Cost Modelling of Floating Wind Farms

Georgios Katsouris
Andrew Marina

March 2016
ECN-E--15- 078

Acknowledgement

This report is written in the context of the “TO2 - Floating Wind” project.

Contents

Summary

The depth limitations for bottom-fixed turbines exclude the possibility to utilize the vast quantities of offshore wind resources in deeper waters. Hence, interest has been drawn recently to different foundation concepts such as floating platforms which are suitable for deeper waters. Currently, only a few floating wind turbines are operational and hence, accurate conclusions cannot be drawn regarding the economic viability of these concepts before their commercial deployment. However, computer models can provide useful insights regarding the most important cost parameters of offshore wind farms and allow the assessment of different concepts.

The objective of this work is to compare the LCOE of a bottom-fixed foundation (monopile) wind farm and a respective floating (semi-submersible) one, installed in the same location with same number and type of wind turbines. In order to meet this objective, two ECN's in-house developed tools were updated. First "ECN Install", an offshore wind installation simulation tool, was upgraded in its second version which now allows cost calculations besides calculations in the time-domain and additionally gives the possibility for parallel installation sequences. Secondly, the "ECN OWECOP" cost model was updated to include the cost calculations for the semi-submersible floating concept.

The results of the installation models created from ECN Install v2.0 indicate the significant cost advantages of the semi-submersible and tension-leg platform concepts due to the possibility for onshore assembly. Particularly, semi-submersible wind turbines can save 50% in installation costs compared to monopile foundations. Combining the results of ECN Install with these of ECN OWECOP, the LCOE of the fixed bottom wind farm is calculated at 138 €/MWh, lower compared to the semi-submersible concept which was calculated to be 159 €/MWh. The overall higher costs for the floating concepts are mainly due to the large floater which requires a large mass of steel.

Overall, the fact that the cost of the floating wind farm is higher compared to bottom-fixed foundations for the case study developed during this work is not dissuasive for exploring and optimizing further floating wind. The clearly visible benefits of floating wind installation and O&M should not be overlooked, even in the case of swallow water wind farms.

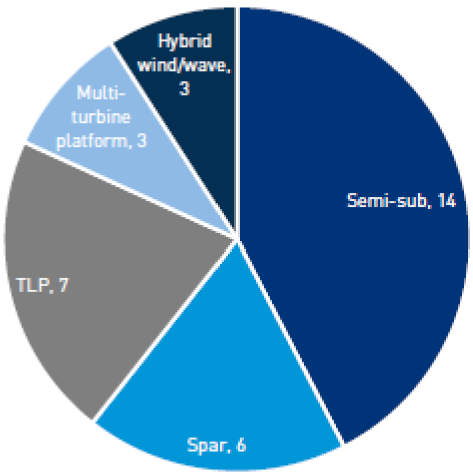
1

Introduction

1.1 Floating wind

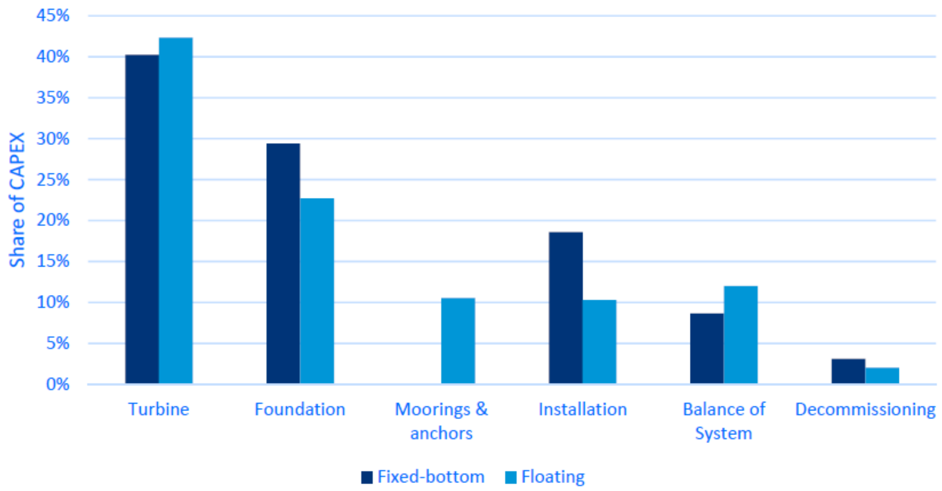
The offshore wind market has so far been dominated by countries with relatively shallow water depths (<50m) and established maritime industries. However, with the limited potential for bottom- fixed structures and the need for a diverse energy supply, more countries are beginning to explore the potential for floating offshore wind. Given the fact that there is extensive wind resource in deep waters (50-200m), floating wind is potentially a highly scalable future energy source in a number of markets including Japan, the United States, and a number of European countries including the UK, Norway, France, Portugal, and Spain [10]. Specifically, Europe has a huge potential for deep offshore wind energy as more than half of North Sea is suitable for deployment of floating wind turbines. A floating substructure allows the exploration of the untapped potential of far offshore wind energy. However, there are still many challenges for floating wind turbines to overcome. **Figure 1** shows the types of floating concepts under development.

Figure 1: Types of floating concepts under development [10].



Since it is in the early phase of its development, floating wind technology has high costs, particularly for early prototypes that have been installed so far. However, early prototypes do not reflect the true costs that can be expected with mass deployment, once designs have been optimized to reduce structural weight, introduce novel component technologies, improve installation methods, adopt serial fabrication processes, and benefit from scale effects more generally [10]. There is therefore significant potential for costs to come down to reach parity with bottom-fixed offshore wind when deployed at large scale. A breakdown of the typical capital expenditure (CAPEX) for a bottom-fixed and floating wind farm can be found in **Figure 2**.

Figure 2: Cost breakdown for typical bottom-fixed and floating offshore wind projects [10].



Like conventional bottom-fixed projects, the cost of the turbine dominates the capital expenditure for floating wind. For deep water sites (beyond ~45m), foundation costs can be expected to be lower for floating wind projects, largely due to the lower structural mass and material costs compared to bottom-fixed deep water structures. However, once the cost of the moorings and anchors is included, the cost is expected to exceed that of bottom-fixed foundations. However, where floating wind can deliver significant cost savings is in installation due to the possibility for onshore assembly. Despite the anticipated higher CAPEX for floating wind, another key driver of cost savings versus bottom-fixed projects is reduced operational expenditure (OPEX). This comes from the fact that the possibility is given to disconnect floating wind turbines from the mooring lines and transport them onshore in order to perform major overhauls.

1.2 Objective

The objective of this work is to compare the LCOE of a floating with a bottom-fixed foundations wind farm for a reference offshore location. For this reason, the necessary updates to the installation planning tool “ECN Install” and ECN “OWECOP” cost model are made to facilitate this cost comparison. The main cost factors (Procurement, Installation and O&M) of an offshore wind farm are calculated from three ECN’s in-house developed tools (OWECOP, ECN Install and O&M Tool respectively).

1.3 Report outline

This report is organized as follows:
Chapter 2 presents the additions that were made to "ECN Install" tool under the framework of this project, as well as the time and cost comparison of the installation of a wind farm with various foundations including monopile, spar buoy, semi-submersible and TLP concepts.
Chapter 3 gives the overview of the updates to ECN's OWECOP cost model in order to include semi-submersible cost calculations and the comparison of the LCOE between bottom-fixed and floating offshore wind farms.
Chapter 4 summarizes the findings of this work and provides the main conclusions.

2

ECN Install v2.0

Under the framework of the current project, the 2nd version of the "ECN Install" tool [1] was developed. This chapter gives an overview of the additions that were made to the tool during the 6 month period from June-December 2015 which involved three internships. Moreover, the installation modelling of a reference wind farm for the Gemini location is presented by using bottom-fixed foundations (monopile) and floaters (spar buoy, semi-submersible and tension-leg platform). Last, the scope of the future work is summarised.

2.1 "ECN Install" tool

ECN Install is a MATLAB based offshore wind installation simulation tool. The main idea is to give the opportunity to the user to model the installation planning and extract as outputs time and cost information of the project. Its structure is highly user-defined which means that the usefulness of the results depends heavily on the quality of inputs. The following sections present the motivation behind the development of ECN Install and the logic of the modelling.

2.1.1 Added value

A variety of users could benefit from the installation modelling of offshore wind farms including wind farm developers, installation contractors and port authorities. The added value of the tool can be summarized in the following key points:

- Provide accurate time and cost overview of the installation activities
- Initiate a dialogue between the actors involved (developers-contractors)
- Identify barriers during the installation and eliminate project risks
- Optimize resource management (e.g. vessels, equipment, ports and personnel)
- Allow the testing of conceptual installation strategies (e.g. new methodologies and vessels)
- Reduce possible delays and overall costs.

2.1.2 The model

A brief explanation of the way the installation modeling is performed by ECN Install is necessary for the reader to get acquainted with the tool. The basic logic that is followed is that the installation is performed in the form of steps. In general, the given weather data is used to provide accessibility vectors for performing each step, according to the applied weather restrictions (wind speed and significant wave height). After the weather restrictions are defined, the accessibility vectors are formed for each step by examining the climate data. Successively, the starting time of the step is used as the starting point for which accessibility is considered.

Two main parameters that affect the completion of one step is the step duration, which shows the time required to complete the step and the step weather duration which corresponds to the necessary weather window. These two can be the same but usually a greater step weather duration is assumed in order to account for uncertainty. All steps are considered as weather non-splittable which means that the necessary weather window should be found in order for a step to be performed. Besides weather limits, shift should be present but it is possible that one working shift starts one step and another shift completes it (shift-splittable step). As long as the necessary weather window is found and shift is present, the step is performed. After one step is completed, the same procedure is carried out for the next step and so on.

2.2 From ECN Install v1.0 to v2.0

In this section, the additions that were made to ECN Install v2.0 are highlighted according for each module of the tool including inputs, planning, pre-processor and outputs. For a detailed analysis of ECN Install v2.0, see [2].

2.2.1 Inputs

The 'inputs' module is organized in several sub-modules assisting the user to define relevant parameters of the installation. Starting from the 'wind turbine type', basic wind turbine characteristics should be given such as power curve, hub height, number of turbines and power output. Wind turbine inputs are used mainly to approximate the energy yield and allow the calculation of the wind speed at the hub height. Moreover, climate data at various locations (e.g. wind farm and ports) where installation activities take place should be included. Then, the 'operation bases' sub-module allows the connection of the climate data with all possible locations. Especially for ports, information regarding their cost, distance to farm and possible fixed delays due to harbour lock may be given. In addition, cost and weight parameters of the components that need to be installed may be included.

Most importantly, relevant inputs of the vessels and equipment that are used during the installation are required. These include cost parameters, speed of activities and weather restrictions (wind speed and wave height) that may apply to each activity. In the updated version of ECN Install, **wave current restrictions** are also included. Additionally for vessels, travel speed is included to allow calculations concerning transportation activities. Furthermore, shift related information including starting and ending times as well as labour costs, can be given in the 'working shifts' module. Another addition that was made concerns **permit constraints**, periods during which specific operations (e.g. piling) cannot be performed. Last, general fixed costs could be provided alongside with the electricity price.

2.2.2 Planning

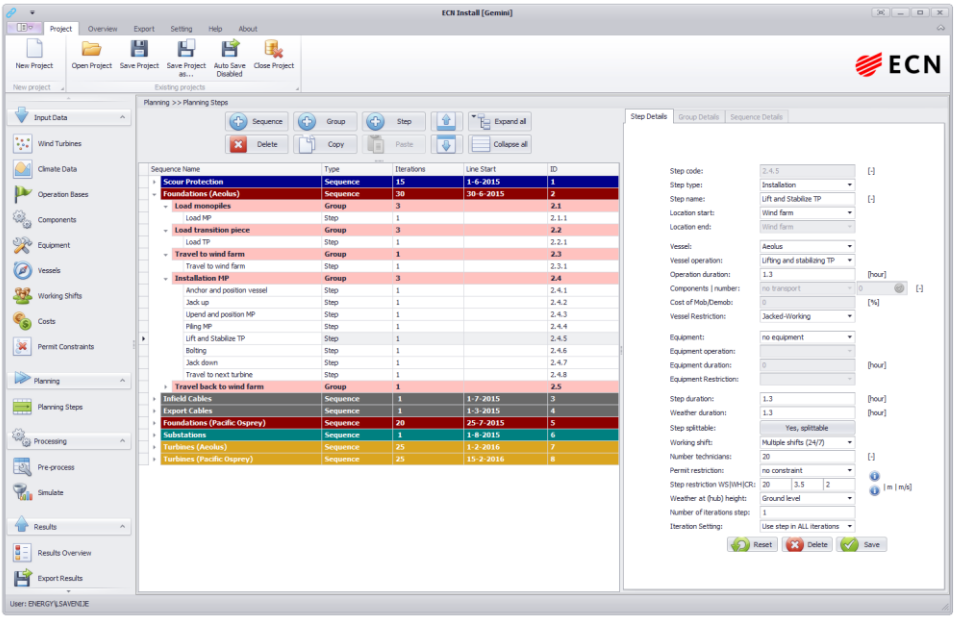
Following the 'inputs' module, the proposed planning of the installation is given in the form of installation steps. Two types of steps are considered:

- **Organization step**, which describes the set of activities to load the components from the ports to the vessel and the **de- mobilization** of the vessels, which was not treated in the 1st version of the tool.
- Installation step, which describes either the travelling of the vessels or construction activities.

The user can select the vessel and equipment that are used at each step, define the step duration and the corresponding weather window as well as the number of technicians involved. Depending on the step type, specific options are enabled or disabled. Additionally, for the first step of a sequence of steps, the starting time should be given.

Most importantly, the possibility is given now to the user to include **more than one sequence** of steps which captures to great extend the actual installation activities occurring in parallel (e.g. foundations and balance of plant). On top of that, the **user-friendly** character of the tool has been significantly enhanced as far as the planning module is concerned since the possibility is given now to group steps, repeat them and easily inspect the given values. For a detailed explanation of the updates in the GUI of the tool, the reader is referred to [3].

Figure 3: ECN Install 'planning module'.



2.2.3 Processing

The **processing module** is now organized in two sub-modules: the **pre-processor** and the **simulation** modules. The pre-processor processes the weather data and provides an immediate indication of the weather uncertainty and the weather windows at the chosen location. Moreover, it displays the project duration in the idealized case where delays are not present. The simulation is the core of the tool where all necessary calculations take place. For the 2nd version of the tool, the logic of the modelling remained the same. However, adjustments were made in order to address the **multiple sequences** of steps and increase the efficiency of the tool (speed and memory usage).

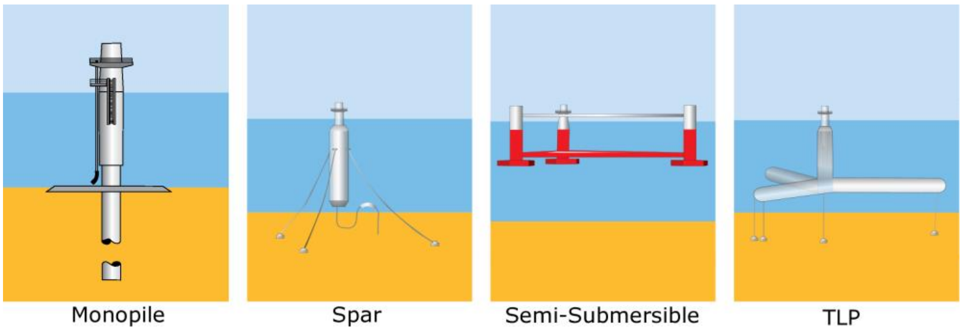
2.2.4 Results

The 'results' module is organized in several outputs which allow the user to assess the outcome of the simulation that was performed. Compared to v1.0 where only average values of delays and project duration were displayed, the cost module that was added offers insights regarding cost figures of the project [4]. As far as the outputs are concerned, they are organized in three sections: **Excel sheet, Gantt Chart and Graphs**. The key outputs of the modeling as well as the inputs are summarized in a **Microsoft Excel** file which enhances also the transferability. Moreover, detailed time overview of each simulation is included which shows when each installation activity was completed. The possibility is also given to the user to extract **Gantt charts** of the installation planning. Hence, a quick time overview of the planning can be created and the most time-consuming steps/sequences can be identified. Last, **outputs graphs** strengthen the user-friendly character of the software while providing useful feedback concerning the installation planning. They are divided in three categories: **time, cost and resources graphs**. The idea is to present to the user graphically the key figures of the simulations. The generated graphs offer a view on the project both on a high level but also on the details during its execution [4].

2.3 Case study: Gemini offshore wind farm

In this section, the results of the installation modelling of the Gemini wind farm are presented. The models that were developed include bottom-fixed foundations, particularly monopile foundations as it is the case in the actual Gemini wind farm installation [5], and floating concepts such as the spar buoy, semi-submersible and tension-leg platform (TLP) floaters.

Figure 4: Offshore wind monopile, spar, semi-submersible and TLP foundations [6].



2.3.1 Development of the models

A detailed overview of the Gemini wind farm installation planning including monopile foundations can be found in [4]. Briefly, the installation is split in several parallel sequences including scour protection, foundations, infield and export cables, substations and wind turbines. As far as the floating concepts are concerned, the overview of the installation planning is presented in [7]. For the purposes of the current work, the modelling of the spar installation follows the installation of Hywind in Norway [8]. In this case, the turbine is assembled to the floater near-shore and then towed to the wind farm and moored to the seabed. Regarding the semi-submersible installation, a representative example is the Windfloat, installed in Portugal by Principle Power [9]. In this case, the wind turbine is assembled onshore and towed directly to the wind farm where it is hooked to the installed mooring lines. Last, the TLP installation differs slightly to the semi-submersible concept in the sense that it is more susceptible to harsh met-ocean conditions due to the lack of buoyancy stability in the platform without mooring tension [10].

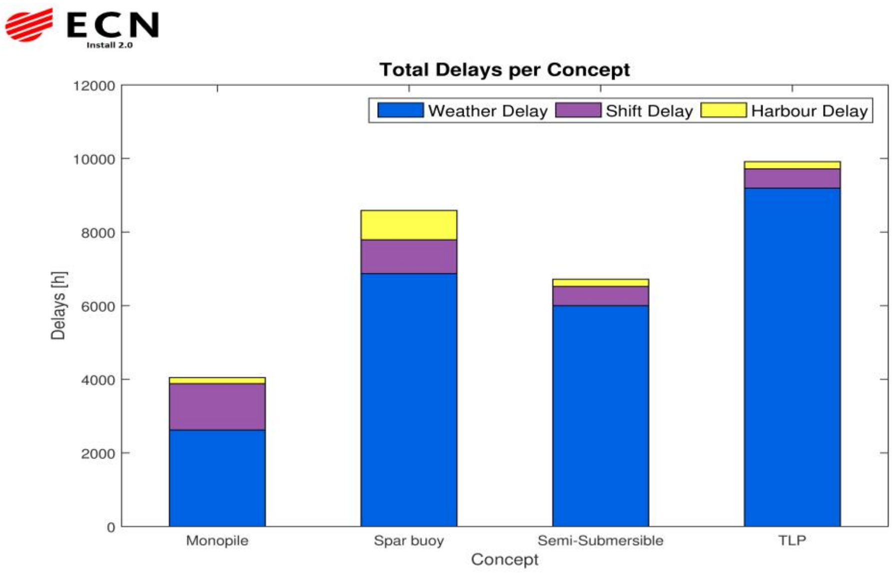
As far as the infield and export cable installation is concerned, minor differences are expected between the aforementioned concepts. Moreover, it is assumed that the floaters (expect the spar and the wind turbines are already assembled in the ports, hence the current study models only installation activities that are performed offshore.

2.3.2 Comparison

The comparison of different foundation concepts is provided in this section in terms of delays during the installation and total installation costs. The delays that are modelled by ECN Install include weather, shift and harbour lock delays. The installation costs consist of costs over different resources that are used during the installation including vessels, equipment, harbours and technicians.

Starting from the delays, as it can be seen in **Figure 5** and according to the models that were developed in the current work, the installation of floating wind turbines is more susceptible to weather delays compared to wind turbines positioned on monopiles.

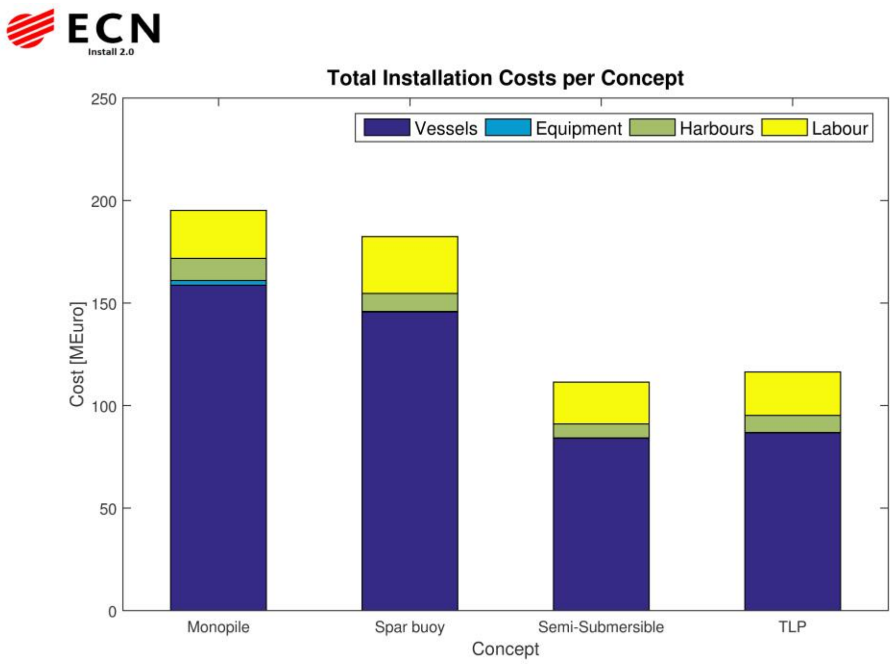
Figure 5: Delays during installation for different foundation concepts.



The reason for the increased delays for the floating concepts is the fact that the installation was also carried out during the winter months compared to the monopiles installation which can only start after end of June in the Netherlands. However, despite the larger delays, the advantage is that the project can be commissioned earlier compared to bottom-fixed foundations. Focusing on the floating concepts, installation of TLPs results in higher delays due to the need of finding sufficient weather windows (>12 hrs) of significant wave heights of less than 1.5 m in order to transport the turbine-floater assemblies to the offshore location. On the other hand, semi-submersible installation is less dependent on weather since the ballasting of the structure allows easier transportation. Finally, spar buoy installation delays occurred during the assembly of the turbines near-shore. Moreover, harbour delays are also important since components are constantly fed to the near-shore location from the harbour.

Besides the delays, the installation costs are also of great importance for evaluating the installation of various concepts (**Figure 6**). As it was mentioned earlier, the current study assumes that assembly of turbines at the port locations is not part of the installation costs. Thus, the installation costs include construction and transport activities and loading of the structures at ports.

Figure 6: Installation costs for different foundation concepts.



To start with, installation of all floating concepts is less costly compared to bottom-fixed foundations. The main reason is that the use of expensive jack-up vessels is not needed. The cost advantage of spar buoy installation is not significant compared to monopiles since barges with heavy-lift cranes are needed to assemble the turbine near-shore. However, semi-submersible and TLP floaters can be assembled with the turbines by using onshore cranes on ports and transported by towing tugs at the offshore locations. This attribute can lead to almost 50% cost reduction compared to bottom-fixed foundations.

2.4 Discussion and future work

In this chapter, the updated version of ECN Install was demonstrated and the results of a case study that was performed by using the updated version were presented. During the current project, several functionalities were added to the tool including parallel sequences, cost calculations and outputs. Moreover, the GUI was upgraded. Besides the aforementioned additions, knowledge was developed about offshore wind installation as well as insights regarding the futher development of ECN Install. The scope of the future work can be summarised in the following points:

- Interdependencies between parallel sequences (start to start steps)
- Possibility for reverse planning (from fixed end date to start date)
- Intermediate milestones (e.g. n^{th} foundation until a specific date)
- Port logistics
- Risk assessment
- Additional weather restrictions (swell, fog).

Despite the additions that are still required for ECN Install, it was shown that the tool can be used for the modelling of new installation methods as well as floating concepts installation. The results that were presented in the current work proved the cost advantage of floating concepts as far as their installation costs are concerned, compared to bottom-fixed foundations. The possibility for onshore assembly that semi-submersible and TLP wind turbines offer, even if it is not translated in less downtime due to the long and weather vulnerable travelling steps, can significantly reduce the costs that are imposed by the use of heavy-lift or jack-up vessels.

3

Wind farm cost analysis

This chapter gives an overview of the wind farm cost modelling and the analysis that has been conducted as part of the TO2 Floating Wind Energy project. The cost modelling has been conducted using the ECN in-house developed OWECOP cost model. Through the project, additional relations were developed and added to OWECOP cost model such that the LCOE of an offshore wind farm containing semi-submersible floater structures could be calculated. The updated cost model was used, combined with results from the ECN Install tool to model the LCOE of the Gemini wind farm, currently being constructed off the coast of Groningen (the Netherlands), comparing the cost for fixed bottom as well as the floating case. Within this chapter, section 3.1 gives a description of the OWECOP cost model, its modules and other details relating to the cost calculation of offshore wind farms. The additions to the model that have been conducted during the TO2 project, limited to mooring and the tri-floater design are given in section 3.2. The results of the cost modelling study are detailed in section 3.4, and finally the conclusions of the study are presented in section 3.5.

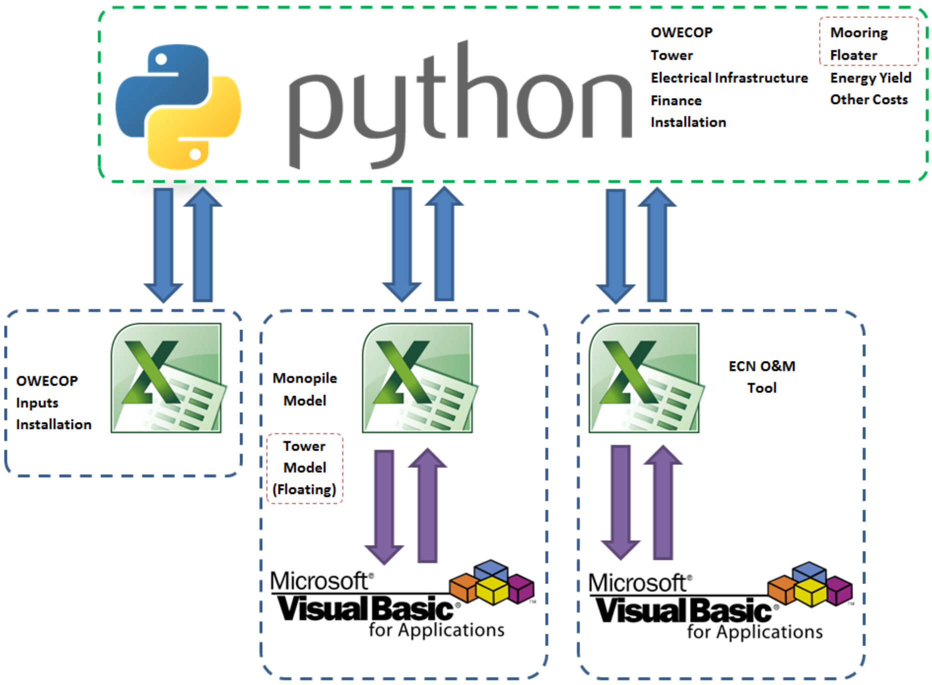
3.1 OWECOP cost model

The OWECOP cost model is an ECN developed modelling tool for predicting the levelized cost of energy (LCOE) of offshore wind farms. The OWECOP modelling program takes a number of user input parameters, and utilises a number of engineering models and relationships, empirical relationships as well as statistical data for wind sites to give a detailed cost breakdown of an offshore wind farm. The energy yield of the farm is calculated through the use of the onsite wind resource, availability calculated from operation and maintenance parameters as well as the Jensen model, which takes into account the spacing of turbines to predict the wake losses in the farm.

The OWECOP model is primarily created utilising the programming language Python, however also utilises a number of Microsoft Excel worksheets in order to model the various cost components of a wind farm. A schematic outline of the tool including an indication of the modules and the data flow can be seen in **Figure 7**. The tool was originally developed in Excel, however in order to extend the functionality of the model it was decided to re-program the model using Python. The original OWECOP Excel model is therefore still utilised for inputting data to the cost model as well as for some calculations relating to installation costs. The extension of the model saw the inclusion of the ECN Operation and Maintenance tool utilised as a means for indicating operation and maintenance costs in the wind farm. Furthermore, a dedicated spreadsheet is used to determine the main dimensions of the tower, monopile and transition piece for fixed bottom wind turbines.

Additions made to the OWECOP cost model through the TO2 project are highlighted in **Figure 7** through the circled items coloured in red. The Excel model utilised to calculate the main dimensions of the monopile, transition piece and tower was modified in order to calculate the main dimensions of the turbine tower used for a floating structure. This modification allows a 'soft-stiff' tower to be designed and dimensioned whereby the Eigen-Frequency of the tower lies between the 1P and 3P rotational frequency of the turbine. Furthermore, a module was added in the Python section of the computer code which allows the basic dimensioning and cost calculations of a semi-submersible floater type support structure as well as the associated mooring elements. The details of these modules are described in sections 3.2.1 and 3.2.2 respectively.

Figure 7: Outline of Data Flow in OWECOP Cost Model



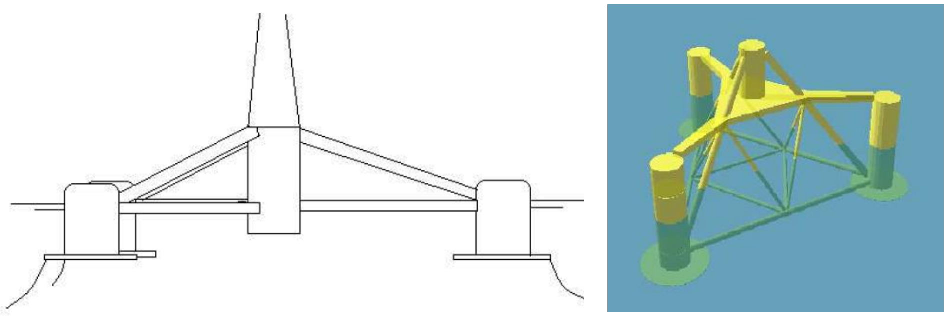
3.2 Floater modelling in OWECOP

In order to conduct modelling of an offshore semi-submersible floater wind turbine support structure, a Floater module containing suitable relationships had to be added to the OWECOP model. This section gives an overview of the changes that were made to the OWECOP model through the TO2 project. Furthermore, the relationships utilised, as well as the methodology utilised for incorporating these are described.

3.2.1 Semi-Submersible Floater

For modelling the cost of the semi-submersible floater structure for offshore wind turbines, relationships were taken from the report ‘Study of the feasibility of and boundary conditions for floating offshore wind turbines’ also known as the ‘Drijfwind’ report [11]. This study was carried out by ECN, MARIN, TUD, TNO and Lagerwey. In this study, a number of concepts for wind turbine floaters were investigated and relationships developed to determine their primary dimensions. The dimensions of various concepts, including the tri-floater depicted in **Figure 8**, are defined based on their construction, weight, volume and stability. The relationships provided in the study were incorporated into the OWECOP model, and used in incorporation with root finding algorithms in order to converge to an acceptable solution.

Figure 8: Semi-Submersible Tri-Floater Design [11]



The calculation of the basic dimensioning of the tri-floater is on the basis of a number of inputs to the model given in **Table 1**. Underlined variables are those calculated by the OWECOP model in previous steps, whereas other parameters are given as inputs in the model definition. Based on the these parameters, multiple calculations are performed using a root finding algorithm. The diameter of the floaters are varied in order to achieve a stability index (Static Stability Moment/Wind Moment) equal to unity based on a maximum inclination of the floater of 10 degrees. A block diagram of the calculation steps is provided in **Figure 9** The outputs of the model are provided in **Table 2**. For reference to the exact equations used for the model, refer to Chapter 5, Appendix 3 of the ‘Drijfwind’ report [11].

It is noted that the calculation of the floater sizing negated the inclusion of large plates underneath the columns (heave plates) and other structural elements. The effect of this on the resulting calculation is twofold. The first result of this is that added hydrodynamic mass is lower that otherwise would be the case, ensuring that the calculated vertical heave period is located close to the high energy range of the wave spectrum, which would not be the case with the addition of the heave plates. Furthermore, the suggested value of 0.12-0.16 T/m^3 given in the Drijfwind report for calculating the mass of the structure, whilst this may be appropriate in theory, is too low for the given calculations. The absence of heave plates, which based on the dimensions given for the OC4 semi-submersible in [12], likely account for the same volume (and therefore mass) as the floaters themselves. Also, the simplified calculations negate other components as well as a platform or central support structure to house the wind turbine which may be present. A conservative value of 0.65 T/m^3 is therefore recommended in the OWECOP cost model.

Table 1: Input parameters for calculating mooring and floater dimensions.

Variable	Description
z_platform	Height of Platform
D_Truces	Diameter of Truces
Tower_F_D	Tower Foot Diameter
Tower_Mass	Tower Mass
Tower_Top_Mass	Mass of Rotor, Nacelle, etc.
Tower_F_Th	Tower Foot Thickness
Tower_T_Th	Tower Top Thickness
Tower_T_D	Tower Top Diameter
Tower_Height	Tower Height
Load_Fatig	Fatigue Load
Nr_Floaters	Number of Floaters
water_depth	Depth of Water
kg_m	Mass Per Unit Length of Mooring
num_mooring	Number of Mooring lines
Mooring_Pos	Position of Mooring Line on Floater
VolMassConstr	Mass per Unit Volume of the Floater

Figure 9: Block diagram of the calculation for the floating support structure – Left: Overview of the module, Right: Detailed floater parameter calculation steps.

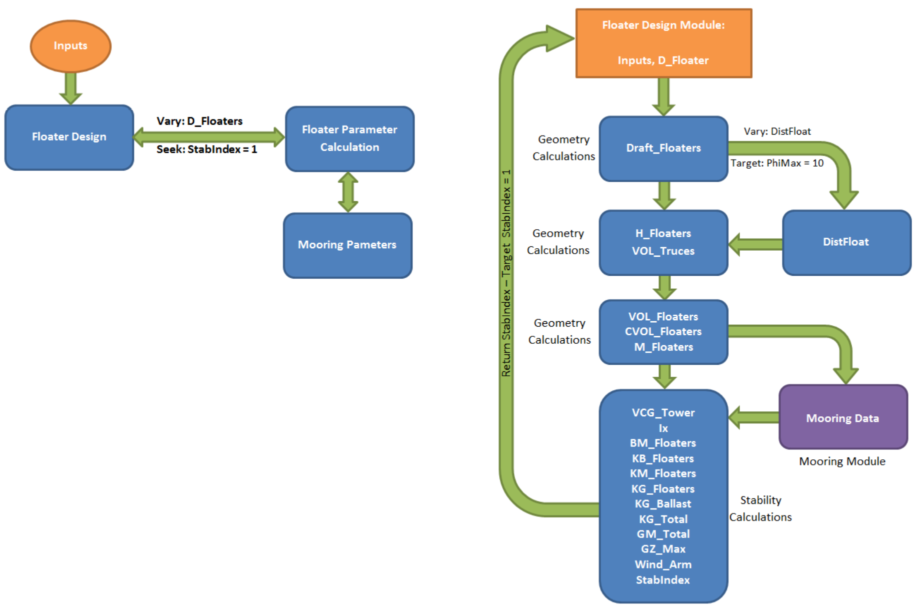


Table 2: Output data from the calculation of the floater design for OWECOP in Python.

Variable	Description
Tphi	Natural Period of Roll and Pitch
GZ_Max	Maximum Arm of Static Stability
KG_Ballast	Vertical Center of Gravity of Ballast
KB_Floaters	Center of Buoyancy of Floaters above BL
Steel_Weight	Weight of Floater and Tower
VOL_Floaters	Submerged Volume of Floaters
Freeb_Floaters	Freeboard of Floater
M_Ballast	Mass of Ballast
VCG_Tower	Vertical Center of Gravity of Tower
D_Floaters	Diameter of Floaters
Kxx	Radius of Gyration for Roll and pitch
StabIndex	Stability Index - Stability Moment/Wind Moment at Phi Max
KG_Total	Vertical Center of Gravity of Floater and Tower
BM_Floaters	Metacenter above Center of Buoyancy
M_Floaters	Mass of the Floaters
Pretension	Vertical Pretension in the Mooring
Draft_Floaters	Draft of Floaters
Total_Mass	Total Mass of the Wind Turbine and Tower
Floater_Cost	Cost of the Floating Structure
DistFloat	Distance between Floaters
Tz	Natural Period of Heave
GM_Total	Metacentric Height of Floater and Turbine
KG_Floaters	Vertical Center of Gravity of Floaters
Ix	Moment of Inertia of Water Plane Area
CVOL_Floaters	Construction Volume of Floater
H_Floaters	Height of Floaters
VOL_Truces	Volume of Truces
Ballast_Percent_Volume	Percentage of Volume of Floater taken up by Ballast
ma	Added Mass for Heave
WindArm	Required Wind Arm at Phi Max
KM_Floaters	Metacenter Height above Keel of Floater
Tz	Natural Period of Heave
GM_Total	Metacentric Height of Floater and Turbine
KG_Floaters	Vertical Center of Gravity of Floaters
Ix	Moment of Inertia of Water Plane Area
CVOL_Floaters	Construction Volume of Floater
H_Floaters	Height of Floaters
VOL_Truces	Volume of Truces
Ballast_Percent_Volume	Percentage of Volume of Floater taken up by Ballast
ma	Added Mass for Heave
WindArm	Required Wind Arm at Phi Max
KM_Floaters	Metacenter Height above Keel of Floater

3.2.2 Mooring data

Inclusion of the relationships for the modelling of mooring data was based on simple relations for catenaries. The possibility exists for the location of the mooring line to be placed on the keel or at the platform height. The basic relationships are defined below.

Based on the height of the mooring location from the surface, the horizontal length of the mooring line can be given by:

$$l = \frac{T_0}{P} cosh^{-1}\left(1 + \frac{Ph}{T_o}\right)$$

Where:

T_0 = Horizontal Tension in Mooring Line
P = Vertical Force per Unit Length
h =Height of the mooring line

This allows the total length of the mooring line to be calculated:

$$l_{Total} = \left(h\left(h + \frac{2T_o}{P}\right)\right)^{1/2}$$

In the model, optimization libraries are utilised in order to calculate the required pretension to achieve the required mooring length. Furthermore, these optimisation libraries are used to take into account the buoyancy of the chain suspended in water.

Properties of the mooring chains and anchors are taken from the cost modelling study by Myhr [13]. In this study, details for mooring are provided for the semi-submersible tri-floater WindFloat system developed by Principle Power which has been demonstrated with a 2 MW turbine. In this study, however, costs were estimated for floater systems housing a 5 MW wind turbine and therefore given numbers are more relevant to systems of this size. The approximations given are €250/m for a chain of 126.5 kg/m. Furthermore, anchor costs are in the order of 110 k€/ anchor.

3.3 Cost model inputs for case studies

In order to give a predication and analysis of the levelized cost of energy of an offshore wind farm, the conditions at the Gemini wind farm (Groningen, Netherlands) are utilised. This allows a comparison of the costs of the between a fixed bottom and floating case with comparisons given to the actual costs given for the wind farm. This section is concerned with the inputs to the OWECOP model as well as details of the available cost data for the Gemini site.

As part of this study, no sensitivity analysis was conducted regarding water depth and distance to shore. Future works regarding cost modelling of offshore floating systems should be conducted with analysis of the variations in these parameters (as well as others) undertaken.

The main parameters given as input to the OWECOP model for the analysis are given in **Table 3**. **Table 4** gives an overview of the cost data that is available for the Gemini wind farm as a comparison. These numbers are compared with the modelled values given in section 3.4.

Table 3: Input parameters given for the Gemini Wind Farm

	GIS Parameters			Assorted Notes
Distance of grid cell to electrical grid on shore	D_grid	**110**	[km]	
Distance of grid cell to harbour	D_harbour	**85**	[km]	
Water depth, distance below MSL	water_depth	**32**	[m]	Values lie between minimum and maximum
Turbine Parameters – Siemens SWT-4.0-130				
cut in wind speed	cut_in	**3.5**	[m/s]	
cut out wind speed	cut_out	**32**	[m/s]	
cp-max (aerodynamic)	cp_max	**0.45***	[-]	*Based on Similar Turbines
nominal turbine power	P_turbine	**4000**	[kW]	
specific power	specific_power	**316**	[W/m^2]	Based on the given rotor area by manufacturer
Wind Turbine Class	turbine_class	**1**	[-]	
Maximum Tip Speed	tip_speed	**95.3**	[m/s]	Calculated based on maximum rotor speed and turbine diameter
Farm Parameters				
number of turbines in the farm	N_OWEC	**150**	[-]	
number of turbines in a group	Nturb_per_group	**12**	[-]	
spacing (x); distance in a line of turbines	spacing_x	**5.5***	[diameters]	Based on the area of 34 sq. km per section and 12x6 turbines in each section with equal spacing
spacing (y); distance between the turbine lines	spacing_y	**5.5***	[diameters]	As above
technical life time wind farm	life_time_farm	**20***	[years]	Contract for O&M at Gemini is actually 15 years. Assumption of 20 is used regardless
technical life time E-infra	life_time_E_infra	**20**	[years]	
technical life time HV-connection	life_time_HV_cable	**20**	[years]	
nr. of measuring towers	nr_meatow	**0**	[-]	

Electrical Infrastructure Parameters				
Power Transportation to Shore	P_trans_method	**AC**	[-]	
voltage of cable to shore	HVac	**220**	[kV]	
maximum current of cables HVAC	Imax_hv	**1800**	[A]	Two cables to shore - Gemini
maximum current of cables MVAC	Imax_mv	**5000**	[A]	33 kV in field voltage in both cases
number of cable crossings (cable to shore)	Ncross	**2***	[-]	2 cables with 2 crossings (4 total)

Table 4: Available cost data for the Gemini Wind Farm

Construction Costs		
Siemens Turbines	800	M€
Van Oord BOP	1300	M€
Other (Studies, grid, cont., etc.)	300	M€
Financing Costs	**400**	M€
Total Cost of Project	**2800**	M€
Decommissioning Costs	**40**	M€
Project Funding		
PCR	200	M€
Equity	400	M€
Junior Debt	200	M€
Senior Debt	2000	M€

Besides the modification to the substructure, the OWECOP model has no built in functionality for modelling other factors such as installation and O&M that contribute to a varying LCOE between floating and the fixed bottom case. In order to give a better indication as the LCOE, various modifications are made to the results.

Installation costs in the OWECOP model are difficult to validate due to the complex nature of the equations in Excel and also due to the period of model implementation meaning they may not be representative of current day costs. Therefore, in order to give a better indication of the installation costs, the results from the OWECOP model are negated and replaced with the results for the installation costs modelled by ECN Install. This methodology of modelling gives far greater confidence in the results of the simulations. This is done for both the fixed bottom as well as the floating case.

Furthermore, the move to floating structures for the wind turbine means that likely the Operation and Maintenance of the wind farm may be altered. ECN predicts that a reduction in the O&M costs by approximately 35% can be achieved in some cases with a negligible reduction in availability of the wind farm through a modified strategy. The floating crane vessel that is used in offshore operation and maintenance is costly and also requires specific weather conditions which increase the cost due to prolonged waiting times. Towing of the floating turbines to sheltered locations whereby O&M can be conducted is a way of achieving this reduced cost. In order to account for this likely reduction in operation and maintenance cost in this study, in comparison with the case of a standard O&M strategy, another case is provided where there is the same relative percentage decrease (35%) in the levelized O&M costs based on the referenced study.

3.4 Results of cost modelling studies

This section presents the results of the cost modelling studies comparing both the cost of the Gemini wind farm for the fixed bottom and the floating cases. The capital costs are compared for both cases as well as the effect on the overall levelized cost of energy. The difference in the results of the models lie in the turbine and support structure elements as well as the installation. A third case of a floating wind farm with reduced operation and maintenance costs is also included for comparison.

For the analysis, the predicted energy yield based on the wind resource, wake prediction and availability calculation resulted in a yearly energy yield of 1622 GWhr/year (capacity factor 31%). The stated expected energy production of the Gemini park is quoted as 2600 GWhr/year (capacity factor 49%). A known discrepancy of the OWECOP cost model is that the wind resource at the site is under predicted. Investigations have identified this is attributed to use wind resource data which is not suitable for the location, under prediction of the power output of the turbine around rated power, over prediction of the wake losses due to the calculation of the thrust coefficient, and the tower height being lower than is realised in the wind farm. Updates in these areas will be implemented in future iterations of the model. Despite the limitation of the model in this area, when comparing various cases, the relative difference in cost estimates are still relevant.

The capital (CAPEX) costs of the farm are compared in **Table 5** and **Figure 10** for both cases. As well as this, for the Gemini park, as it is being constructed, the possibility of comparing this with the actual park costs is possible as seen in **Table 5**. Despite the costs of the wind farm being available, the details of these costs, and what is and is not inclusive is somewhat unclear making a direct comparison difficult.

The turbine costs (assume to be the tower and nacelle assembly) are under predicted in the OWECOP model by 266 M€ or 33% and other capital costs in the order of 587 M€ or 43%. When looking at the relative CAPEX per installed capacity, not including the costs of financing, the calculated costs are 4000 €/kW, compared with the predicted OWECOP price of 2413 €/kW. The reported value from Gemini seems high when considering the OWEZ wind farm had a reported CAPEX per installed capacity of approx. 2083 k€/kW. This makes it difficult to validate the data without having a more detailed breakdown of these capital costs.

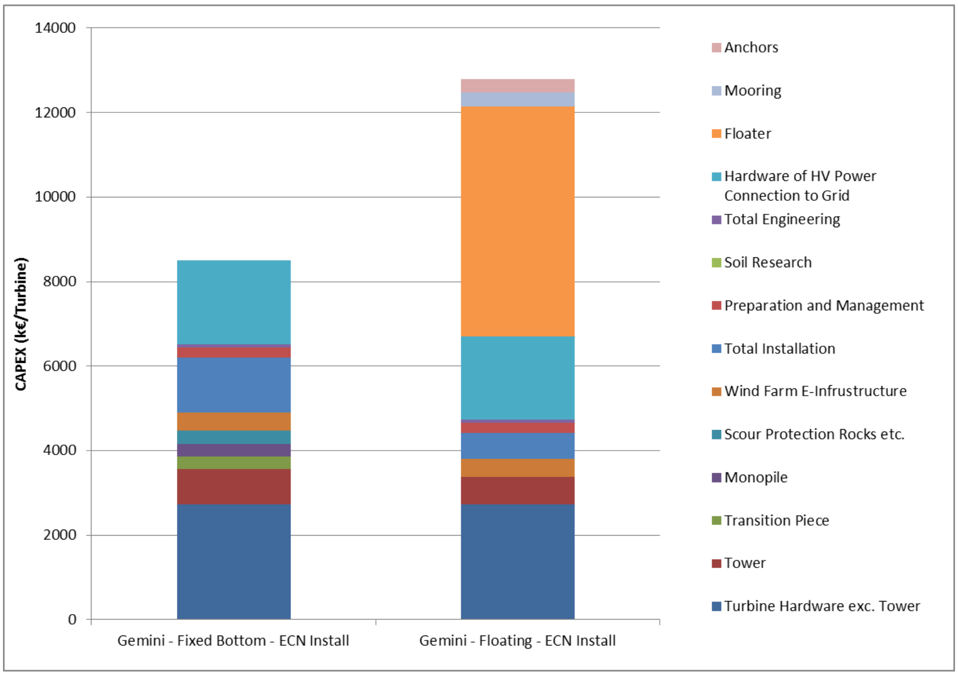
Table 5: Results comparison of capital costs

	Actual	Fixed Bottom	Floating
Turbine Costs - ass. Nacelle Assembly and Tower (M€)	800	534	506
Other Capital Costs(M€)	1600	913	1388
CAPEX/Installed Capacity (€/kW)	4000	2413	3157

CAPEX of the fixed bottom wind farm are calculated at 1448 k€/turbine (2413 k€/kW) for the fixed bottom case, and calculated at 1894 k€/turbine (3157 k€/kW) for the floating case. This represents a relative increase of 31% if the Gemini wind farm was to be constructed using semi-submersible floaters.

The capital cost difference in the model is limited to the transport and installation, as well as tower and support structure. The total installation costs for the wind farm are calculated form the ECN Install tool to be 196 M€ for the fixed bottom and 91 M€ for the floating case. It is therefore estimated that installation costs can be reduced by 54% by moving away from a traditional support structure. Despite this large reduction in cost, the results, as illustrated in **Figure 10** show the large floater cost, which significantly increases the CAPEX cost. The support structure cost of the fixed bottom system is 843 M€ for the farm whilst the floating costs are calculated at 1394 M€, representing a 65% increase in the cost. It should be noted that the mass of the support structure is calculated to be 1500 T in the OWECOP model. The OC4 support structure has a reported mass of 3800 T [2] which is concerning. It is therefore possible that the model utilised for the basic design of the floater structure is under predicting both mass and cost, which may indicated the 65% increase that is calculated is too conservative. Further investigation is required to validate the reasons for this.

Figure 10: Breakdown of the CAPEX costs for Bottom Mounted and Floating Cases



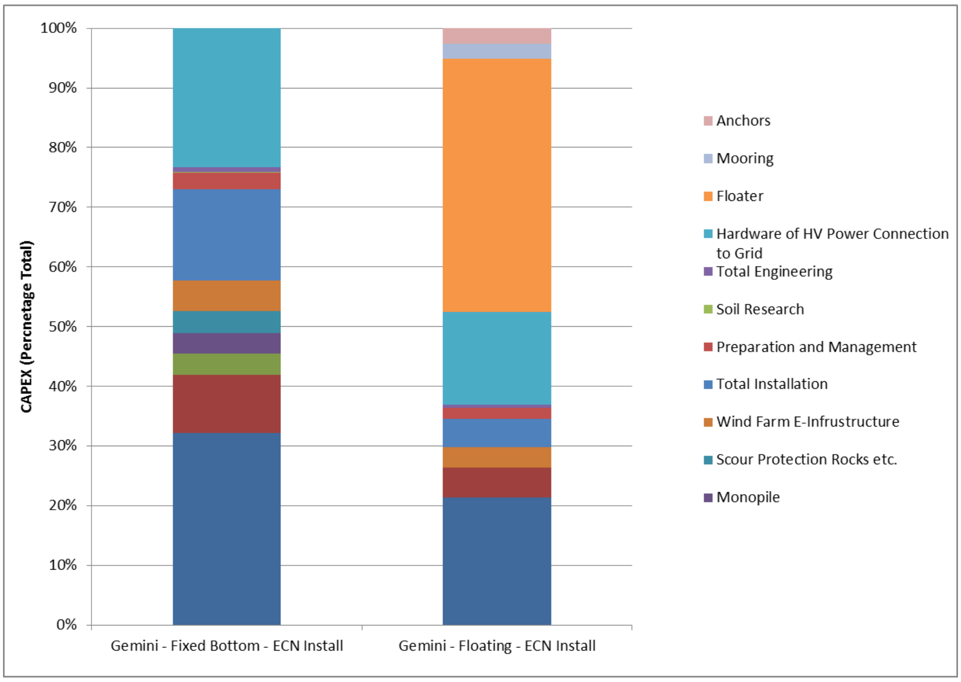
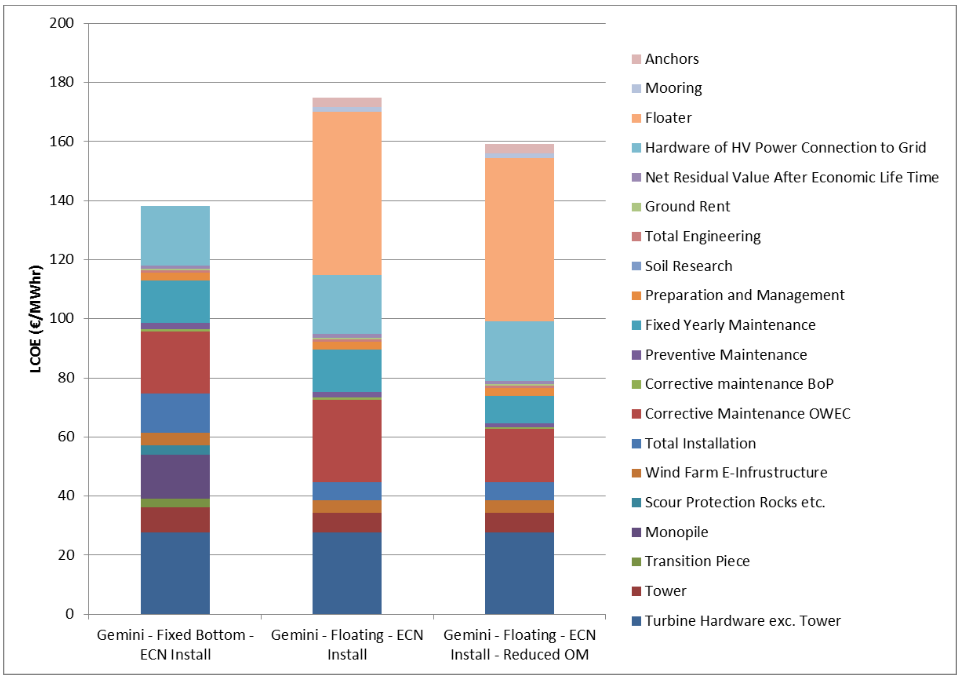
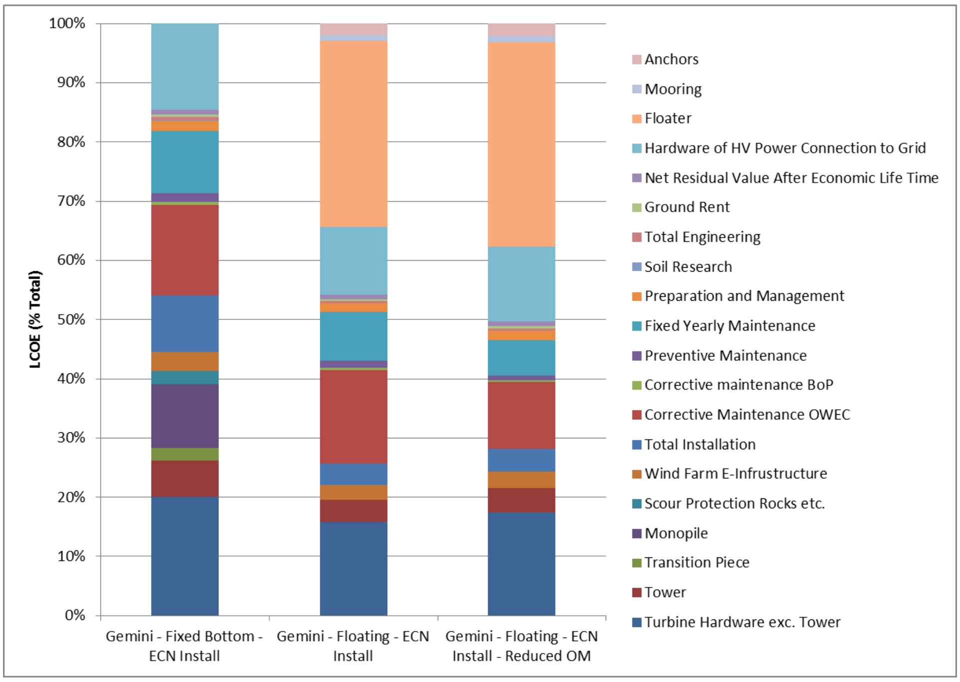


Figure 11 and **Figure 12** give a breakdown of the total costs which contribute to the overall LCOE. **Figure 11** provides a breakdown listing all the main costs, whilst **Figure 12** provides more of an overview as to the main components to the cost breakdown. As indicated previously, for the floating case, two cases are presented, one whereby the O&M costs are the same as that of the fixed bottom case, and a second whereby they are reduced by 35%, an ECN estimate as to the reduction in O&M costs if the turbines can be towed to a sheltered area at shore in which maintenance can be carried out.

Figure 11: Breakdown of the LCOE of all Wind Farm Expenditures



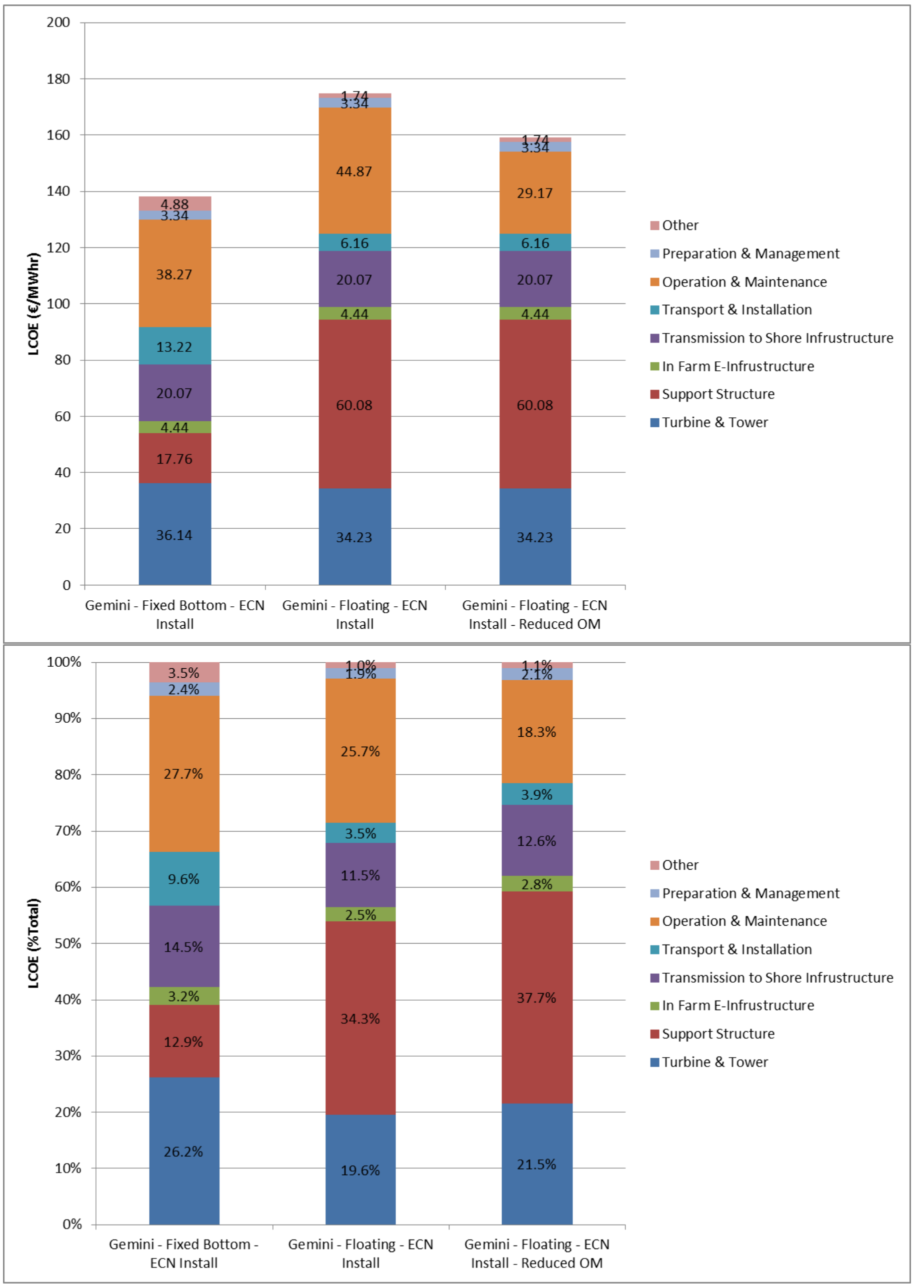


The LCOE of the bottom fixed wind farm was calculated as being 138 €/MWh. For the floating case, the LCOE for the case for the standard O&M strategy was calculated at 174 €/MWh (increase 26%) whereas for the modified O&M strategy was calculated as 159 €/MWh (increase 15%).

Turbine and tower costs are closely matched between the cases. With the floating case, the tower dimensions are somewhat altered through the design procedure in order to achieve a soft-stiff design which results in a 1.91 €/MWh reduction in the LCOE. Despite this, as covered previously, the support structure supply cost increases by 42.3 €/MWh, which is a 238% increase in supply costs.

O&M costs for the floater are increased by 6.6 €/MWh from the fixed bottom case. Despite the same O&M strategy, the increase in the cost is attributed to the higher CAPEX which is used as an input for determining the OPEX costs. With the reduction in the O&M costs due to the modified strategy however, it is estimated that O&M costs are reduced by 9.1 €/MWh. This represents a 24% reduction in O&M costs for the wind farm between the fixed bottom and floating cases. This result means that the O&M costs take up a lower (18.3%) proportion of the total LCOE when compared with the fixed bottom case (27.7%).

Figure 12: Breakdown in the LCOE of Primary Wind Farm Expenditures



3.5 Conclusions and further works

This chapter outlines the cost modelling work conducted as part of the TO2 project. The ECN developed OWECOP cost model was updated to account for a semi-submersible floating wind energy support structure as well as the associated mooring chains and anchors by utilising engineering design relationships. The mass of the various components was calculated and then related to the cost of the various components.

To demonstrate the results of the updated OWECOP model, details of the Gemini wind farm (Netherlands) were input to the OWECOP model for bottom fixed foundations (monopile) as well as utilising the new floater relationships. The outputs of the OWECOP model were combined with those from ECN Install as this provides a more accurate method of the calculation of installation costs. A third case was also provided which had reduced O&M costs based on a changed O&M strategy where the turbines are towed to shore for heavy maintenance.

The LCOE of the fixed bottom wind farm was calculated as being 138 €/MWh. For the floating case, the LCOE for the case for the standard O&M strategy was calculated at 174 €/MWh (increase 26%) whereas for the modified O&M strategy was calculated as 159 €/MWh (increase 15%). The large increase in the LCOE is attributed to the large floater which requires a large mass of steel. The support structure capital cost was increased from 843 M€ for the farm with fixed bottom foundations, whilst for the floating case, the capital costs are calculated at 1394 M€, representing a 65% increase in the cost.

The following recommendations are made for future works to be conducted in regards to cost modelling of the offshore floating support structures within the OWECOP model:

- Update OWECOP model for better prediction of the energy yield. The causes are known and thus, should be possible in a short time frame
- Further verification and validation of the offshore floater design due to discrepancies with the OC4 design [12]
- Determine modifications to other areas of the farm (i.e. electrical infrastructure) when floating platforms are utilised
- Inclusion of ECN Install within the OWECOP model
- Update the ECN O&M tool within OWECOP for offshore floating wind energy strategies.

4
Conclusions

In the current report and under the framework of the TO2 project, a cost comparison was performed between a wind farm using monopiles as support structures and the corresponding floating one. This section provides the main conclusions of the work.

Starting with the installation costs, the results provided by ECN Install tool indicate that moving from a bottom-fixed foundation wind farm to a floating one can save as much as 50% of the installation costs. This cost advantage of floating wind farms is detected in the possibility for onshore assembly and the direct transportation of the entire structures to the wind farm location by using tug-boats. However, delays due to weather are not expected to be less for floating wind farms because of long and highly weather dependent travelling steps from the harbour locations to the wind farm.

As far as the fabrication costs are concerned, OWECOP cost model calculated 65% higher costs for the semi-submersible floater compared to the monopile for the case studied in this work. Taking into account the reduced O&M costs that are expected for floating wind farms, the LCOE of the fixed bottom wind farm is calculated at 138 €/MWh, lower compared to the semi-submersible concept which was calculated to be 159 €/MWh.

To sum up, the results capture the higher costs expected for floating wind at the current state of development. However, the figures provided by this work correspond to a specific case and generic conclusions should not be drawn. Nevertheless, knowledge was developed in this work in terms of modelling floating wind farms. On the one hand, ECN Install tool was updated in order to model the installation planning with greater accuracy and as it was shown, floating wind farms installation modelling can prove their added value. On the other hand, OWECOP cost model was enhanced to include cost calculations of the semi-submersible floating concept. Combining these two, a detailed cost overview of floating wind farms is available and useful insights about their further development are provided.

References

[1] A. Dewan, M. Asgarpour, and R. Savenije, "Commercial proof of innovative offshore wind installation concepts using ECN Install tool," 2015.

[2] A. Dewan, M. Asgarpour, M.H.R. Stuurman, "ECN Install User Manual v2.0," 2015.

[3] M.H.R. Stuurman, "Development GUI ECN Install 2.0," Internship Report, TU Delft, Delft University of Technology, 2015.

[4] G. Katsouris, "Cost Modeling of the Installation of Offshore Wind Farms," Internship Report, TU Delft, Delft University of Technology, 2015.

[5] 4C Offshore, "Gemini Offshore Wind Farm." http://www.4coffshore.com/windfarms/gemini-netherlands-nl18.html. Accessed 15 October 2015.

[6] A. Arapogianni, A. Genachte, R. M. Ochagavia, J. Vergara, C. Castell, A. R.Tsouroukdissian, J. Korbijn, N. Bolleman, F. Huera-Huarte, F. Schuon, et al., "Deep water - the next step for offshore wind energy.," European Wind Energy Association (EWEA), Brussels, Belgium, ISBN, pp. 978–2, 2013.

[7] V. Parab, "Comparison of Installation time and cost for Floating wind farms," Internship Report, TU Delft, Delft University of Technology, 2015.

[8] Technip, "Hywind Demo - Technip Experience with Offshore Wind," 2015.

[9] Roddier, D., Cermelli, C., Aubault, A., & Weinstein, A. (2010). WindFloat: A floating foundation for offshore wind turbines. Journal of Renewable and Sustainable Energy, 2(3), 033104.

[10] Carbon Trust, "Floating Offshore Wind: Market and Technology Review," 2015.

[11] A. Henderson, B. Bulder, M. van Hees, R. Huijsmans, E. Snijders, J. Pierik, and G. Wijnants, "Study to feasibility of and boundary conditions for floating offshore wind turbines," Public Rep., no. December, 2002.

[12] A. Robertson, J. Jonkman, and M. Masciola, "Definition of the Semisubmersible Floating System for Phase II of OC4," no. September, p. 38, 2014.

[13] A. Myhr, C. Bjerkseter, A. Ågotnes, and T. a. Nygaard, "Levelised cost of energy for offshore floating wind turbines in a life cycle perspective," Renew. Energy, vol. 66, pp. 714–728, 2014.

ECN
Westerduinweg 3
1755 LE Petten
The Netherlands

P.O. Box 1
1755 LG Petten
The Netherlands

T +31 88 515 4949
F +31 88 515 8338
info@ecn.nl
www.ecn.nl