For the Gemini location, if the start of the installation of foundations is carried out in different seasons, the benefit of incorporating breakwaters is different. For e.g. in the winter period (end of January) of installation, there will be a difference of 42 days as compared to baseline (reference wind farm with 0% wave reduction). For the other two seasons (early spring and late autumn) considered, 26 days and 84 days can be saved as installation time. However, it should be noted that the difference in installation days (for installing 75

foundations) with 60% wave attenuation is marginal. The maximum difference observed is of 7 days. This clearly highlights that wave breakers are effective in all seasons. This further implies that with breakwaters in place, installation of foundations and turbines can be done in any season and is not entirely dependent on the weather during a particular season.

- Analysis is done for other locations considering the installation pattern as same. For an offshore wind farm around 50 km from shore, GodeWindII, the use of breakwaters generates different results. It is observed that with a 60 % wave attenuation, 25 days (in the season of early spring) are saved while installing the 75 turbines. Further, another wind farm location close to the shore, YM6, is analysed. In this case, the difference with 60% wave reduction as compared to baseline (0% wave reduction) is 12 days only. In the case of Gemini which is the reference wind farm (85 km from shore), the difference was higher than that of GodeWind. Hence, intelligent decisions should be made while installing breakwater structures.

The points discussed above are visualised in the graphs below. **Figure 44**, **Figure 45** illustrate the comparison between the different % wave attenuation for installation of foundations and turbines at Gemini location. Further, **Figure 46** and **Figure 47** give the same comparison for other two offshore wind farm locations- YM6 and GodeWind II. Note the difference in the wave attenuation for different offshore sites.

Figure 44: Innovation Foundations: Gemini location with different % wave reduction. The start date is the same for all the 4 cases.

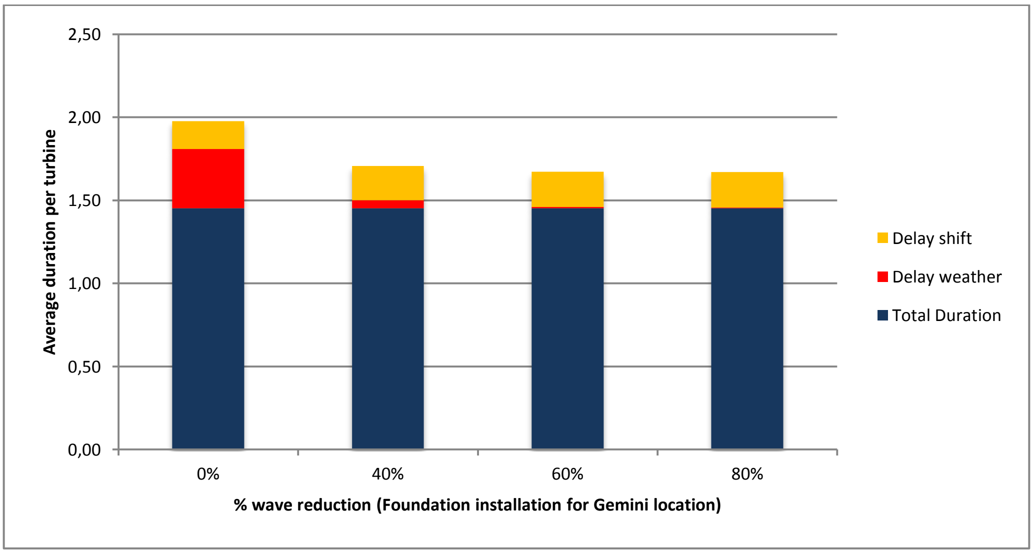


Figure 45: Innovation Turbines: Gemini location with different percentage wave reduction

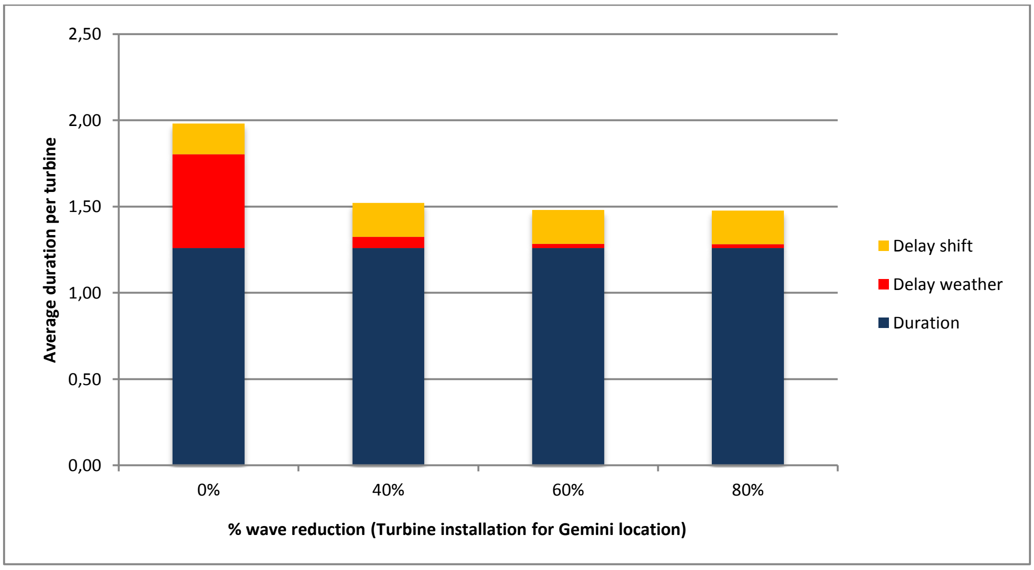


Figure 46: Innovation Turbines: YM6 location with different percentage wave reduction. It should be noted that there is a marginal difference in the start date of installation.

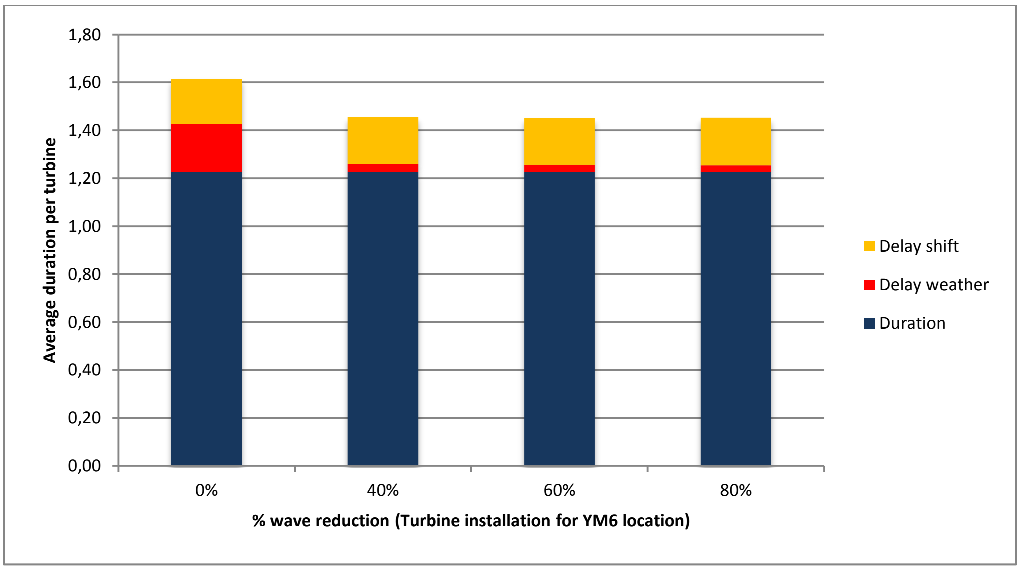
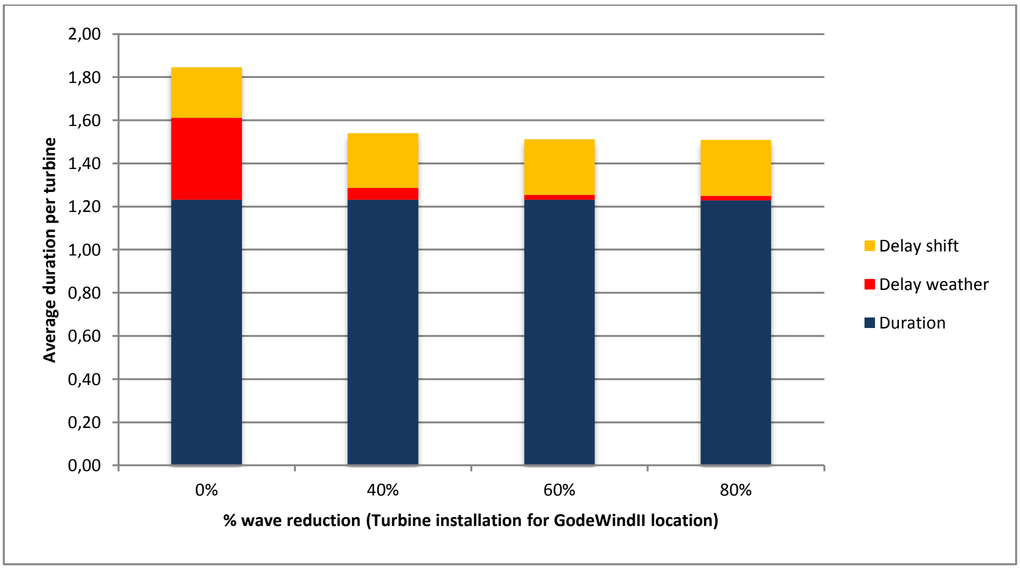


Figure 47: Innovation Turbines: GodeWindII location with different percentage of wave reduction. It should be noted that there is a marginal difference in the start date of installation.



5.4 Discussion

The concept of floating breakwaters is still at a developing stage. However, there are innovative designs being introduced in the market. The implementation of a semi-floating breakwater at Monaco was a revolution in itself. The method of mounting floating breakwaters also highlights that weather conditions are still important while installing and operating the wind farm offshore. Further, with the use of standard vessels and equipment and the rest of procedures being the same, significant days of installation can be saved with even 40% wave attenuators.

In general, the time and risk involved in installation of turbines is reduced. Overall, it's the decision of the operator to understand whether he wants to invest in improvement of turbine assembly (as introduced in the above chapter) or there is a preference for innovating the outer structure. However, it should be noted that in both the cases the structures installed (offshore harbour and breakwaters) are useful even in the operational phase of the wind farm.

6

Innovation: Cluster Assembly

Offshore wind energy has matured significantly in the last decade of development. With far-offshore wind farm locations chosen for installation, the concept of floating offshore wind farms has come to existence. The concept of floating wind turbine systems was for the first time introduced in 1972 by professor Heronemus [12]. However, in 2007, Blue H technologies installed the first test floating wind turbine in Italy. It generated 80 kW and after a year of testing and data collection it was decommissioned. Two years later, in 2009, Statoil installed the first grid connected floating wind turbine, Hywind, in Norway. With a 2.3MW Siemens turbine, it is the first large scale floating wind structure installed in Europe [25]. A brief introduction to floating offshore wind concepts was given in Figure 9 of section 2.3. Further, Chapter 4 introduced the concept of one step installation of turbines. As a part of this innovation, the concept of onshore assembly is introduced for floating offshore turbines. Moreover, complete floating turbines are installed with minimum equipment and vessel.

6.1 Baseline Concept

Out of the total capacity, 65% is installed in the North Sea, 19% in the Atlantic and the remaining 15% in the Baltic Sea. The majority of the installed wind turbines are supported by monopiles (74%), then by gravity based foundations (16%) followed by jackets (5%), tripiles (3%) and tripods (2%). At the same time, over the past five years a new wrinkle has emerged in the form of floating technologies, which could potentially alleviate two of the major challenges associated with offshore wind: logistical and environmental difficulties associated with siting; and the challenge of building a robust ‘permanent’ bottom mounted structure in a hostile marine environment in ever-increasing water depths; all of this in pursuit of the stronger, more stable and less turbulent wind resource offshore [24] .There are 4 floating concepts online currently, two down-scaled (Poseidon 33kW and Sway 150kW) and two full-scale models [25]. One of the scale models is considered as a reference wind farm installed in 2009

(Hywind) and the other concept, i.e. of Wind Float from Principle Power installed in 2012 has been considered as part of innovation. Also, last summer two floating offshore platforms were installed off Goto island near Nagasaki in southern Japan; first one being a 100kW Fuji machine and the other a 2MW Hitachi machine, both atop a spar buoy [24].

The baseline concept uses a Spar Buoy concept, which possess a very large cylindrical buoy stabilizing the wind turbine using ballast. The centre of gravity is much lower in the water than the centre of buoyancy. The Hywind concept consists of this slender, ballast-stabilized cylinder. Hywind, the first large scale floating wind structure installed in Europe was installed in 200 meters of water depth off the south-western coast of Norway (**Figure 48**). A submerged 100-metre ‘spar buoy’, eight meters in diameter, supports a six-meter diameter foundation, held in place by three anchors. Atop of this sits a fairly standard Siemens 2.3MW turbine, set up for offshore operation. Commissioned in September 2009, the project was a complete success, generating power at around a 40% capacity factor, and surviving storms with waves up to 11 meters high [24].

Figure 48: Statoil’s successful Hywind floating offshore platform is towed into position. (courtesy Statoil)

6.1.1 Baseline Planning

Hywind was one of the first major floating projects installed. Hence, precaution was followed throughout the process. More importantly, it should be understood that it was the first large scale floating offshore wind turbine. **Figure 49** gives an overview of the actual installation of one turbine for the Hywind project. However, in line with the other models, the modelling is done as part of the baseline corresponds to the Gemini location. The analysis is performed for the installation of 75 floating turbines at Gemini site using the methodology of Hywind. The planning steps used for the analysis are tabulated in **Table 11**.

Figure 49: Planning steps followed during the installation of Hywind Floating offshore turbine [32]

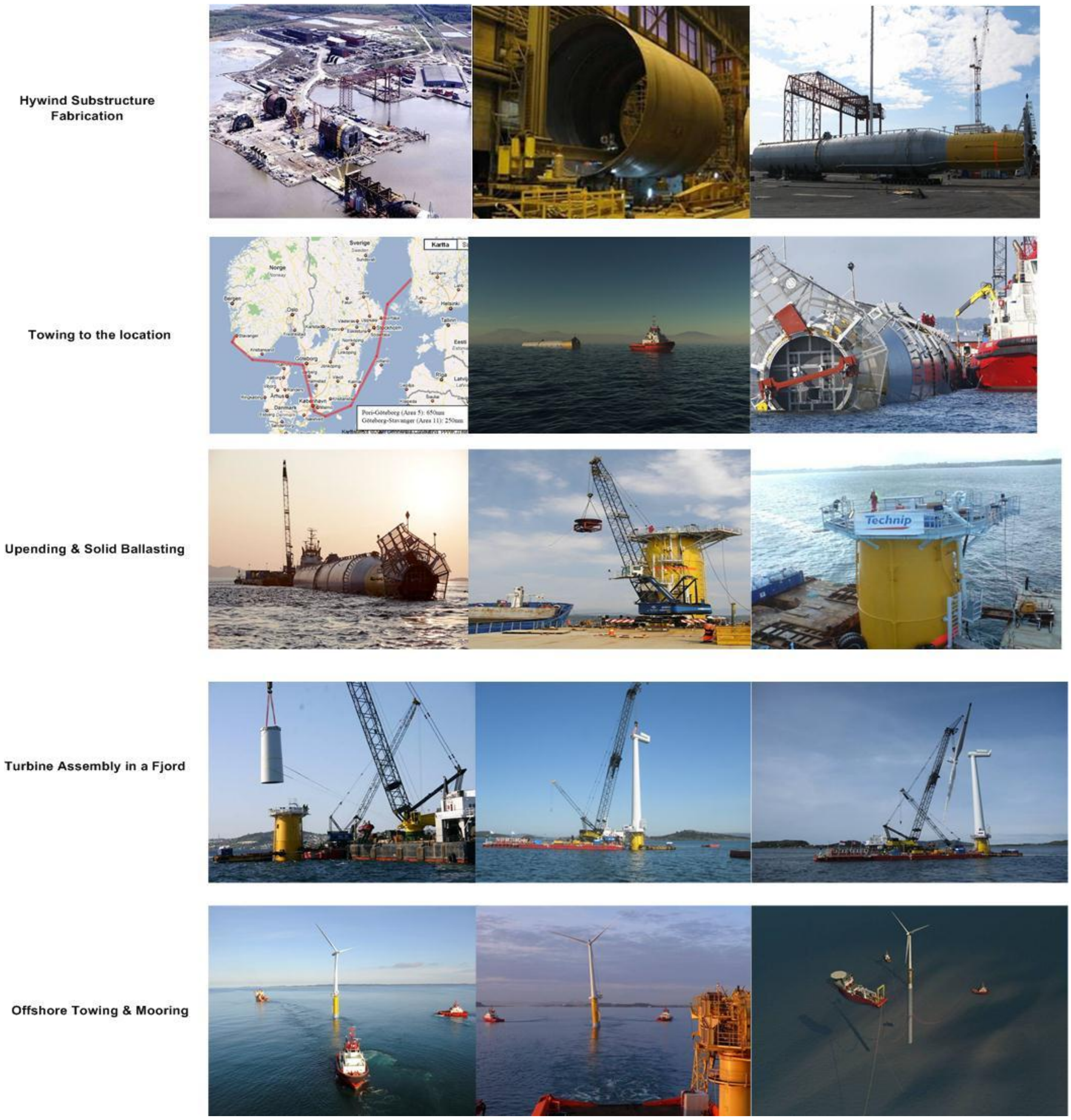


Table 11: Planning steps for the Baseline floating concept of installing 75 turbines

Step Number	Step Description	Duration [hrs]	Wind Speed limit [m/s]	Wave Height limit [m]
1.1	Assembling a single substructure to the tug boat	2	10	4
1.2	Travelling with sub-structure to the inshore location	0,5	10	4
1.3	Substructure mooring and up-ending (2 tug boats + 1 medium sized work barge)	6	10	2
1.4	Solid Ballasting (from the work barge)	3	10	4
1.5	Assembly of middle tower (inshore location)	3	10	4
1.6	Work Barge travels back to onshore harbour	0,5	10	4
1.7	Loading and travelling of Nacelle and Upper tower	2	10	4
1.8	Assembly of Nacelle & Upper Tower (inshore location)	4	10	4
1.9	Work Barge travels back to onshore harbour	0,5	10	4
1.10	Loading and travelling of work barge with rotor	2	10	4
1.11	Assembly of Rotor (inshore location)	4	10	2
1.12	FWT inshore tow to offshore field	4.6 (auto)	14	2
1.13	FWT offshore installation	6	14	2
1.14	Return back to onshore harbour	4.6 (auto)	14	2
	go back to step 1.1 and repeat 75 times			

6.1.2 Baseline Model Assumptions

- Following the conventional approach of Hywind installation, the process is repeated for each of the 75 turbines. However simulations are also performed (as part of a sensitivity analysis) using double the same vessels (4 Tug boats) and 2 medium sized barges. In this case, two turbines can be installed in parallel.
- It is not clear whether the Hywind installation was also performed during night time. For the same, simulation for both the regular shift (only day) and 24*7 (day and night) is performed.
- The assembly of the turbine is partially done in Fjord and remaining in the offshore location.

6.1.3 Baseline Model Results

The baseline model is simulated using two tug-boats and one barge. The procedure followed is already discussed above in the planning table. Considering the installation time to begin on 29th March, the installation of 75 turbines are completed in more or less 200 days (**Figure 50**). It is clear that during a period of mid- April to starting of May, the weather limits the installation of turbines. The latter half of the turbines are installed in quick time with average being 1 days per turbine. Also, the installation time (in hours) per step is visualised in **Figure 51**. Loading operation corresponds to the maximum weather delay. **Figure 52** gives the Gantt chart showing the first 18 steps of installation.

Figure 50: Average duration and delay (per turbine) for installing 75 floating turbines

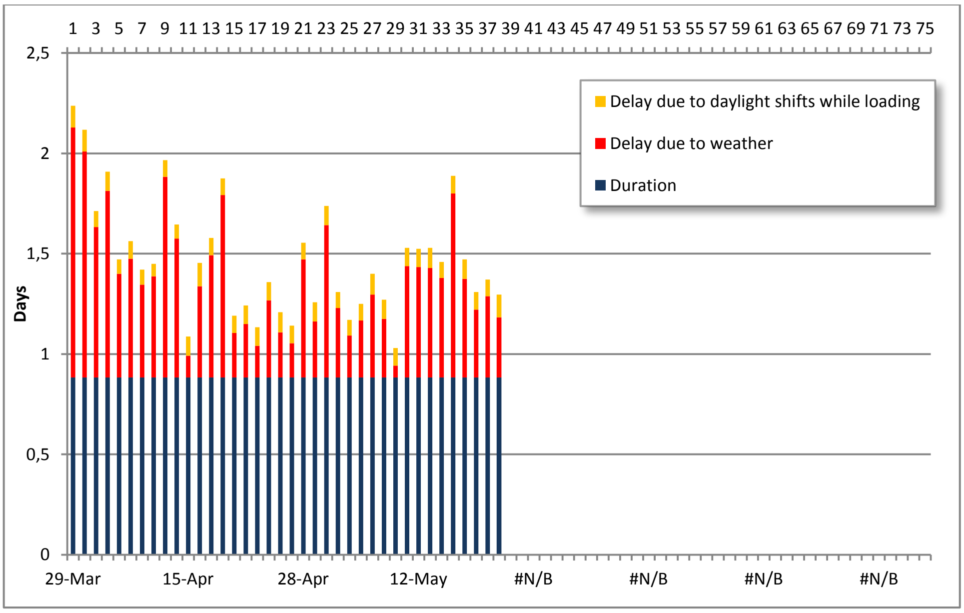


Figure 51: Average duration and delay per step (floating turbines)

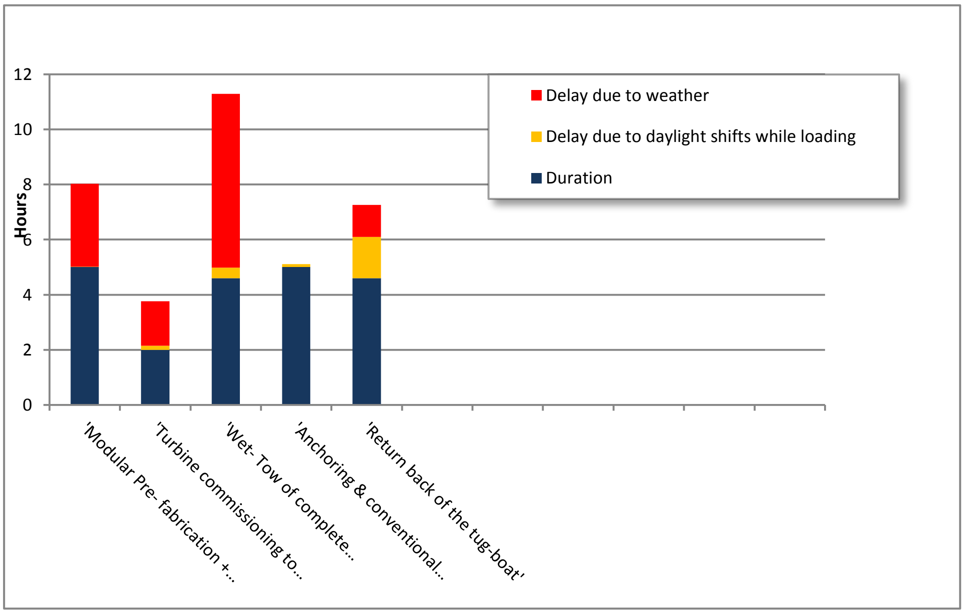
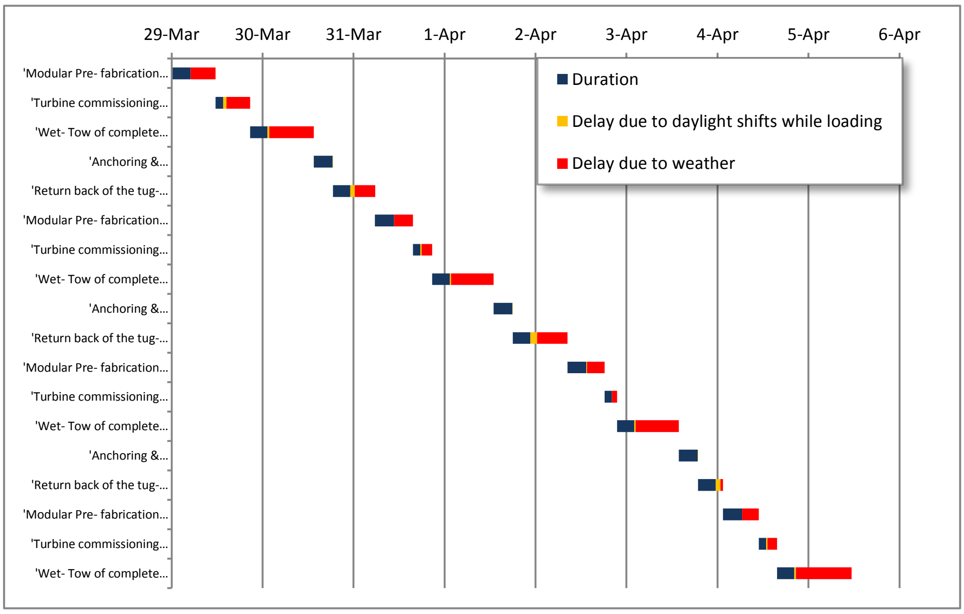


Figure 52: Planning chart of first 18 steps of installation (floating turbine)



It should be noted that the remaining sensitivity analysis for Hywind baseline case will be discussed in later section. In the next section, the innovation approach of onshore assembly, less usage of vessels and a different floater concept will be introduced. Also, the single lift approach using Huisman vessels will be used to analyse this innovation as well.

6.2 Innovation Concept

In the case of baseline floating (Hywind), the wind turbine was assembled partially at the Fjord and partially offshore. As part of this innovation, the idea is to assemble the entire structure onshore. Since we are considering floating turbines, the structures will be immersed in shallow water (at the harbour). The complete turbine structure is wet towed and is depth independent. Another advantage of assembling the structure onshore is that a lot of structures can be assembled parallel with cranes installed at the harbour.

Further, the second part of the innovation is the difference in the floater. For the same, semi-submersible floating concept, which is the combination of previously developed designs, a semi submerged structure is added to reach the necessary stability. One of such floaters are being used by WindFloat. The WindFloat is fitted with patented water entrapment (heave) plates at the base of each column. The plates improve the motion performance of the system significantly due to damping and entrained water effects. This stability performance allows for the use of existing commercial wind turbine technology [34]. **Figure 53** illustrates the various floater concepts for floating offshore wind turbines. Specifically, **Figure 54** gives a glance to the patented technology proposed by Principle Power. Although it should be noted that the mooring system employed in this case is the conventional one.

Lastly, instead of using medium sized crane vessels, only tug-boats are used for final installation. This is due to the complete assembly of turbine onshore.

Figure 53: Illustration of the different concepts, from left to right; TLWT, WindFloat, TLB B, TLB X3, Hywind II, SWAY, Jacket, Monopile and the onshore reference. The mooring systems are not to scale in the horizontal direction. [26]

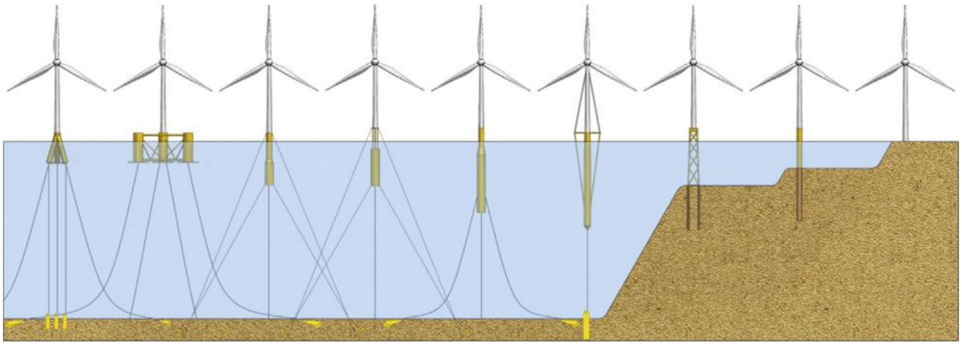
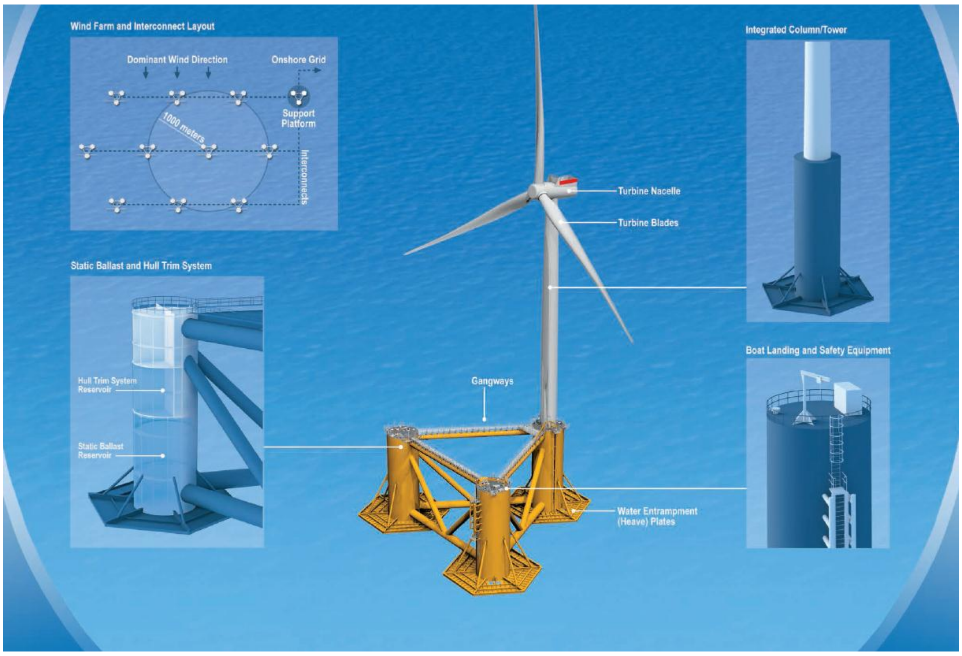


Figure 54: Principle Power Wind Float Technology [33]



Besides, the WindFloat concept, WindPlus from Principle power has been awarded by European Commission. The project funding proposes to build the 27MW NER 300 'pre-commercial' second phase of its Aguçadoura floating offshore wind farm off north-west Portugal, consisting of five WindFloat platforms developed by Principle Power. The final build-out phase is planned to have a capacity of 150MW. The current 2MW WindFloat prototype is the first offshore wind turbine to be installed without the use of heavy lift equipment [33]. The fabrication, transit and commissioning of the Wind float is summarized in the next section.

6.3 Installation Model

The Installation model to demonstrate the clustering assembly operation for floating offshore wind turbines is approached as is done in the case of WindFloat installation. The subsections below summarize the actual planning steps followed for the installation of WindFloat and the table mentions the planning steps modelled in ECN Install.

6.3.1 Planning

For the actual assembly and installation of a WindFloat, following are the requirements and steps [34] :

- The mast and turbine are fully integrated with the platform at quayside during fabrication.
- The platform is then towed to its installation site using a tugboat. Due to its exceptional stability performance, this operation can be conducted with minimal restrictions on weather conditions.

- There is no lifting operation of the turbine and on-site operations consist only of deploying mooring lines and connecting to the platform.
- The platform is towed after pre-commissioning to avoid the large cost and risk of placing the tower and turbine onto a floater in open water.
- The mooring system needs to be pre-laid and ready to be connected. Tensioning of the mooring lines should be done from the platform with chain jacks.

For the modelling through ECN Install, the points are summarized in **Table 12**.

Table 12: Planning steps for Innovation of Clustering assembly onshore (floating turbines)

Step Number	Step Description	Duration [hrs]	Wind Speed limit [m/s]	Wave Height limit [m]
1.1	Modular Pre- fabrication + Quayside assembly	2	10	4
1.2	Turbine commissioning to the tug-boat	0,5	10	4
1.3	Wet- Tow of complete system to offshore site	6	10	2
1.4	Anchoring & conventional mooring of the system	3	10	4
1.5	Return back of the tug-boat	3	10	4

6.3.2 Model Assumptions

Following are some of the assumptions considered specifically for this innovation:

- In the original planning proposed for installing WindFloat, the platform and the mooring lines are pre-installed, i.e. they are installed before the assembled turbine is wet-towed. However, in **Table 12**, the anchoring and mooring of the system is done at the end.
- It is considered that one medium sized tug-boat is sufficient for installation of the turbine. Moreover, two tug-boats are used for the baseline innovation to install two turbines in parallel.
- The system as proposed is capable of travelling with weather conditions prevalent 85kms from shore, i.e. the installation is performed at Gemini location. In all, 75 turbines are needed to be installed and the starting date (29th March) of the installation is same as that of reference floating wind farm.
- The values chosen for weather restrictions and the step duration are only indicative of reality, but not the actual values.
- Multiple shift strategy (24*7) is considered for the installation.

6.4 Installation Model Results

Table 13 presents the duration and delays of installing the 75 turbines using 2 tug boats in parallel. Again, the installation is performed at the Gemini location (85km from shore).

Table 13: Results for Installation of Floating turbines using innovation (average days per turbine)

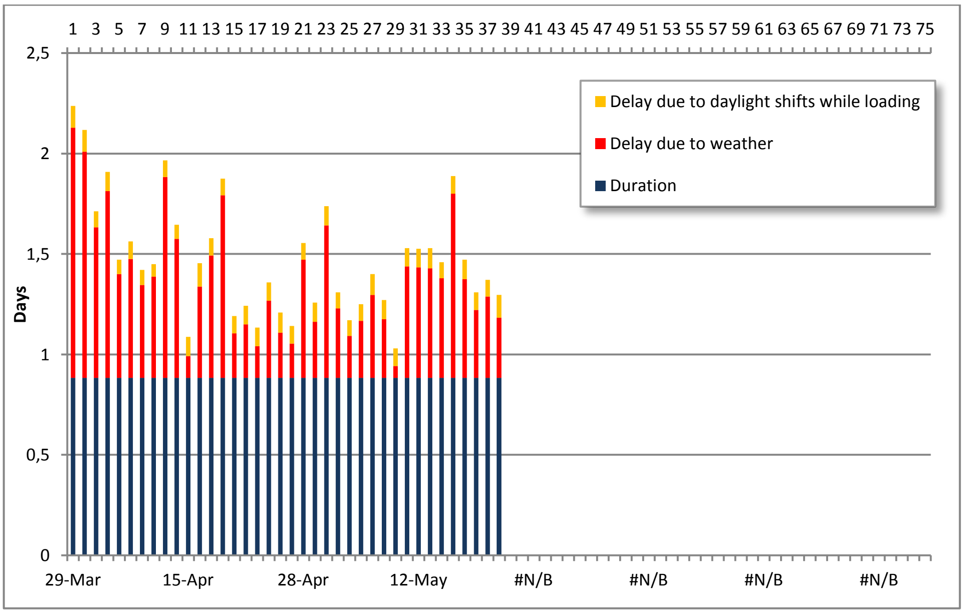
	Start Date	End Date	Duration Total [days]	Duration work [days]	Delay total [days]	Delay weather [days]	Delay shift [days]	Delay harbour [days]
Turbines	29-Mar	24-May	0.75 ±0.74	0.45	0.30	0.26	0.05	0.00

The results above highlight that the total average duration is quite less but there is a certain risk as signified by the standard deviation. The reason for this high standard deviation is the weather delay which is in turn caused by stringent weather restrictions while installing the floating offshore wind energy. Both wind speed and wave height play a limiting factor when wet-towing the entire structure offshore. Also with the average duration, 75 turbines can be installed in around 56 days. The sub-section below illustrate the graphs for turbine installation.

6.4.1 Turbines

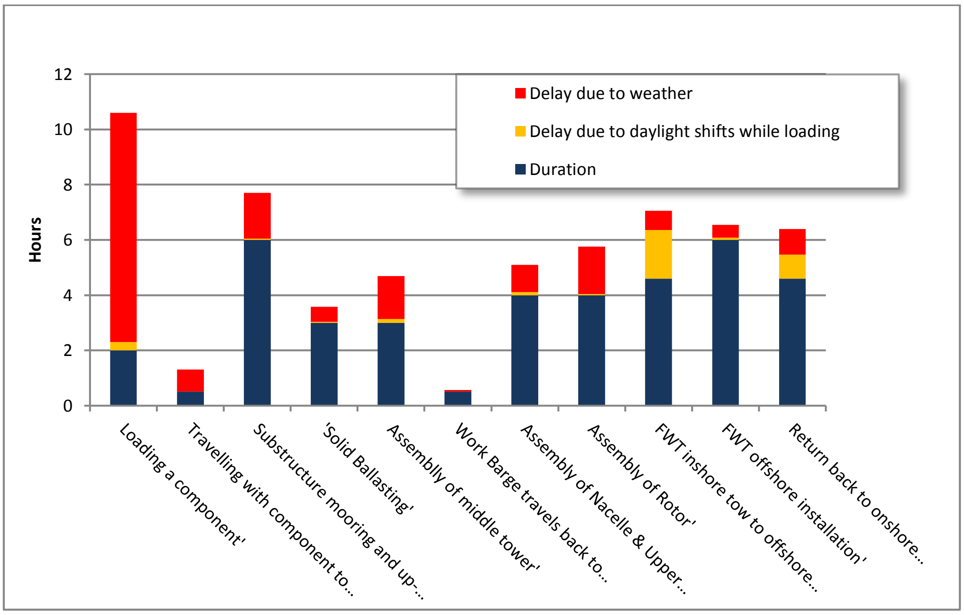
Floating turbine installation using the WindFloat concept generates the following results (shown in **Figure 55**, **Figure 56** & **Figure 57**) using 2 tug-boats in parallel.

Figure 55: Average duration and delay per turbine for installing floating turbines[3].



In **Figure 55**, it is observed that that there is significant weather delay in each of the turbine installations. It has been already seen that the weather during the period from April to May is quite unfavourable. This, together with rigorous weather restrictions lead to high weather delay. It would be interesting to start the installation in a different season, preferably during late summer. **Figure 56** confirms the high weather delay, especially in the step- 'Wet Tow of complete system to offshore site. Additionally, **Figure 57** show the first 18 steps in the form of a Gantt chart.

Figure 56: Average duration and delay per step for installing floating turbine



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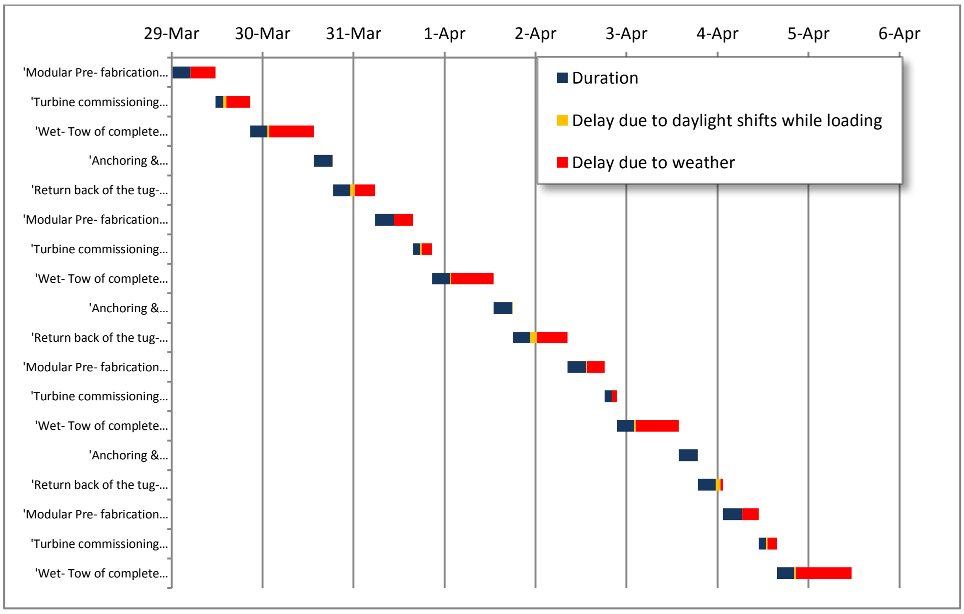
[3] Note that only 38 turbine sets are shown in this figure. As considered in the model assumptions, two tug boats work in parallel to install the turbines. That is, parallel turbine installation takes equal time.

Figure 57: Gantt chart demonstrating the average duration and delay for the initial 18 steps of installation.[4]



6.4.2 Sensitivity Studies

The following inputs are varied to study the sensitivity of the results.

- Difference in the number of tug-boats used for installing the floating turbines. The number is varied from 1 tug boat to 5 tug-boats. Additionally, the analysis is performed for both regular shift (day) and multiple shift (24*7).
- Concept of using Huisman vessel (used in Chapter 4) is used even for installing floating offshore wind turbines. The consideration is the same as used in the above case, i.e. two turbines (with the floater pre-assembled) can be transported per visit to the wind farm.
- As discussed before, baseline case of Hywind is also analysed for both single shift and multiple shifts. Additionally, instead of using only 2 tug boats and a medium sized barge, modelling is done for installation using double the vessel strength. This will enable two turbines being installed in parallel.

The results for the sensitivity studies are illustrated in **Figure 58**, **Figure 59** and **Figure 60**. Additionally a comparison between all the concepts for installing floating turbine (including baseline Hywind installation) is visualized in **Figure 61**. For detailed results and numbers for each case, reference to **Table 14:** Results for Cluster assembly Innovation (days average per turbine) **Table 14** can be made.

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[4] The complete name of the step names can be read from **Table 12**.

Figure 58: Innovation Onshore assembly for floating turbines with varied number of tug boats (using single shift(SS) or regular shift strategy

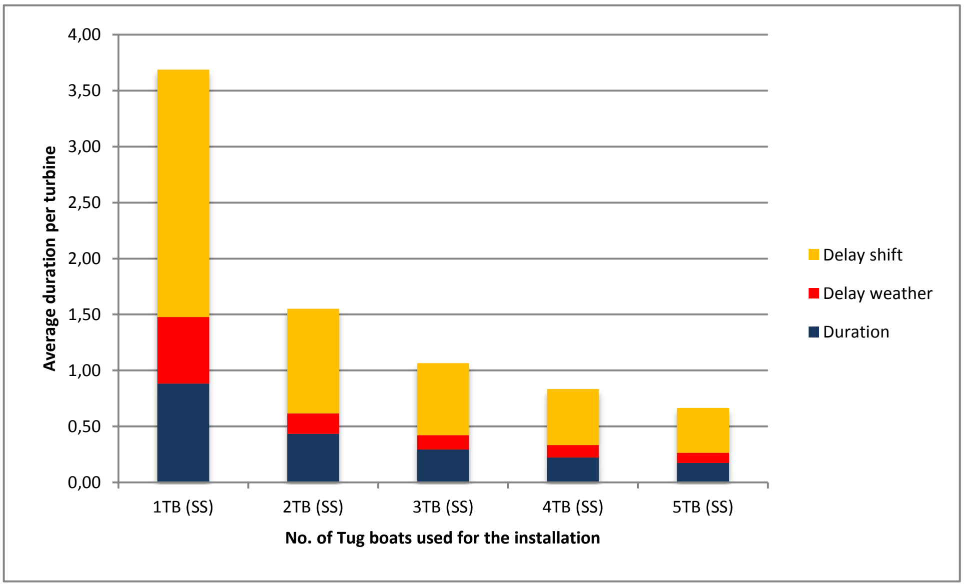
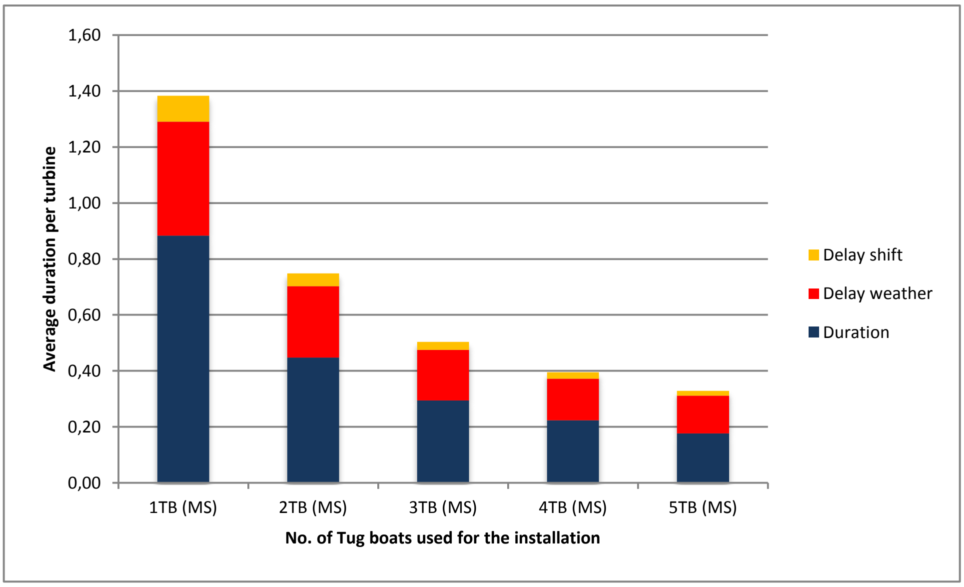


Figure 59: : Innovation Onshore assembly for floating turbines with varied number of tug boats (using multiple shift(MS) or 24*7 shift strategy



From the above two diagrams, it is clear that with higher number of tug-boats being employed in parallel, the average duration of installation per turbine will decrease. However, for each extra tug-boat leased or bought, the costs will also be higher. Hence, a wise decision needs to be made. Moreover, using two tug-boats would be not a bad proposition as there is a difference of more than 50% reduction in time either using regular shift strategy or 24*7 shift strategy. Also, it is interesting to note that employing regular shift or 24*7 shift strategy can also cause huge impact on the overall completion time of the project. It shall take twice[5] the time to finish installation using single shift strategy as compared to 24*7 strategy.

Further, from **Figure 60** it can be inferred that the Huisman concept would an interesting concept for floating offshore wind turbine. The major difference is the reduction in weather delay as the vessel can operate in difficult weather conditions. Although, it should be noted that such a vessel will face some difficulties while placing the turbines. This is outside the scope of the project and needs to be investigated.

Figure 60: : Comparison of installing floating turbines using conventional approach (Hywind), WindFloat approach and using Huisman vessel (using multiple shift(MS) or 24*7 shift strategy)

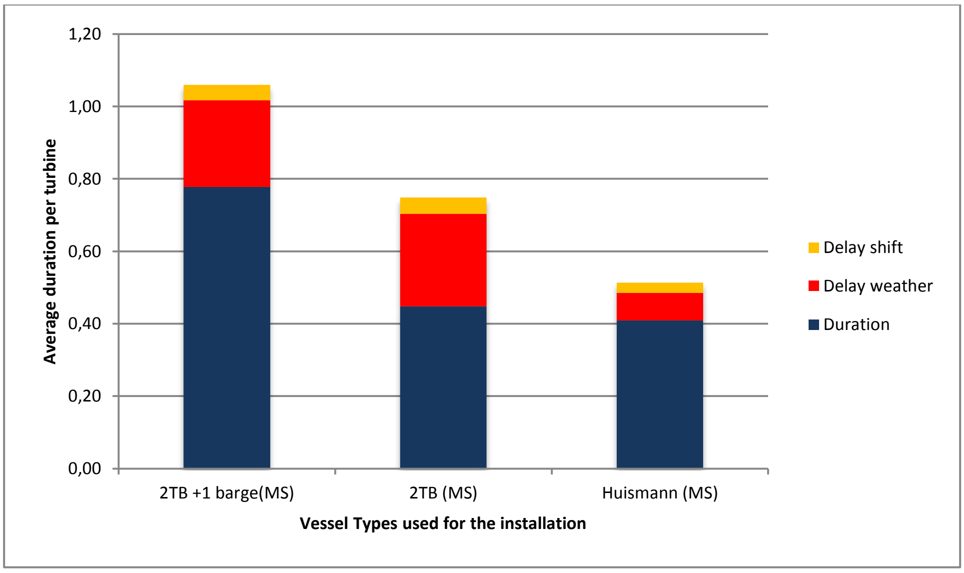
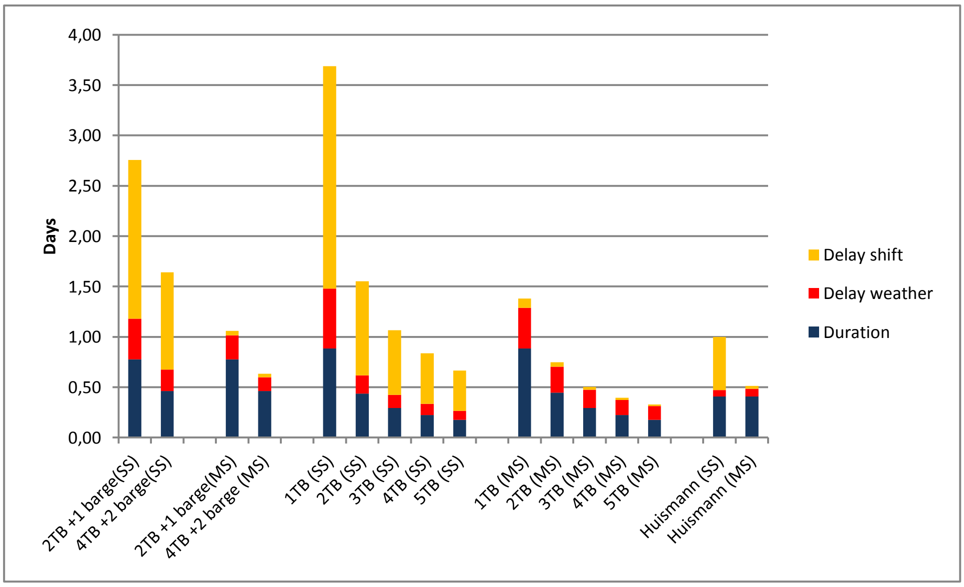


Figure 61: : Comparison of all the different concepts for installing floating turbines (average duration in days per turbine)



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[5] This is due to the fact that following regular shift strategy, the crew can only work for 12 hours.

Table 14: Results for Cluster assembly Innovation (days average per turbine)

Baseline complete turbine installation (1-shift)

Vessels	Start Date	End Date	Duration Total [days]	Duration work [days]	Delay total [days]	Delay weather [days]	Delay shift [days]
2TB +1 barge(SS)	29-Mar	17-Aug (next year)	2,76	0,78	1,98	0,40	1,58
4TB +2 barge(SS)	29-Mar	11-Dec	1,64	0,46	1,18	0,21	0,97
Baseline complete turbine installation (2-shifts)							
2TB +1 barge(MS)	29-Mar	17-Oct	1,06	0,78	0,28	0,239	0,042
4TB +2 barge (MS)	29-Mar	6-Jul	0,63	0,46	0,17	0,137	0,035
Innovation Turbines: Complete assembly of floating turbines onshore (1-shift)							
1TB (SS)	29-Mar	13-Dec	3,69	0,88	2,80	0,60	2,21
2TB (SS)	29-Mar	26-Jul	1,55	0,44	1,12	0,18	0,93
3TB (SS)	29-Mar	16-Jun	1,07	0,29	0,77	0,131	0,641
4TB (SS)	29-Mar	30-May	0,84	0,22	0,61	0,110	0,503
5TB (SS)	29-Mar	17-May	0,67	0,18	0,49	0,090	0,400
Innovation Turbines: Complete assembly of floating turbines onshore (2-shift)							
1TB (MS)	29-Mar	10-Jul	1,38	0,88	0,50	0,406	0,092
2TB (MS)	29-Mar	24-May	0,75	0,45	0,30	0,255	0,045
3TB (MS)	29-Mar	5-May	0,50	0,29	0,21	0,180	0,029
4TB (MS)	29-Mar	27-Apr	0,39	0,22	0,17	0,149	0,023
5TB (MS)	29-Mar	22-Apr	0,33	0,18	0,15	0,135	0,018
Innovation H Turbines: Using Huisman vessel with complete turbines (1-shift)							
Huisman (SS)	29-Mar	12-Jun	1,00	0,41	0,59	0,06	0,53
Innovation H Turbines: Using Huisman vessel with complete turbines (2-shift)							
Huisman (MS)	29-Mar	6-May	0,51	0,41	0,10	0,08	0,03

6.5 Discussion

The concept of onshore assembly is in discussion for some while now. Moreover, a part of the innovation, i.e. clustering assembly can be applied for fixed bottom turbines as well. In that case, while the foundations are installed independently, the turbine can be towed to the site. Further, with the recent interest of floating offshore turbines, the concept proposed above will be more applicable in near future with wind turbine sites planned more than 80 km from shore.

In general, the European offshore wind industry has matured because of water depths in North Sea and Baltic sea being around 10-40 meters. With promising markets like Japan, South Korea, US, the installation of floating turbines will be more significant. The weather conditions in the Atlantic are much harsher and the sites quite deep. The onshore assembly of floating turbines would be a definite solution to the market in those countries. With 75 turbines being installed in 56 days with two tug-boats (onshore assembly), the market with this concept is quite promising.

7

Discussion

7.1 Discussion

This report examined several installation concepts, by modelling their effects on the installation time using ECN Install. The results show not only the potential of the ideas, but also what effects of each idea are most important.

The conventional method of installation led to installation time of more than 3 days per foundation or turbine. The three introduced innovations significantly reduced the actual installation time. For example: using the concept of offshore harbour and single lift installation, the installation time per turbine installation can be as low as 0.78 days. Further, it is always observed that the weather conditions play a critical role in the successful completion of the installation process. Innovative concepts like breakwaters substantially reduce this risk (standard deviation of 0.14 days) and the owner or the contractor can be more assured of finishing the installation within stipulated time. However, it should be noted that the technological feasibility of such concepts is still to be explored. There are still some challenges and risks developing structures like an offshore harbour or a floating breakwater. Finally, with offshore wind farms being placed far offshore, innovative concepts for floating turbines are essential. Onshore assembly and minimum use of vessels is the key to reduction of time and costs.

Innovative installation concepts studied in this feasibility study show that significant reductions in installation time and risk can be achieved. However, it is essential that the costs of such innovations are also included.

7.2 Future Work

The scope of the project has been limited to the comparison of installation time alone. However, it would be interesting to the see the cost implications corresponding to these innovative concepts. This can be done once ECN Install software has that module to compute and compare cost.

Also, it would be worthwhile to perform resource assessment of vessels and equipment. The optimization of the use of these vessels can significantly impact the installation costs. Besides the resource assessment, capacity management of crew is significant. Both modules will be added in the ECN Install software in a later release of the software.

Further, the comparisons of innovations are made with respect to fixed baseline concepts. It would be interesting to model different baseline concepts and then observe the added value of these innovations.

Finally, there are certain assumptions and limitations corresponding to each innovation. It would be interesting to verify these results with due discussion with companies and industry associated with concepts like those mentioned in the report.

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